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Contributor contact details

(* = main contact)

Editor

Dr Jamal M. Khatib
School of Engineering and the Built Environment
University of Wolverhampton
Wulfruna Street
Wolverhampton
WV1 1LY
UK

E-mail: j.m.khatib@wlv.ac.uk

Chapter 1

William H. Langer
Research Geologist
United States Geological Survey
MS 973, PO Box 25046
Denver
CO 80025
USA

E-mail: blanger@usgs.gov

Chapter 2

Dr M. Asif
School of the Built and Natural Environment
Glasgow Caledonian University
Cowcaddens Road
Glasgow
G4 0BA
UK

E-mail: Muhammad.Asif@gcal.ac.uk

Chapter 3

Dr Holmer Savastano Jr*, S. F. Santos and V. Agopyan
Faculdade de Zootecnia e Engenharia de Alimentos
Universidade de São Paulo
Av. Duque de Caxias Norte, n. 225
13635-900, Pirassununga
São Paulo
Brazil

E-mail: holmersj@usp.br

Chapter 4

Dr Pav Bingel* and Dr A Bown
School of the Built Environment
Leeds Metropolitan University
Leeds
LS1 3HE
UK

E-mail: p.bingel@lmu.ac.uk

Chapter 5

Mette Glavind
Danish Technological Institute
Concrete Centre
Gregersensvej
2630 Taastrup
Denmark

E-mail: mette.glavind@teknologisk.dk

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Chapter 6

Professor Paul Lambert
Mott MacDonald Visiting Professor
Centre for Infrastructure Management
Sheffield Hallam University
Sheffield
UK

E-mail: paul.lambert@mottmac.com

Chapter 7

Dr Chris Atkins
Materials and Corrosion Engineering
Mott MacDonald
Spring Bank House
33 Stamford Street
Altrincham
Cheshire
WA14 1ES
UK

E-mail: Chris.atkins@mottmac.com

Chapter 8

Assoc Prof H R Milner
Department of Civil Engineering
Monash University
Wellington Road
Clayton
Victoria 3800
Australia

E-mail: Bob.Milner@eng.monash.edu.au

Chapter 9

Dr Nikolaos Oikonomou* and S. Mavridou
Laboratory of Building Materials
Department of Civil Engineering
Aristotle University of Thessaloniki (A.U.Th),
PO Box 482
541 24
Greece

E-mail: ikonomou@civil.auth.gr; smavrido@civil.auth.gr

Chapter 10

Dr Jiping Bai
Department of Engineering
Faculty of Advanced Technology
University of Glamorgan
Pontypridd
Mid Glamorgan
CF37 1DL
UK

E-mail: jbai@glam.ac.uk

Chapter 11

Associate Professor Mette Rica Geiker*
Department of Civil Engineering
Technical University of Denmark
Brovej, Building 118
DK-2800 Kgs. Lyngby
Denmark

E-mail: mge@byg.dtu.dk

Dr Maj Munch Andersen
Department of Management Engineering
Technical University of Denmark
Building 426
DK-2800 Kgs. Lyngby
Denmark

E-mail: mmua@man.dtu.dk

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Introduction

J. M. KHATIB
University of Wolverhampton, UK

Sustainable development is defined as 'a development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987). It is a broad term covering economic, social and environmental issues. Sustainable development should be shaping the future of our planet and those living on it. Human activities, such as construction, are having an impact on our environment. The construction industry consumes large amounts of raw materials; for example, in the United Kingdom alone, with a population of only 61 million, the annual consumption of material resources amounts to an alarming 420 million tonnes, and 6500 hectares of land are converted from rural to urban areas annually (Environment Agency website, www.environment-agency.co.uk). The extraction, processing and transportation of these resources cause large emissions of carbon dioxide (CO_2) into the atmosphere and thus contributes to the pollution of the environment. The world consumption of these natural resources, especially by the construction industry, can not be sustained at the present rate. Therefore, construction professionals – including practising engineers, environmentalists, construction managers, researchers and academics – have a major role to play in sustaining our environment. This can be achieved through efficient utilisation of natural resources, re-use and recycling of waste.

There are many published books on construction materials. These books mainly focus on the engineering properties of such materials and few are devoted to environmental issues and sustainability. This book on sustainable construction materials aims to serve those professionals involved in construction in helping to achieve a sustainable environment. In addition to covering some fundamental properties of traditional construction materials that are used in construction, the book benefits from sections devoted to sustainability. This includes life cycle assessment, embodied energy and durability of construction materials. The construction materials that were examined in this book include aggregates, concrete, masonry, timber, metals, glass, natural fibres, fibre composites and waste rubber.

Aggregates are the dominant materials that are used in construction applications. Therefore, the first chapter of the book considers the sustainability of aggregates in construction. The ways in which aggregates are produced – covering extraction and processing, transportation and reclamation – are described. The

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potential environmental impacts and their mitigation are also dealt with in the chapter. This covers aspects such as changes to the landscape, noise and dust, vibration from blasting, impact on ground water and surface water, impact from transportation and energy consumption. Managing impacts through best management practice is also discussed. Other sections of this chapter discuss the performance of aggregate in use, substitutes and manufactured aggregates, waste products from aggregate mining and processing, and how to extend aggregate availability through recycling. The sustainability of natural aggregates covering the environmental, economic and societal values and their responsibilities are described. Life cycle assessment of aggregate operations is explained as well as general approaches and issues related to sustainable aggregate resource management. Four case studies on the sustainability of aggregates from various parts of the world are included. The first case study is concerned with government actions for resource protection and environmental restoration in Italy, while the second case study deals with government and conflict resolution in Canada. An example of corporate social responsibility for a quarry expansion is dealt with in the third case study and the fourth case study is on industry and transportation issues. The chapter concludes with a discussion of the future trends for aggregates in construction.

The sustainability of timber, wood and bamboo as construction materials is the subject of Chapter 2. The chapter starts by describing the types of wood (soft and hard), followed by the chemical composition, growth and structure, and seasoning (air and kiln) of wood. Sustainability of wood is described in general. Next, the durability/degradation and preservation of the wood – including treatment types, application of preservatives and the associated European standards – are illustrated. Wood repair using various methods (e.g. manual, mechanical) is also covered followed by the disposal of wood and recycling. The chapter includes a section on wood composites including cement and polymer composites; however, engineered wood products are dealt with in detail in Chapter 8. The final section is dedicated to bamboo, and describes the structure and properties of bamboo followed by its applications and sustainability.

Chapter 3 is concerned with the sustainability of vegetable fibres in construction. At the beginning of the chapter, there is general information related to the availability and extraction of fibre, the manufacturing and processing of the raw materials from which the various types of fibres (e.g. sisal, coir, bamboo, sugar cane, banana, jute) are derived, and the advantages and disadvantages of using vegetable fibres. The general uses of the different types of fibres, including their use in cement- and polymer-based composites, as well as the environmental benefits of using vegetable fibres are included in the chapter. The chapter includes a case study on the use of vegetable fibre in cement-based composites. This covers the raw materials required, preparation, testing methods, weathering conditions, mechanical and physical properties and the production of roofing materials (e.g. roofing tiles) using vegetable fibres. The chapter demonstrates that

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using vegetable fibres plays a role in sustaining the environment and can have important social and economic functions.

The fourth chapter of this book explores the sustainability of masonry in construction. After the general information on masonry, the manufacturing processes for masonry units and mortar are described. This includes the various types of bricks (fired and unfired clay) and concrete blocks (aggregate and autoclaved aerated), and mortar. The various standards related to masonry are indicated followed by the various properties of masonry. Properties include engineering properties such as strength, density and dimensional stability, durability properties (e.g. freeze–thaw), absorption and fire resistance. The historical use of masonry is described in a separate section. There is a comprehensive section on sustainability. This section starts by stating the general aspects of sustainability and moves on to quantifying the sustainability of masonry using different types of profiles: cradle to factory gate, cradle to installed-on-site and cradle to grave. The various tools for assessing the environmental and economic performance are included. Whole-life costing, reclamation, recycling and thermal mass are also described in this section. Four UK examples on sustainable masonry construction are included in the chapter. The first two examples are the Beddington Zero Energy Development and Winterton House in London. The third example is Queen Square in Leeds while the fourth is the Community Centre at Swaffham in Norfolk. The last section of the chapter is devoted to future developments in masonry construction.

Concrete is consumed in large quantities in construction. Each human being consumes one tonne of concrete per year, which makes it the substance with the second-highest consumption, only water is higher (Concrete Centre, 2003). Chapter 5 of the book is dedicated to the sustainability of cement, concrete and cement replacement materials in construction. After the general introduction, there is a section on life cycle aspects of concrete, followed by a section on the raw materials required to make concrete. These raw materials include cement, supplementary cementitious materials, aggregates and admixtures. The production of cement, the various types of blended cement and new clinker types are described. With regard to supplementary cementitious materials, the natural pozzolans, by-products, inert fillers and manufactured products are described. Natural aggregate and recycled aggregate are covered. In the section on the manufacturing of concrete, various aspects of sustainability are covered. These include: the re-use/recycling of concrete materials such as aggregates and water; environmental impact and the use of self-compacting concrete; energy from plants; transportation; and optimisation of concrete mix design. The various uses of concrete are highlighted, and the section on demolition and recycling also covers CO_2 uptake during carbonation. The chapter benefits from three case studies on sustainable construction. The first case study is on CO_2 uptake for a roof tile and an edge beam. A concrete bridge with various green solutions is the subject of the second case study, while the third case study is concerned with the reduction of energy for heating and cooling. The future trends of concrete in construction are also covered. In addition there is an

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additional chapter (Chapter 10), as will be described later, that is concerned with concrete materials.

Metals and alloys are established materials that are used in construction and these are described in Chapter 6. An overview of the chapter is included in the introduction, which describes various features such as recycling and life cycle assessment. The chapter consists of various sections covering ferrous alloys, stainless steel and non-ferrous metals and alloys. In the ferrous alloy section, cast iron, wrought iron and steel are described. There is a comprehensive description of the various types of stainless steel including, ferritic, austenitic, martensitic, precipitation hardening and duplex stainless steel. In the non-ferrous metals and alloy section, there are descriptions of aluminium, copper and copper alloys, and lead. There is also a section on weathering steels. Corrosion is related to durability, thus the various types of corrosion are described including general, pitting, crevice, galvanic and high-temperature corrosion. Other aspects relating to sustainability and durability, such as corrosion protection and prevention (e.g. cathodic protection) are also described. Furthermore, and towards the end of the chapter, a section on future trends is included indicating the need to prolong the life of components with the least maintenance.

The sustainability of glass in construction is reported in Chapter 7. The chapter covers the history of glass, glass manufacture and its composition, and the various types of glass and their usage. The re-use, recycling, geographical constraints and alternative uses of glass are described. Data on the recycling rate across Europe are included. There are specific sections on the use of glass in bound materials (such as concrete and bituminous mixtures) and non-bound materials (such as roadbase and aggregate in water treatment plants as replacement for the sand).

Dealing with the waste generated by the timber industry presents potential problems. For this reason, Chapter 8 of the book is concerned with the sustainability of engineered wood products in construction; this chapter is different from Chapter 2 which deals with wood, timber and bamboo. The chapter deals with adhesively bonded wood and timber that are mainly made from waste in order to produce high-grade structural elements and thus contribute to the sustainability of our environment. The chapter starts by a general introduction and description of wood and sawn timber products. There are then detailed descriptions of the applications and manufacture of the various types of products including finger jointed timber, structural glulam, structural composite lumber, structural I-beams, oriented strand board, plywood, chipboard and fibreboard. A section on structural life and service environment is included followed by a section on sustainability, life cycle assessment and embodied energy. Structural adhesives are the subject of another section which includes specification of performance requirements. Two case studies are reported, the first is the glued laminated timber construction of the Australian Maritime Museum while the second case study is the Superior Dome at Northern Michigan University, USA.

The use of waste tyre rubber in civil engineering works is the subject of Chapter

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9. The chapter describes the use of waste tyre rubber in mortar and concrete applications, pavement (asphalt mixtures) applications and geotechnical applications, as well as other applications. With regard to the section dealing with mortar and concrete applications, different properties are described including the effect on the workability, strength and microstructure, as well as the durability properties, of mortar/concrete when waste tyre is included in the mixture. As far as the pavement applications are concerned, the wet and dry processes for producing rubberised asphalt mixtures are described and the effect of incorporating waste tyre on the properties of asphalt mixtures is examined. In the description of geotechnical applications, the physical and mechanical characteristics of soil modified with waste tyre are highlighted; these include compaction characteristics, permeability, conductivity, shear strength, consolidation and bearing capacity ratio.

As mentioned earlier, concrete material is used in large quantities in construction applications. Chapter 10 deals with parameters that affect the durability of sustainable construction/concrete materials, which are not highlighted in Chapters 5 and 6. Various parameters that affect durability are described in the chapter; these include, freeze–thaw and abrasion, cracking, alkali–silica reaction, sulphate attack, chloride-induced corrosion and efflorescence.

Nanotechnology is going to play an important role in the sustainability of the built environment in general and the construction industry in particular. This book benefits from the inclusion of Chapter 11 on nanotechnologies for sustainable construction. At the beginning, the chapter defines nanotechnology and describes the potential benefits for the construction industry. This is followed by a section on health and environmental risks. The chapter describes many examples of the potential applications of nanotechnology in construction. These include: nanostructured materials, such as insulation materials and cement pastes with altered microstructure; nanostructured surfaces, including ultraviolet-hardening painting; nano-optics, such as optical sensors for intelligent sensors; nanosensors and -electronics, such as embedded wire sensors; nano-related integrated energy production and storage, such as polymer solar cells; and integrated environmental remediation, such as self-cleaning and pollution by photocatalysis.

Owing to the nature of this book and the fact that different construction materials – such as brick, concrete, steel and timber – are normally used in construction projects to produce, for example, a structure, a certain amount of duplication is bound to occur; however, this has been kept to a minimum. In addition, since this book deals with sustainability, different authors have used different approaches to sustainability and this should enhance the content of the book.

Finally, this book should provide a good source of reference of great benefit to all those professionals involved in the construction industry. These include practicing engineers, construction managers and associated professionals, environmentalists, policy makers, researchers and academics. Undergraduate and postgraduate students will also find this book very useful. It is intended that future editions of this book will cover other construction materials such as earthen

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construction and bituminous materials. It is hoped that this book will increase awareness of using natural resources for construction applications more efficiently and contribute towards achieving sustainable development.

References

Concrete Centre (2003), Sustainable development in the cement and concrete sector, Concrete Centre, Project Summary 2003, www.concretecentre.com.

World Commission on Environment and Development (1987), *Our Common Future*, Oxford University Press, Oxford.

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Sustainability of aggregates in construction

W. LANGER
United States Geological Survey, USA

Abstract: Aggregate consists of manufactured crushed stone and sand created by crushing bedrock, and naturally occurring unconsolidated sand and gravel. The infrastructure created using aggregate is a major contributor to our current standard of living. Maintaining our lifestyle, passing that lifestyle on to our progeny, and supporting others to achieve developed nation status, will require huge amounts of aggregate. This chapter describes the aggregate industry and sustainable aggregate resource management, including the complex environmental, societal, and social issues associated with the exploration, mining, processing, transportation, and recycling of aggregate resources, and the reclamation of mined-out aggregate deposits.

Key words: aggregate, gravel, crushed stone, sustainability

1.1 Introduction

Natural aggregate consists of manufactured crushed stone and sand created by crushing bedrock, or naturally occurring unconsolidated sand and gravel. It is a major component of asphalt and concrete, and is required in streets, highways, railroads, bridges, buildings, sidewalks, sewers, power plants, and dams – just about every part of the built environment. Aggregate is the world's number-one non-fuel mineral commodity in terms of both volume and value (Fig. 1.1). During 1998, worldwide, about 20 billion tonnes of aggregate worth about 120 billion Euros were produced (Wellmer and Becker-Platen, 2002). Worldwide demand is estimated to be rising by 4.7% annually (Bleischwitz and Bahn-Walkowiak, 2006).

This chapter describes the natural aggregate industry and methods to sustain aggregate resources. Sections 1.2–1.6 describe aggregates and the aggregate industry including: Section 1.2 – production, transport, reclamation, potential environmental impacts, and methods to manage those impacts; Section 1.3 – substitutes; Section 1.4 – recycling; Section 1.5 – performance in use; and Section 1.6 – waste products from aggregates. Sections 1.7 to 1.9 describe sustainable aggregate resource management (SARM), including: Section 1.7 – the environmental, economic, and social aspects of SARM; Section 1.8 – the status of SARM; and Section 1.9 – general approaches to SARM. Section 1.10 contains four case studies. Section 1.11 discusses the future of SARM and Section 1.12 describes sources of further information.

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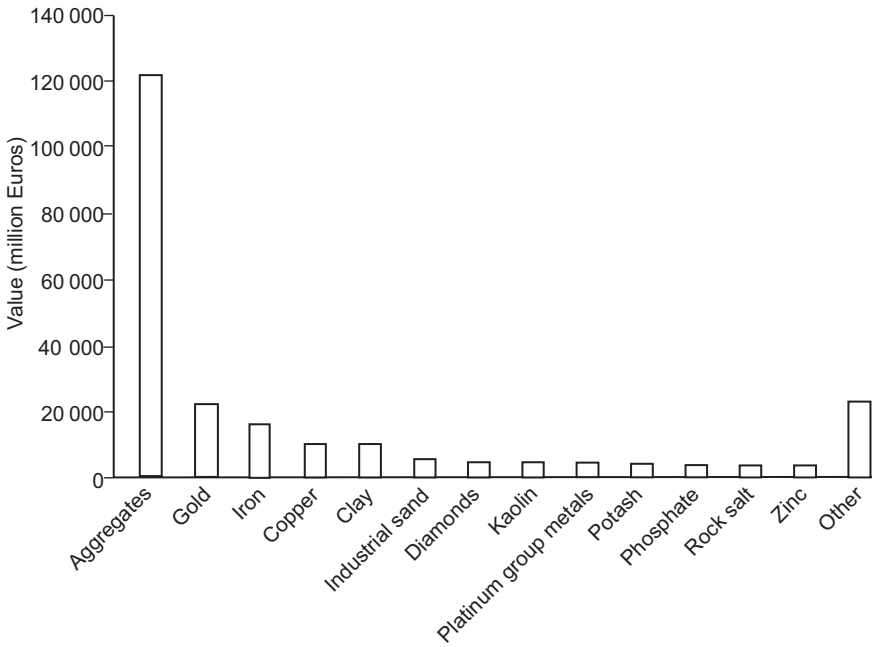

1.1 Graph showing the value of worldwide non-fuel mineral production during 1998. Data from Wellmer and Becker-Platen (2002).

1.2 Production of aggregate

If aggregate is to be produced from new sources, certain conditions must be met.

- Sand, gravel, or rock must exist in sufficient quantity and quality to make mining worthwhile, and it must be accessible to transportation systems and to markets.
- The property must be of sufficient size to locate a pit or quarry and processing equipment, and be owned by a person or people willing to sell or lease it at a reasonable price.
- The deposit must physically be able to be mined without causing unacceptable impacts to the environment.
- The extraction and processing site must qualify for all necessary permits.
- The approving officials and the public must be convinced that the operation can take place without adversely affecting the environment or their lifestyle. In other words, the operator must be able to obtain a 'social license' to mine.
- The operation must be profitable considering all costs including: exploration, acquisition, permitting, operation, environmental controls, compliance with regulations, transport to market, and reclamation.

The production of aggregate involves extraction and processing of the raw

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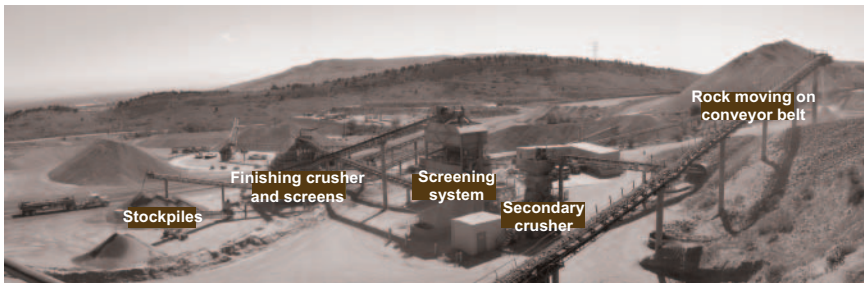

1.2 Typical crushed stone processing plant.

material into a useable product, transport of that commodity to the point of use, and the reclamation of mined-out pits or quarries. The following is a general description of the production of natural aggregate. More detailed discussions can be found in the sources of further information listed in Section 1.12.1.

1.2.1 Extraction and processing

Sand and gravel deposits commonly are excavated from pits utilizing conventional earth-moving equipment. Mining crushed stone generally requires drilling and blasting of solid bedrock (also referred to as ledge or ledge-rock), which breaks the rock into rubble of a size suitable for crushing. Crushed stone and sand and gravel commonly are obtained from dry pits or quarries, but in some settings may be mined from water-filled excavations using dredges mounted on barges, or with draglines.

Sand and gravel or rock rubble at the mine face are transported by truck or conveyor to a processing plant. The material is crushed, passed over a screening device, and sorted according to size (Fig. 1.2). The crushing, screening, and sorting process is repeated until the proper mix of particle sizes is reached. Sand and gravel may or may not be crushed, depending on the size of the largest gravel particles and the desired product. Depending on the specifications of the final product, the processed material may be washed to remove dust. Sand may be screened from the mixture and processed separately. After screening, sorting, and washing (if necessary), the sand and different size gravel/rock particles are moved by conveyors to separate stockpiles where they are stored until sold and shipped.

1.2.2 Transportation

Most aggregate is sold in bulk. Upon sale, aggregate is loaded on trucks, railcars, barges, or freighters for transport to a destination. Aggregate is a high-bulk, low-value commodity, and transportation can add substantially to the cost at the point of use. For example, the cost of transportation of aggregates in the European Union

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is about 13% of the total cost of the aggregate (Bleischwitz and Bahn-Walkowiak, 2006).

The method of transport depends on a number of factors including volumes of material, distance to the point of use, delivery schedules, and access to rail or water transport systems. Trucks are by far the most flexible and most common means of transporting aggregate. They can be loaded and unloaded at many locations using a variety of techniques and can accommodate most delivery schedules. Rail and barge are much less flexible because they utilize fixed route systems following strict schedules and require considerable investment capital in terms of loading facilities, off-loading facilities, and distribution yards. Trains and barges achieve economy by moving large volumes of aggregate long distances on regular schedules (Hayes, 1991).

1.2.3 Reclamation

Reclamation may be implemented following four reclamation strategies: progressive, segmental, interim, or post-mining (Norman and Lingley, 1992). Progressive reclamation immediately follows the removal of aggregate, but may be impractical for operations that must blend mined material from different parts of the pit or quarry. Segmental reclamation follows the removal of minerals in designated sections of the mine, is cost efficient, establishes final slopes as part of the mining operation, and works best in homogeneous deposits. Interim reclamation temporarily stabilizes disturbed areas with fast-growing grasses or legumes, and at a later time implements the final reclamation plan. Post-mining reclamation does not begin until the entire mine has been exhausted, which may lead to deterioration of stockpiled soils, a longer revegetation time frame, and high bonding liability (Norman and Lingley, 1992).

The following examples (from Arbogast *et al.* (2000), unless otherwise noted) illustrate the many different ways that sites can be reclaimed. Reclamation can produce economic benefits by reusing pits or quarries as residential property, industrial and commercial properties, office parks, landfills, golf courses, recreational areas, and botanical gardens. Water-filled pits or quarries are especially well suited for lake-form residential properties, reconstructed wetlands, and water storage reservoirs. These types of reclamation often occur in or near urban centers with large populations. For example, beginning in 1904, Buchart Gardens in British Columbia, Canada, reclaimed 50 acres of an exhausted limestone quarry to create a premier botanical garden (Fig. 1.3).

Some reclamation uses an artistic approach where the site is celebrated as a work of beauty and unique experiences. For example, Robert Smithson, a pioneer in the earthworks-as-art movement, created a circular jetty and canal entitled 'Broken Circle' from a sand pit and body of water in the Netherlands. The symmetrical landform is about 40 m in diameter and evokes images of the dikes and polders that are the backbone of the Dutch landscape. Another form of art can be illustrated by

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1.3 Buchart Gardens, a reclaimed limestone quarry. Notice the cement kiln stack in the background.

the festival stage Dalhalla at Rättvik, Sweden. The stage was built in a former limestone quarry created in an amphitheater shape, which was reclaimed to seat about 4000 people. In this unique setting, Dalhalla hosts operas, choir music, jazz and big band concerts, symphonies, and chamber music (Langer, 1999).

Quarry Cove, on the Oregon coast, USA, is a quarry that was converted into a man-made tidal zone nourished by wave action. The site was designed as an educational tool where visitors (the site is wheel-chair accessible) can view nature taking its course as marine life invades the area. A mined-out sand and gravel pit along the South Platte River in Littleton, Colorado, USA, was reclaimed as a natural wildlife area. The design made use of native seed mixes, and incorporated

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trails, fishing along the river, and educational tours at a nature center. The South Platte Park is one of the largest wildlife parks within city limits in the USA.

1.2.4 Potential environmental impacts and their mitigation

The overall contribution of aggregate extraction to resource depletion, competing land-uses, global warming, and energy use is rather low (Bleischwitz and Bahn-Walkowiak, 2006). Consider, for example, competing land-uses. All types of mining and quarrying in the EU-15 during 2003 were estimated to use 0.2% of the land compared with 0.6% for industry, commerce, energy production, and wastewater treatment; 2.0% for transportation infrastructure; 2.3% for residential; and 41.5% for agriculture (EUROSTAT, 2003). The impact is even less when considering aggregate mining alone. For Germany, the land used for the extraction of sand, gravel, and crushed rock was equivalent to less than 0.005% of the total area of Germany (Gwosdz and Röhling, 2003).

Nevertheless, aggregate extraction and processing cause environmental impacts including changes to the landscape, noise, dust, vibrations from blasting, and degradation of groundwater and surface water. Potential environmental impacts and methods for mitigation are briefly discussed below. More detailed discussions can be found in the sources of further information listed in Section 1.12.1.

Changes to the landscape

The most obvious environmental impact of aggregate extraction is a change to the landscape, generally from undeveloped or agricultural lands to a pit or quarry. Careful site selection can minimize the amount of surface area that must be disturbed by resource extraction. Pre-production site inventories can identify rare or endangered species so that habitat can be set aside, selected species can be relocated, or extraction operations can be suspended during critical breeding or migrating seasons. Loss of habitat can be compensated for by creation or improvement of buffer areas and off-site habitat designed to retain the characteristics of the original habitat. After closure, the pit or quarry may be reclaimed to function as the original habitat. Progressive, segmental, or interim reclamation can speed habitat recovery.

The area of extraction may have contained important archaeological, paleontological, or geological features that can be identified during pre-quarry inventories. Ironically, such features may be recognized only after aggregate operations begin because aggregate extraction uncovers a relatively large area at a relatively slow pace, sometimes leading to serendipitous discoveries.

Noise and dust

The primary source of noise and dust from aggregate extraction is from vehicle

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1.4 Equipment in sound-deadening, vacuum-equipped enclosure.

movements, processing equipment, and blasting. Aggregate producers are responsible for ensuring that the noise and dust emitted from the pit or quarry do not exceed regulated levels. Carefully prepared and implemented noise and dust control plans can keep emissions within the required limits. The size and design of blasts can be modified to limit generation of noise and dust. Blasting can be scheduled for certain times of the day and restricted during adverse weather conditions. Low-noise equipment and dust suppression or collection systems can significantly reduce impacts. Equipment that is noisy or generates dust can be located so that naturally vegetated areas, landscaping, earthen berms, quarry walls, stockpiles, and topographic barriers shield or absorb noise and block the wind that transports dust. Equipment that generates noise or dust can be located in sound-deadening, vacuum-equipped enclosures (Fig. 1.4). Proper location and surface treatment of haul roads and careful routing of trucks can help reduce noise and dust. Conveyors can be used instead of trucks for in-pit movement of materials.

Vibrations from blasting

Blasting may occur daily or as infrequently as once or twice a year, and usually is restricted to quarry operations. Most of the energy of a quarry blast is expended on breaking the rock. A small amount of energy is released as vibrations that go through and along the surface of the earth. Some energy from a quarry blast

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escapes into the atmosphere and causes audible noise and sub-audible noise referred to as 'airblast' or 'air concussion'. Airblast is most noticeable within a structure, and frequently is mistaken for ground vibrations. Airblasts are less likely to cause damage to structures than ground vibration because the mechanics of airblast vibrations are different from vibrations that cause ground shaking.

Extensive research by the former US Bureau of Mines resulted in ground vibration and airblast standards that are recognized worldwide and have become industry standards for safe blasting (Siskind *et al.*, 1980a, 1980b). Impacts from blasting can be mitigated by maintaining blast vibrations below well-documented limits on ground motion and air concussion (Langer *et al.*, 2004).

Impacts on groundwater

The environmental impacts of aggregate operations on groundwater are highly dependent on the local geology, hydrology, and climate. In dry climates, evaporation of water from pits or quarries may lower the water table. In humid climates, precipitation may flow into a quarry and recharge groundwater. Groundwater flow in springs, gaining streams, and wells may be impacted by nearby aggregate operations that pump groundwater from the pit or quarry. Extracting rock from karst areas can have a severe impact on the groundwater, but the impact can commonly be controlled with well-designed and implemented environmental management procedures (Langer, 2001b). Impacts on the water table as a result of dewatering can be monitored by use of observation wells, and recharging aquifers or augmenting flows to streams with water that has drained into the pit or quarry can maintain water levels. In highly permeable deposits, slurry walls or grouting may be necessary to isolate the operation from the water table.

Impacts on surface water

Aggregate operations entail removal of vegetation, which can increase runoff. Aggregate extraction may change runoff patterns and promote erosion, which can result in increased sediment in nearby streams. Slope stability, water quality, erosion, and sedimentation are commonly controlled by sound engineering practices. Finished slopes, roads, drainage ditches, and operational areas must fit the particular site conditions. Disturbed areas can be protected with vegetation, mulch, diversions, and drainage ways. Sediment can be retained on site using retention ponds and sediment traps. Regular inspections and maintenance help ensure continued erosion control.

Water from aggregate processing and storm runoff over pit or quarry sites can increase the suspended material (turbidity) in stream runoff. Turbidity is generally greatest at pit or quarry and wash-plant water discharge points and decreases downstream. Turbidity can be controlled by filtering or by containing runoff or wash water at sediment traps. Aggregate production within stream floodplains

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may have an impact on stream-channel morphology. Careful hydrologic studies and application of best management practices can allow aggregate to be extracted from certain parts of active stream channels with little environmental impact. However, improper aggregate extraction may cause widespread erosion and loss of riparian habitat (Langer, 2002b).

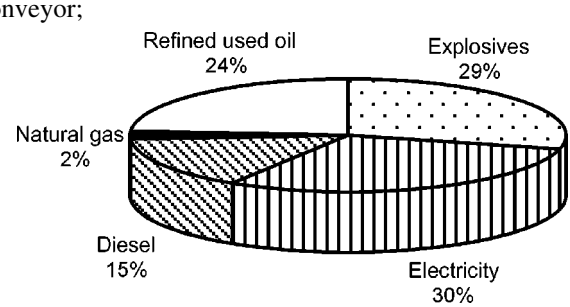
Impacts from transportation

Aggregate is commonly delivered from the pit or quarry to the construction site by truck, which can create problems of noise and exhaust as the trucks pass nearby dwellings. Truck traffic ultimately intermingles with automobile traffic creating potential hazards such as those caused by trucks that transport other consumer products. The environmental impacts and hazards of trucks can be minimized when the trucks are well maintained and operated, and when automobile drivers allow reasonable space for truck drivers to maneuver and stop safely. Trucks can be equipped with mud flaps and load covers to prevent loose material from being thrown from wheels and loads. Limiting the number of quarry entrances and exits, and constructing acceleration and deceleration lanes at pit or quarry entrances can allow trucks to enter and exit traffic smoothly. Delivery routes can be designed to minimize interference with neighborhood traffic.

1.2.5 Energy consumption

Producing aggregate requires the use of energy (Fig. 1.5), which in turn causes the release of greenhouse gases to the atmosphere. The energy consumption required to bring aggregate to a useful state is referred to as 'embodied energy'. The energy-consuming activities of aggregate extraction and processing include:

- removing vegetation and soil, building the processing facilities, and otherwise preparing the site for operation;
- drilling, blasting (for crushed stone), and excavating the material;
- transporting material from the excavation site to the processing facility by truck or conveyor;



1.5 Distribution of energy costs in a typical crushed stone operation. From Moray *et al.* (2006).

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Table 1.1 Embodied energy for some common building materials. From Alcorn (2001)

Material	MJ/kg	kW h/tonne
Aggregate, general	0.04	11.11
Sand	0.1	27.78
River gravel	0.03	8.33
Crushed stone	0.06	16.67
Asphalt paving	0.2	55.56
Brick, high technology	2.7	750.00
Concrete (40 MPa)	1.5	416.67
Gypsum plaster board	7.4	2055.56
Timber, pine, gas dried, dressed	9.5	2638.89

- processing, including multiple stages of crushing, screening, dust collection, sand classification, washing, and stockpiling;
- load-out and transporting to market.

Embodied energy has been calculated for a number of building materials by a number of investigators. The values vary from one investigator to another because of variations in inputs and analytical approaches. Table 1.1 shows embodied energy values for a number of common building materials, including aggregate. All values are from one investigator (Alcorn, 2001) to ensure conformity. The values in Table 1.1 are generalized. In practice, energy consumption varies greatly from one aggregate operation to the next, and has been calculated to range from 6 to 139 kW h/tonne (0.022–0.5 MJ/kg) (GoodQuarry, 2008). Actual consumption is dependent on a number of factors including: the size of the operation; plant layout and design; the type of rock or sand and gravel being mined and processed; the amount of drilling or blasting required; the type, efficiency, and maintenance of equipment being utilized; the experience and training of drillers, blasters, and other operators; and the method of transport and distance to market.

Methods to reduce the embodied energy in aggregate resources include:

- efficient plant design;
- proper drilling and blasting to create appropriately sized crusher feedstock;
- selecting the right equipment (e.g. matching the crusher to the rock being processed, or matching motors to the equipment being used) and operating the equipment properly (e.g. monitoring drill rates, or matching the feed rate to the crusher);
- properly maintaining equipment (e.g. drilling, crushing, processing, on-site power generation, dust collectors, water pumps, conveyors, excavating equipment, and trucks);
- reducing idle time of truck, maintaining haul roads, driver education and awareness.

Generally the transportation of finished goods to the customer is not included in

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the embodied energy calculations for a product. However, aggregate is a high-bulk commodity and transportation can be a significant part of the put-in-place cost. For comparison, Eastman (1980) reported that the distance one liter of fuel can move one tonne of material is 23 km by truck, 78 km by train, and198 km by barge.

1.2.6 Managing impacts through best management practices

Limiting environmental impacts from aggregate mining commonly requires following best management practices, which are available as handbooks and guidelines published by various organizations including government agencies (e.g. Ministry of Energy and Mines, 2002) and industry associations (e.g. Groundwork, 2001). Industry practices have become so advanced in many industrialized countries that aggregate extraction adhering to best management practices can be considered a temporary, rather than permanent, land use (Wellmer and Becker-Platen, 2002).

Increasingly, aggregate companies are receiving certification from the International Organization for Standardization (ISO) by complying with ISO 14000 (ISO, 2007), a voluntary international standard for environmental management. This standard is primarily concerned with the activities an organization takes to minimize harmful effects on the environment and to continually improve its environmental performance.

1.3 Substitutes and manufactured aggregates

Crushed stone can generally substitute for sand and gravel, and vice versa. There are only a few naturally occurring materials that have the properties necessary to make an in-kind replacement for aggregate. Shells, caliche (carbonate-cemented soil typical of arid areas), and clinker (rock hardened by heat from natural coal fires) can substitute for aggregate in some low-specification applications. Some manufactured products can also substitute for aggregate. Slag, a by-product of iron and steel refining, can sometimes be used as aggregate. Perlite, vermiculite, and some types of clay and shale can be expanded by heating and used as lightweight aggregate (Bush *et al.*, 2006; Hack and Bryan, 2006). Occasionally, other materials have been used as substitutes for aggregate in concrete and asphalt products designed for special applications. Shredded rubber tires are used in asphalt to reduce tire noise. Broken glass or cullet are sometimes used in aggregate base courses. Burned coal cinders are used in cinder blocks (Hack and Bryan, 2006). Recycled brick or concrete block can substitute for low-specification uses. There are some building materials that can replace the function of products made from aggregate. For example, dimension stone, wood, or steel can replace concrete in some applications.

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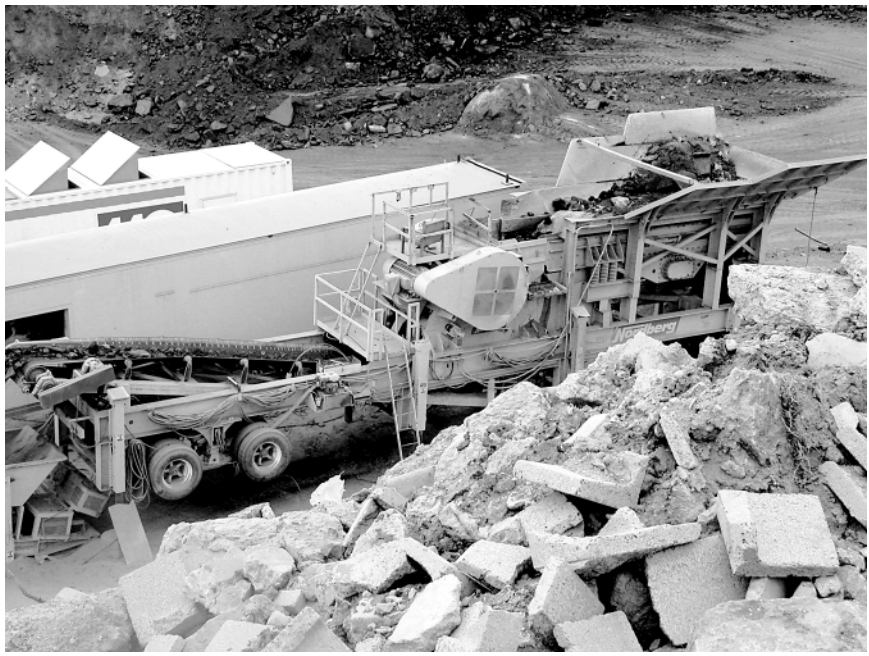

1.6 Recycling concrete using a portable crusher. Photo courtesy of Metso Materials, Tampere, Finland.

1.4 Extending aggregate availability through recycling

Demolition of roads and buildings generates large quantities of waste. Previously, most waste was disposed of in landfills. Today, asphalt pavement and cement concrete are commonly recycled (Fig. 1.6), thus saving huge amounts of space in landfills and reducing the amount of natural aggregate needed to be mined. The following is a general description of recycling of asphalt and cement concrete.

When aggregate has been used in an unbound form such as railroad ballast, it generally can be scooped up and reused with minimum reprocessing. However, aggregate is commonly used in a bound form as asphalt or cement concrete, which complicates recycling. Concrete commonly contains reinforcing steel bars, which require magnetic separation. Recycled concrete also contains cement paste, which has markedly different properties from aggregate. This affects the overall properties of the recycled material. Consequently, recycled concrete generally is used in low-specification applications, such as base course, and even then it is generally blended with fresh aggregate. Recycled concrete is generally not used in new concrete (Hack and Bryan, 2006), although there is potential to use recycled concrete in concrete production.

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Asphalt roads and parking lots commonly are recycled. Worn out surfaces can be ground and reincorporated, at a limited percentage, into new hot-mix asphalt surfaces. Recycled asphalt can also be used as base course or as road surfacing on unpaved secondary roads to prevent dust and improve performance (Hack and Bryan, 2006).

The decision of whether to recycle concrete or asphalt or dispose of it in landfills is usually based on contract terms, legal mandates, and economics. The decreasing availability of landfill space, tipping fees (the cost of depositing material in landfills), and environmental concerns have stimulated the recycling of asphalt- and concrete-bound aggregate. The future for recycling aggregates will be influenced by landfill availability, greater product acceptance, government recycling mandates, increased availability of demolition material for recycling, and the demand for the sustainable and wise use of resources in the economy (Wilburn and Goonan, 1998).

1.5 Performance of aggregate in use

High-quality aggregate used in an unbound state commonly will last indefinitely. The performance of aggregate used in a bound state, such as in cement concrete or asphalt, is dependent on a number of factors including the physical and chemical properties of the aggregate, the specifications for use, preparation of the blended product (asphalt or cement concrete), method of emplacement, and care taken during emplacement.

The physical and chemical properties of aggregate are a result of its geologic origin, mineralogy, and subsequent alteration and weathering. The properties that are important depend primarily on the application of the aggregate (Langer and Knepper, 1998; Smith and Collis, 2001). Aggregate should be strong enough to support the intended load; should resist mechanical breakdown resulting from the action of mixers, mechanical equipment, and traffic; and should be able to withstand stresses caused by repeated freezing and thawing, or wetting and drying. Aggregate to be used in the manufacture of cement concrete should not contain minerals that cause adverse chemical reactions with the cement or with the steel reinforcing bars in the cement concrete structure. Aggregate used in asphalt should have the proper electrochemical properties to allow it to adhere to the bitumen.

Organizations in Australia, the European Union, the USA, and many other countries have established specifications for the use of aggregate and have designed engineering tests to determine compliance with specifications. These tests commonly expose aggregate to conditions that simulate the conditions under which the aggregate will be used. Specific requirements commonly are determined by the users of the material, which include federal, state, county, and city governments, and private industry. Aggregate used in road building and concrete construction is subject to very rigorous specifications, but these specifications, as well as the specifications for other applications, vary from area to area.

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1.6 Waste products from aggregate mining and processing

Mining and processing of aggregates commonly result in the unintentional production of waste products, often with no readily available market. Processing wastes, also referred to as quarry fines, are fine-grained material resulting from crushing and screening. They generally are inert and non-hazardous, but commonly are difficult to handle, especially when wet, and are prone to movement by water, wind, and gravity. Production of fines ranges from 15% to 40% of the material being processed.

Most fines can be used in low-specification applications including fill, walkways, horse track surfaces, and so forth, and to a limited degree in higher-specification applications including hot-mix asphalt and cement concrete. Limestone fines have a number of special applications including use in animal feed, in concrete blocks, as cement replacement in the production of concrete, for flue gas desulfurization (Hudson *et al.*, 1997), and possibly for use as an agent to sequester CO_2 by accelerated weathering of limestone (Langer *et al.*, 2007).

1.7 Sustainability of natural aggregate

Natural aggregates are the major ingredients in concrete and asphalt and as such are the mainstay of our infrastructure. They are cheap and readily available. There is no convenient substitute for the function they serve, and the demand for aggregate can not be met from recycled products alone. If we wish to maintain our current lifestyle and pass the ability to maintain that lifestyle on to our progeny, we will need huge amounts of natural aggregate.

Aggregates, like all mineral resources, are a 'wasting asset'. Eventually individual deposits become depleted, pits and quarries close, new deposits must be found, and new pits and quarries will be opened. Although the worldwide supply of potential aggregate resources is nearly infinite, potential sources of aggregate exist only in specific geologic environments and are not always where we need them. As examples: The Netherlands lacks hard rock resources suitable for the production of crushed stone; Austria does not have broad alluvial lowlands and has a shortage of sand and gravel (ECO-SERV Network, 2004); geologic sources of coarse gravel and high-quality rock for crushed stone are very limited in the USA in the Gulf Coastal Plain, the Colorado Plateau, the Wyoming Basin, and the Great Plains (Langer, 2002a).

Even if sources of aggregate are present, the aggregate must be of sufficient quality to be put to use. Quality parameters can restrict the development of some aggregate resources. Many easy-to-locate resources have already been mined. Urban expansion, zoning, encroachment by incompatible land uses (referred to as sterilization), and citizen opposition can further limit production of aggregate. Large parcels of land have been divided into small parcels, and dealing with

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multiple owners has confounded the purchase of aggregate properties. It is not uncommon for producers to take 10 years to bring new supplies of aggregates on line (Wagner *et al.*, 2002; Bleischwitz and Bahn-Walkowiak, 2006). Aggregate is heavy and bulky, and transporting it 30–50 km can double its price. The longer haul distances also result in higher rates of traffic accidents, more greenhouse gas emissions, and increased road and vehicle maintenance.

Sustainable aggregate resource management (SARM) is an appropriate framework for addressing these complex issues associated with aggregates development (Shields and Šolar, 2004). It is an approach that supports the development of policies that reflect good science, public preferences, and financial and social constraints (Šolar *et al.*, 2004). SARM can be organized according to the environmental, economic, and social dimensions of sustainability.

1.7.1 Environmental value and responsibilities

Environmental value

SARM has tremendous potential to improve our quality of life, create additional wealth, and restore the environment. In today's expanding suburban areas, recently mined-out aggregate pits and quarries, as well as abandoned sites, are routinely converted into beneficial second uses; often these uses replicate natural conditions (Fig. 1.7) and create biodiversity (Langer, 2003; Minerals and Nature, 2007). In addition, aggregate is used for a number of environmental applications including flue gas desulfurization, lake and watershed liming, acid mine drainage abatement, landfill construction, treatment of water and waste water for municipalities and industry, and for erosion control (Moulton, 1991; Remick, 1991).

Environmental responsibilities

SARM requires the development of aggregate resources in an environmentally responsible manner that does not result in long-term environmental harm, even if short-term environmental impacts are unavoidable. Three environmental principles generally apply: the precautionary principle, the polluter pays principle, and eco-efficiency.

The precautionary principle states that we should not take actions when sufficient information is not available, if those actions have a high probability of causing significant environmental damage. The polluter pays principle requires the cost of a quarry to include funding of reclamation and remediation of negative impacts within the quarry and over the mine life cycle including after-care. Eco-efficiency requires efficient exploitation of reserves and resources (Šolar *et al.*, 2004).

There are many voluntary and regulatory tools that can be used to control environmental impacts. These include environmental impact assessments, best

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1.7 Sand and gravel pit reclaimed as natural wetlands.

management practices, environmental management systems, environmental accounting, environmental reporting, monitoring, and life cycle analyses.

1.7.2 Economic value and responsibilities

Economic value

Employment in urban and suburban areas is commonly defined by the workplace and transportation structures, which are comprised largely of aggregate. The natural capital embodied in aggregates is transformed into economic capital derived from the profits from the sale of aggregates. The physical economy grows

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at an estimated rate of 10 tonnes per capita per year (Bringezu, 2002). In other words, each year this amount of material, which consists mostly of aggregates and downstream products like asphalt and concrete, is being added to new buildings and infrastructures.

As aggregate flows throughout the economy, the 'value added' multiplies repeatedly. For example, each step of the process of extracting and processing aggregate, incorporating aggregates into concrete, and pouring and finishing concrete for a building, bridge, and so forth, adds to the economy through sales and salaries.

Economic responsibilities

There are four main economic responsibilities embodied in SARM: (a) providing aggregates to meet the material requirements of society; (b) maintaining a viable business environment; (c) encouraging value-added production and employment; and (d) employing full cost accounting while remaining competitive. The first three of these are the responsibility of government; the fourth is the responsibility of the firm (Šolar *et al.*, 2004).

Meeting the material needs of society involves ensuring that sufficient aggregate resources are available to the marketplace. This requires the identification and protection of sufficient reserves and resources, provision of land access, creation or maintenance of production capacity, and development and maintenance of infrastructure (transportation and energy networks). All these issues are interconnected and need to be balanced by policy makers and resource managers (Šolar *et al.*, 2004). Unfortunately, the identification and protection of aggregate resources is generally not well understood or integrated into the planning framework (Wernstedt, 2000; Richards and Peel, 2003; Baker and Hendy, 2005).

Aggregate businesses need to remain competitive to stay in business. Maintaining a viable business environment requires a stable and feasible permitting regime; consistent application of rules and regulations; functioning capital markets; reasonable levels of taxation; and well-defined property rights (Šolar *et al.*, 2004).

Development of value-added manufacturing (such as ready-mix operations, asphalt plants, pre-stressed concrete panels, and concrete pipe and block manufacturing) is an important economic aspect of SARM. The presence of a value-added sector can reduce the need for imported materials while allowing the local economy to capture the economic benefits (profits, employment, tax revenues) that would otherwise accrue in another region (Šolar *et al.*, 2004).

Aggregate businesses have a responsibility to accept the full cost of operation, including costs of prevention or remediation of environmental damage. When all the costs are taken into consideration, some quarries will not be viable economic enterprises. However, firms can increase competitiveness by following best management practices, maintaining a well-trained workforce, modifying production processes, and upgrading product quality. Product quality can be an important

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market element that can be labeled and traded (Šolar *et al.*, 2004). Quality can be achieved through voluntary quality assurance/quality control procedures, such as adherence to ISO 9000 requirements (ISO, 2007).

1.7.3 Societal value and responsibilities

Societal value

The infrastructure necessary to build and maintain the social systems of developing or developed countries cannot be created or sustained without aggregate. Paramount among the components of the infrastructure system is transportation. Simply put, the workforce and material necessary to maintain a healthy economy and social system cannot reach the market without an efficient transportation system.

The regional importance of the aggregate industry as a source of employment can be substantial. Each quarry job may result in the creation of four or five other jobs including subcontractors for various parts of the quarry operations, transportation, equipment manufacture and repair, and downstream users of aggregates such as the concrete ready-mix and asphalt operations (Lafarge, 2007).

Societal responsibility

The aggregate industry exposes workers to potential hazards, and reduction of operational risk is an essential part of aggregate extraction and processing. Occupational health and safety issues are commonly addressed through training programs, monitoring, health screenings, and by following best management practices. Identifying the values, interests, and goals of stakeholders is a necessary step to resolve the complex social issues of SARM. For example, the benefits of aggregate development are dispersed over very large areas, but the community where extraction occurs suffers most of the adverse consequences of resource development. SARM depends on fairness to those living near or impacted by quarrying while considering the regional benefits from aggregate extraction (Šolar *et al.*, 2004).

Corporate social responsibility

Corporate social responsibility (CSR) is an integral part of SARM. Companies that practice CSR commonly define themselves as being: accountable to stakeholders; responsible for social, environmental, and financial performance; accountable everywhere they do business; and open to external codes of conduct. Such companies demonstrate their commitment to CSR by instituting standards and goals at all levels of the organization (WBCSD, 2000; Dunnett, 2004). CSR can

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increase long-term business viability, including growth and profits, and sends a signal to stakeholders that the company is a responsible corporate citizen (Shields *et al.*, 2006), which can help companies acquire the 'social license' to mine.

1.7.4 Life cycle analysis of aggregate operations

From mining and processing perspectives, the net environmental, economic, and societal contribution of aggregate extraction should be positive over the entire life of the aggregate operation. A life cycle analysis (LCA) can be used to assess aggregate operations by including exploration, project development, resource extraction, material processing, storage, and reclamation. LCA should also take into consideration the fact that aggregate resources provide potential benefits or consequences that can far outlast the mining life cycle, and should include assessment of the long-term impacts as well as the life cycle of the aggregate operation itself. On the one hand, for example, an aggregate operation may last 10 years, while the building the aggregate was used to construct may last for 100 years. Similarly, the post-closure benefits from the reclaimed site may last indefinitely. On the other hand, potential environmental impacts such as those to the groundwater, may last well beyond the life of the operation if they are not properly addressed.

1.8 Status of sustainable aggregate resource management

A stringent policy on SARM does not exist in most countries. However, governments of some states, provinces, and territories in Australia, Canada, and the USA, some of the member states within the European Union, and some other countries have elaborated sustainable mineral resource management policies that recognize the broader minerals and mining sector. A few of those policies (e.g. DETR, 2000) recognize the aggregate industry as a key sector contributing to jobs, a high quality of life, and wealth for its citizens. Some of the policies identify actions that can be undertaken to help industry meet society's demand for aggregates, although most of the policies regulate only the aggregate extraction and production processes (Langer, 2002c; Bleischwitz and Bahn-Walkowiak, 2006).

There is a slow but inexorable move by the aggregate industries towards implementation of SARM principles (Langer *et al.*, 2003a; Bleischwitz and Bahn-Walkowiak, 2006). For example, the European Aggregates Association (UEPG) encourages, endorses, and practices sustainability (UEPG, 2007). Some member-state associations of the UEPG have their own sustainability initiatives (e.g. Quarry Products Association, 2006). Some aggregate producers, especially large multinational companies, have voluntarily issued sustainability policy statements and annual sustainability reports, and made those documents available via the World Wide Web. Some companies have embraced the principles of CSR even

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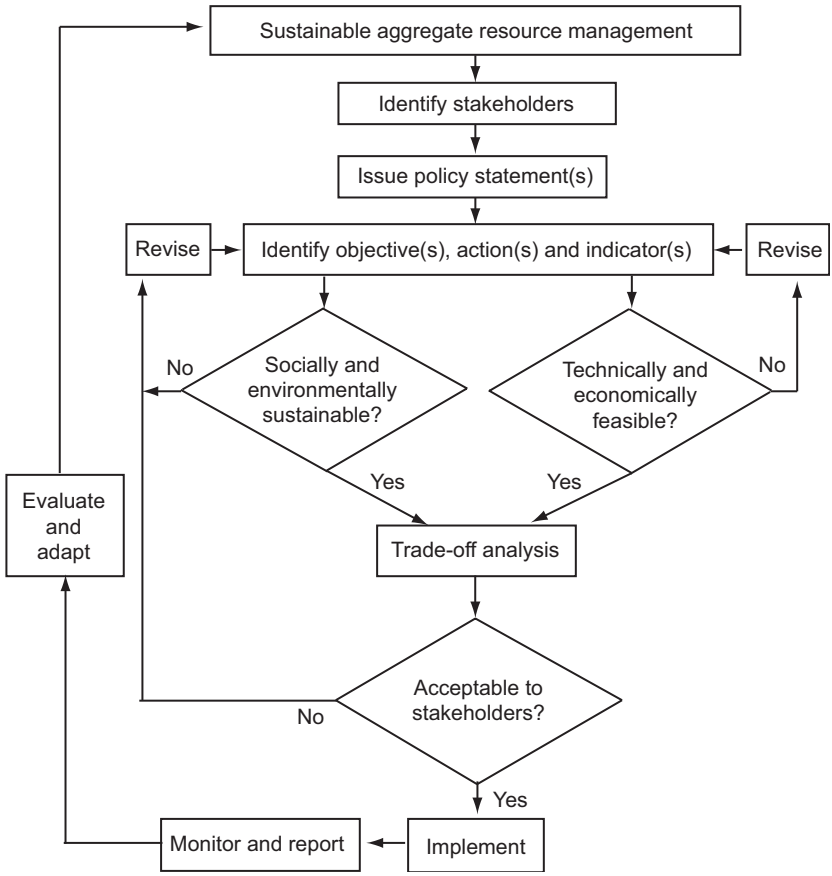

1.8 Implementation process for sustainable aggregate resource management (SARM). Modified from Shields and Šolar (2004).

though they have not elaborated their policies using sustainability terminology. Sustainability tends to focus on the closure of mining operations (Barker and McLemore, 2005) and community relations.

1.9 General approaches to sustainable aggregate resource management

There is no specific process that must be followed when applying SARM, but, in general, the process followed is iterative and consists of a number of hierarchical steps (Fig. 1.8). These steps may include, for example: issuance of policy statements, elaboration of objectives, establishment of actions, identification of indicators, and monitoring.

Policy statements issued by governments commonly identify the aggregate

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industry as a key industry contributing to jobs, wealth, and a high quality of life for its citizens. The policy statements commonly commit the government to estimate the need for aggregates; assess the availability of aggregate; protect critical aggregate resources; and protect citizens from the unwanted impacts of aggregate extraction. Industry policy statements commonly identify environmental and societal concerns and commit the company to CSR.

Objectives describe what is intended to be accomplished. Actions are associated with objectives and describe the approach taken to reach the objective. Examples of paired objectives (in italics) and actions (modified from Plant and Haslam, 1999) are given below.

- *Maximize availability of, and access to, aggregate* – by forward planning that protects important resources from sterilization; by extracting as much aggregate as possible from an area and using it for the most valuable application appropriate for the aggregate quality; by avoiding high grading (picking the best parts of the resource and limiting the ability to utilize the remainder); by finding uses and markets for all of the mined material; and by encouraging use of substitutes and recycled aggregate.
- *Minimize societal impacts and maximize societal benefits* – by forward planning that separates incompatible land uses; by creating community benefits for areas impacted by aggregate development; and by involving the local community in planning activities, expanding community awareness, and outreach. Minimizing societal impacts may lead to community acceptance and a 'social license' to mine, which can be just as important as the legal permits.
- *Minimize environmental impacts* – by following best management practices and employing environmental management systems to identify and control potential impacts from aggregate extraction and processing; and by providing for conservation of natural surroundings by management of buffer areas that maintain or enhance vegetation and wildlife habitats and corridors.
- *Maximize rehabilitation of disturbed areas* – by reclaiming abandoned sites; by allowing for reclamation as an integral part of the quarry/pit design process; by following progressive, segmental, or interim reclamation processes where possible; and by being flexible enough to allow for advances in technology and changing local needs.
- *Identify and resolve legitimate concerns* – by constructively contributing to a decision-making process that addresses not only the interests of individual stakeholders, but a wide range of objectives and interests of others.

Indicators measure progress towards reaching objectives and the effectiveness of actions taken. Indicators are specific to the target and actions, but tend to be similar in many situations. Examples of indicators from a government perspective (DETR, 2000; Langer *et al.*, 2003a) include:

- the amount of aggregate produced compared with estimated production;

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- the volume of material produced compared with the surface area converted for extraction;
- the proportion of aggregate coming from areas preferred for extraction;
- the proportion of aggregate coming from environmentally sensitive areas;
- the proportion of natural aggregates compared with recycled material;
- the proportion of sites covered by modern operating conditions;
- the area of reclaimed land compared with the area of land undergoing extraction.

Examples of indicators from an industry perspective (European Commission, 2006) include:

- the number of hours of training as a percentage of total work hours;
- the working time lost from accidents as a percentage of total hours worked;
- the total number of events arranged for neighboring communities;
- the energy consumption per tonne of saleable product;
- the total land area in operation as a percentage of saleable products;
- the total number of reportable environmental incidents.

Monitoring, feedback, and the regular reconsideration of requirements as events develop help to refine the SARM process. Establishment of a joint monitoring process presents an opportunity to forge partnerships with communities and involve citizen groups.

1.10 Case studies

The following are condensed descriptions of case studies chosen to illustrate the variety of actions that have been taken as part of the sustainable management of aggregate resources. More detailed descriptions can be found in the associated references.

1.10.1 Government actions for resource protection and environmental restoration

Province of Modena, Italy, Intraregional Plan for Extractive Activities (Langer et al.*, 2003b)*

The Province of Modena, located in the Emilia Romagna Region in northern Italy, recognized that natural aggregate is necessary to sustain the economic well-being of the region. Modena Province prepared a Variant of the Intraregional Plan for Extractive Activities (IPEA) that had been in place for about 10 years. Two objectives of the Variant of the IPEA were to: (a) minimize the impacts from quarrying, and (b) guarantee the reclamation of quarries in a manner consistent with the existing landscape. In order to accomplish those objectives, the Emilia Romagna Region developed the innovative concept of

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the '*polo estrattivo*' (extractive district), which is not just one or more quarries, but is the whole area characterized by the prevalence of quarrying, including the intervening and surrounding territory that is subject to quarrying impacts (Langer *et al.*, 2003b).

The Variant of the IPEA encourages the management of quarrying through the extractive district. Aggregate can efficiently be extracted by mining aggregate between adjacent quarries within a district, or by deepening the pit, if that can be accomplished without harming the quality or quantity of the groundwater. The extraction of additional aggregate from abandoned quarries within the extractive district is encouraged. Both approaches could result in the extraction of more aggregate without disturbing more land surface area outside the extractive district. Previous aggregate extraction activities in rivers and floodplains, and channel modifications for flood control, have degraded the environment. Future quarrying in these already disturbed areas, followed by reclamation to natural habitat, is encouraged to make a positive contribution to biodiversity.

1.10.2 Government and conflict resolution

Management of aggregate resources in the Calahoo–Villeneuve region, Alberta, Canada (Richards and Peel, 2003)

A conflict of interests between rural citizens and the extractive industry resulted from the development of aggregate resources in the Calahoo–Villeneuve region of Alberta, Canada. Citizen opposition resulting from noise, dust, truck traffic, and concerns about environmental pollution, compounded by a lack of compensation by the aggregate industry to the local community, threatened to close access to regionally important aggregate resources. A government-led development of an Area Structure Plan (ASP) implemented a number of programs to satisfy the concerns of residents while safeguarding access to aggregate resources. The plan included a voluntary levy on aggregate production, proceeds from which are paid into a Community Enhancement Fund. In general, the plan was well developed and executed, and it resolved the local concerns. However, the aggregate resource inventory for the area prepared by the Alberta Geological Survey was not utilized in the ASP, resulting in the sterilization of approximately half of the regional resources. When the aggregate resources identified in the ASP are depleted, the additional cost to haul materials from more distant deposits will be about CDN$1.6 billion (2003 CDN$). The County will forego approximately CND$45 million in contributions to the Community Enhancement Fund that would have resulted from development of the resources. Additional road hazards and maintenance costs will occur along with the production of about 682 000 tonnes of additional CO_2 in exhaust emissions.

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1.10.3 Corporate social responsibility

Quarry expansion and community involvement (Langer, 2005)

A multinational aggregate producer proposed to expand its reserves in an operating quarry in a county near Denver, Colorado, USA by exchanging company-owned land for existing, county-owned, dedicated open-space land adjacent to their quarry. The county is home to four of the five crushed stone operations in the Denver region. Crushed stone comprises 30% of the aggregate produced in the area and plays a major role in regional aggregate resource needs.

A similar proposal submitted by a different company about 10 years earlier had been denied. The new proposal was predicated on public trust whereas the earlier proposal was predicated on public relations. The company with the new proposal had earlier established a strong, long-term, favorable presence in the community. They openly, consistently, and effectively communicated their business plan to all stakeholder groups, and were visible and accessible.

The local government had no sustainability policies, and was not accustomed to facilitating industry/community interactions. Consequently, the company not only assumed their corporate social responsibilities, but they also assumed the role of facilitator to encourage and enable other stakeholders to resolve legitimate concerns regarding the quarry proposal. The company successfully presented an enlightened proposal where the county ultimately gained 745 acres of new open-space land in exchange for 60 acres of existing open-space land adjacent to the quarry. The company doubled the life of its quarry, secured a location for a ready-mix plant and an asphalt plant, and eliminated the need to start a new quarry at an undeveloped location. The process involved collaborative efforts by all stakeholders and resulted in an outcome that balanced the needs of society, the environment, and business.

1.10.4 Industry and transportation issues

Transporting aggregate products in Derbyshire, UK (Aggregate Industries, 2007)

A large, multinational aggregate producer installed satellite tracking devices into a fleet of 30 tipping trucks within their Derbyshire, UK operations. This initiative resulted in a number of specific benefits:

- improved customer service by providing real-time, accurate information on deliveries;
- improved vehicle utilization and performance by reducing the occurrence of empty return journeys and turn-around time of trucks, resulting in the potential use of fewer vehicles to move more materials, benefiting all road users;
- improved communication between sites and the vehicle**,** providing advance warning of the arrival of a vehicle to pick up product, thus reducing idle time, energy consumption, plant costs, and emissions;

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- improved ability to monitor vehicle speed and driver performance, providing improved enforcement of local agreements and legal requirements in routing deliveries; haulers are more accountable for their behavior and consequences, and communities have greater confidence in the company's ability to manage vehicles.

1.11 Future trends

Industry will be able to meet society's needs for aggregate. However, the industry already faces local shortages of aggregate, a situation that will occur more frequently owing to inadequacies of present policies, urban encroachment, and citizen opposition. Leaving the management of aggregate resources to chance is likely to result in unintended consequences such as further sterilization of resources, juxtaposition of incompatible land uses, undesirable environmental impacts, and negative impacts on traffic. Price increases, land use conflicts, and shortages may encourage some local or regional governments to become more proactive in protecting access to aggregate resources as the availability of local supplies dwindles.

The factors that can be controlled to reduce the demand for aggregate are limited. The consumption of local aggregate can be slowed through use of alternative resources, such as recycled concrete and asphalt pavement, and by importing aggregate from other areas. The local aggregate supply can be expanded through technological advances and beneficiation of lower-quality aggregate, and in some instances through underground mining. Aggregate consumption, in general, can be slowed through the modification of application designs to require less aggregate or by modifying specifications to allow the use of lower-quality aggregate in certain low-end uses.

The application of SARM will advance, spurred on by green building, citizen opposition, and recycling mandates. Companies that practice SARM will appreciate advantages in obtaining their 'social license' to mine. However, the aggregate industry consists of thousands of companies, and many will choose not to implement sustainability.

1.12 Sources of further information and advice

1.12.1 Information on the aggregate industry

Aggregates (Smith and Collis, 2001), *Sand and Gravel Production* (Littler, 2000), and *The Aggregate Handbook* (Barksdale, 1991) are comprehensive descriptions of the aggregate industry. The 7th edition of *Industrial Minerals and Rocks* (Kogel *et al.*, 2006; Langer, 2006a and 2006b) and previous editions, and *Geology of Construction Materials* (Prentice, 1990) contain chapters on the geology of aggregates. Six collections of papers describe global issues related to aggregate

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resources: *Aggregate 2001* (Kuula-Väisänen and Uusinoka, 2001), *Aggregates* (Primel and Tourenq, 2000), *Aggregate Resources – A Global Perspective* (Bobrowsky, 1998), *Aggregates – Raw Materials' Giant* (Lüttig, 1994), the *Proceedings from the International Symposium on Aggregates* (International Association of Engineering Geology, 1984), and *Natural Resources in the Geological Environment* (Kelk, 1992). Environmental impacts from developing aggregate resources and methods to limit those impacts are described in *Aggregate and the Environment* (Langer *et al.*, 2004) and 'Environmental impacts of mining natural aggregate' (Langer, 2001a).

1.12.2 Information on sustainable aggregate resources management

There are relatively few readily available published papers specifically addressing sustainability relative to aggregate resources; most are cited in this chapter. Key papers include: 'Important features of sustainable aggregate resource management' (Šolar *et al.*, 2004); 'Planning for sustainable construction aggregate resources in Australia' (Baker and Hendy, 2005); *Sustainable development in the European aggregate industry – A case for sectoral strategies* (Bleischwitz and Bahn-Walkowiak, 2006), *Sustainable development in the European aggregates industry – For the benefits of future generations* (UEPG, 2007); and 'Sustainability indicators for aggregates' (Langer *et al.*, 2003a).

The European Aggregates Association (www.uepg.eu) and the United States National Stone, Sand and Gravel Association (www.nssga.org), as well as many of their other members, describe their SARM efforts on the World Wide Web (www.uepg.eu). Information about SARM efforts of some of the larger individual aggregate producers can be found by visiting corporate web pages. The Industrial Minerals Association – Europe (www.ima-eu.org) and the Industrial Minerals Association – North America (www.ima-na.org) have posted descriptions of sustainability from a broader industrial minerals perspective on their web pages.

1.13 References

Aggregate Industries (2007), Available at http://sustainability.aggregate.com/PDF/2005 ⁄.205USReport.pdf, accessed 21 January 2009.

Alcorn A (2001), *Embodied energy and CO_2 coefficients for NZ building materials*, Wellington, New Zealand, Victoria University of Wellington Centre for Building Performance Research.

Arbogast B F, Knepper Jr D H and Langer W H (2000), *The human factor in mining reclamation*, Reston, Virginia, USA, US Geological Survey Circular 1191.

Baker D and Hendy B (2005), 'Planning for sustainable construction aggregate resources in Australia'. In Sidwell A C (Ed.), *QUT Research Week 2005, Conference Proceedings*, Queensland University of Technology, Brisbane, Australia, pp. 4–15.

www.EngineeringEBooksPdf.com

Barker J M and McLemore V T (2005), 'Sustainable development and industrial minerals'. *Mining Engineering*, **57**(12), 48–52.

Barksdale R D (Ed.) (1991), *The Aggregate Handbook*, Washington, DC, National Stone Association.

Bleischwitz R and Bahn-Walkowiak B (2006), *Sustainable development in the European aggregate industry – A case for sectoral strategies*, Wuppertal, Germany, Wuppertal Institute for Climate, Environment and Energy.

Bobrowsky P T (Ed.) (1998), *Aggregate Resources – A Global Perspective*, Rotterdam, Netherlands, A.A. Balkema.

Bringezu S (2002), *Towards sustainable resource management in the European Union*, Wuppertal Paper 121, Wuppertal, Germany, Wuppertal Institute for Climate, Environment and Energy.

Bush A L, Bryan D P and Hack D R (2006), 'Lightweight aggregates', in Kogel E K, Trivedi N C, Barker J M and Krukowski S T (Eds), *Industrial Minerals and Rocks*, 7th Edition, Littleton, Colorado, USA, Society for Mining, Metallurgy and Exploration, pp. 181–194.

DETR (2000), *Planning for the supply of aggregates in England*, London, Department of the Environment, Transport and the Regions.

Dunnett A (2004), *Embedding CSR Is the Key to Better Performance*, London, Ethical Corporation.

Eastman S E (1980), *Fuel efficiency in freight transportation*, Arlington, Virginia, USA, The American Waterway Operators, Inc.

ECO-SERVE Network (2004), *Baseline report for the aggregate and concrete industries in Europe*, Hellerup, Denmark, European Commission.

European Commission (2006), *EU Non-energy extractive industry, Sustainable development indicators, 2001–2003*, Brussels, Belgium, European Commission Enterprise and Industry Directorate Raw Materials Supply Group.

EUROSTAT (2003), *The Lucas Survey – European statisticians monitor territory – Updated edition June 2003*, Luxembourg, European Commission, Office for Official Publications of the European Communities.

GoodQuarry (2008), University of Leeds, Leeds, UK, available at http://www.goodquarry.com/, accessed 21 January 2009.

Groundwork (2001), *Extractive industry good practice guidelines*, Taringa, Queensland, Australia, Groundwork Environmental Management Services.

Gwosdz W and Röhling S (2003), Flächenbedarf für den Abbau von oberflächennahen Rohstoffen (Steine und Erden, Braunkohle und Torf) im Jahr 2001, in *Commodity Top News*, 19, Hannover, Bundesanstalt für Geowissenschaften.

Hack D R and Bryan D P (2006), 'Aggregates'. In Kogel E K, Trivedi N C, Barker J M and Krukowski S T (Eds), *Industrial Minerals and Rocks,* 7th Edition, Littleton, Colorado, Society for Mining, Metallurgy and Exploration, pp. 1105—1119.

Hayes V L (1991), 'Product transportation and distribution system'. In Barksdale R D (Ed.), *The Aggregate Handbook*, Washington, DC. National Stone Association, pp. 10.1–10.20.

Hudson W R, Little D, Razmi A M, Anderson V and Weissmann A (1997), *An investigation of the status of by-product fines in the United States*, Research Report ICAR-101-1, Austin, Texas, International Center for Aggregates Research.

International Association of Engineering Geology (1984), *Proceedings from the International Symposium on Aggregates,* Nice, France, Bulletin 29, Paris, International Association of Engineering Geology.

www.EngineeringEBooksPdf.com

ISO (2007), ISO 9000 and 14000, Available from http://www.iso.org/iso/en/iso9000-14000/index.html, accessed 21 January 2009.

Kelk B (1992), 'Natural resources in the geological environment'. In Lumsden G I (Ed.), G*eology and the Environment in Western Europe,* New York, Oxford University Press, pp. 34–138.

Kogel E K, Trivedi N C, Barker J M and Krukowski S T (Eds) (2006), *Industrial Minerals and Rocks*, 7th Edition, Littleton, Colorado, Society for Mining, Metallurgy, and Exploration.

Kuula-Väisänen P and Uusinoka R (Eds) (2001), *Aggregate 2001 – Environment and Economy*, Vols 1 and 2, Tampere, Finland, Tampere University of Technology.

Lafarge (2007), *Quarrying and Sustainable Development – Aggregates in France*, Issy-les-Moulineaux, France, Lafarge Granulats.

Langer W H (1999), 'Reclamation – A new art form'. *Aggregates Manager*, **3**(12), 64.

Langer W H (2001a), 'Environmental impacts of mining natural aggregate'. In Bon R L, Riordan R F, Tripp B T and Krukowski S T (Eds), *Proceedings of the 35th Forum on the Geology of Industrial Minerals – The Intermountain West Forum 1999*, Salt Lake City, Utah Geological Survey Miscellaneous Publication 01–2, pp. 127–137.

Langer W H (2001b), *Potential environmental impacts of quarrying stone in karst – A literature review*, US Geological Survey Open File Report OFR-01-0484, Reston, Virginia, US Geological Survey.

Langer W H (2002a), 'An overview of aggregate resources in the United States'. In Scott P W, Bristow C M (Eds), *Industrial Minerals and Extractive Industry Geology*, London, The Geological Survey, pp. 9–16.

Langer W H (2002b), *A general overview of the technology of in-stream mining of sand and gravel resources – Associated potential environmental impacts, and methods to control potential impacts*, US Geological Survey Open File Report OFR-02-153, Reston, Virginia, US Geological Survey.

Langer W H (2002c), *Managing and protecting aggregate resources*, US Geological Survey Open File Report OFR-02-415, Reston, Virginia, US Geological Survey.

Langer W H (2003), 'Creating a sustainable future – part 2'. *Aggregates Manager*, **8**(7), 34.

Langer W H (2005), 'A case study demonstrating sustainable management of natural aggregate resources'. In Rajaram V, Dutta S and Parameswaran K (Eds), *Sustainable Mining Practices – A Global Perspective*, London, Taylor & Francis Group, pp. 254–265.

Langer W H (2006a), 'Construction sand and gravel'. In Kogel E K, Trivedi N C, Barker J M and Krukowski S T (Eds), *Industrial Minerals and Rocks*, 7th Edition, Littleton, Colorado, Society for Mining, Metallurgy, and Exploration, pp. 159–169.

Langer W H (2006b), 'Crushed stone'. In Kogel E K, Trivedi N C, Barker J M, and Krukowski S T (Eds), *Industrial Minerals and Rocks*, 7th Edition, Littleton, Colorado, Society for Mining, Metallurgy, and Exploration, pp. 171–180.

Langer W H, Šolar S V, Shields D J and Giusti C (2003a), 'Sustainability indicators for aggregates'. In Agioutantis Z (Ed.), *Proceedings of the International Conference on Sustainable Development Indicators in the Mineral Industries*, Milos, Milos Conference Center – George Eliopoulos, Greece, pp. 251–257.

Langer W H, Giusti C and Barelli G (2003b), 'Sustainable development of natural aggregate, with examples from Modena Province, Italy'. *SME Transactions*, **314**, 138–144.

Langer W H, Drew L J and Sachs J S (2004), *Aggregate and the environment*, American Geological Institute Environmental Awareness Series 8, Alexandria, Virginia, American Geological Institute.

Langer W H, Rau G H and Caldeira K (2007), 'Accelerated weathering of limestone for CO_2

www.EngineeringEBooksPdf.com

mitigation: opportunities for stone and cement industries'. In Shaffer N R and DeChurch D A (Eds), *Proceedings of the 40th Forum on the Geology of Industrial Minerals*, Bloomington, Indiana, Indiana Geological Survey Occasional Paper 67, pp. 129–136.

Littler A (2000), *Sand and Gravel Production*, Nottingham, UK, The Institute of Quarrying.

Lüttig G W (1994), 'Aggregates–raw materials' giant'. In *Report on the 2nd International Aggregate Symposium*, Erlangen, 22–27 October, 1990, Erlangen, Germany, University of Erlangen-Nuremberg.

Minerals and Nature (2007), *Biodiversity*, available at http://www.mineralsandnature.org.uk/biodiversity.php, accessed 21 January 2009.

Ministry of Energy and Mines (2002), *Aggregate Operators Best Management Practices Handbook for British Columbia, Victoria*, Vol. I *Introduction and Planning*, and Vol. II *Best Management Practices,* British Columbia, Canada, British Columbia Ministry of Energy and Mines, available at http://www.em.gov.bc.ca/Mining/MiningStats/55AOBMPHand_pdf.htm, accessed 21 January 2009.

Moray S, Throop N, Seryak J, Schmidt C, Fisher C and D'Antonio M (2006), 'Energy efficiency in the stone and asphalt industry'. *Industrial Energy Technology Conference*, Texas A&M University, College Station, Texas, available at, http://txspace.tamu.edu/handle/1969.1/2887, accessed 21 January 2009.

Moulton L K (1991), 'Aggregate for drainage, filtration, and erosion control'. In Barksdale R D (Ed.), *The Aggregate Handbook*, Washington, DC, National Stone Association, pp. 12-1–12-93.

Norman D K and Lingley Jr W S (1992), 'Reclamation of sand and gravel mines'. *Washington Geology*, **20**(3), 20–31.

Plant J and Haslam H (1999), 'The geological environment – links with the human dimension'. *Earthwise*, **13**, 6–7.

Prentice J E (1990), *Geology of Construction Materials: Topics in the Earth Sciences, 4*, London, Chapman and Hall.

Primel L and Tourenq C (Eds) (2000), *Aggregates*, Rotterdam, A.A. Balkema.

Quarry Products Association (2006), *A sustainable development report from the aggregates and quarry products industry*, Quarry Products Association Sustainable Development Report, March 2006, London, Quarry Products Association.

Remick B W (1991), 'Non-construction uses of stone'. In Barksdale R D (Ed.), *The Aggregate Handbook*, Washington, DC, National Stone Association, pp. 14-1–14-36.

Richards J and Peel D (2003), 'The application of sustainable development principles to the Alberta Aggregates Resource Sector', *Exploration and Mining Geology*, **12**(1–4), 79–95.

Shields D J and Šolar S V (2004), *Sustainable mineral resource management and indicators: case study Slovenia*, Ljubljana, Slovenia, Geological Survey of Slovenia.

Shields D J, Šolar S V and Langer W H (2006), 'Sustainable development of industrial minerals'. In Kogel E K, Trivedi N C, Barker J M and Krukowski S T (Eds), *Industrial Minerals and Rocks*, 7th Edition, Littleton, Colorado, Society for Mining, Metallurgy, and Exploration, pp. 133–142.

Siskind D E, Stagg M S, Kopp J W and Dowding C H (1980a), *Structure response and damage produced by ground vibrations from surface mine blasting*, US Bureau of Mines Report of Investigations 8506, Washington, DC, US Bureau of Mines.

Siskind D E, Stachura V J, Stagg M S and Kopp J W (1980b), *Structure response and damage produced by airblast from surface mining*, US Bureau of Mines Report of Investigations 8485, Washington, DC, US Bureau of Mines.

Smith M R and Collis L (Eds) (2001), *Aggregates – sand, gravel and crushed rock*

www.EngineeringEBooksPdf.com

aggregates for construction purposes, Geological Society Engineering Geology Special Publication No. 17, London, The Geological Society.

Šolar S V, Shields D J and Langer W H (2004), 'Important features of sustainable aggregate resource management'. *Geologija*, **47**(1), 99–108.

UEPG (2007), *Sustainable development in the European aggregates industry – For the benefits of future generations*, Brussels, Belgium, European Aggregates Association.

Wagner L A, Sullivan D E, Sznopek J L (2002), *Economic drivers of mineral supply*, US Geological Survey Open File Report OFR-02-335, Reston, Virginia, US Geological Survey.

WBCSD (World Business Council for Sustainable Development) (2000), *Sustainable Development Reporting: Striking the Balance*, Geneva, WBCSD.

Wellmer F W and Becker-Platen J D (2002), 'Sustainable development and exploitation of mineral and energy resources: A review'. *International Journal of Earth Sciences*, **91**, 723–745.

Wernstedt K (2000), 'Plans, planners, and aggregate mining'. *Journal of Planning, Education and Research*, **20**, 80–90.

Wilburn D R and Goonan T G (1998), *Aggregates from natural and recycled sources*, US Geological Survey Circular 1176, available only online at URL http://pubs.usgs.gov/circ/1998/c1176/c1176.html, accessed 21 January 2009.

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2

Sustainability of timber, wood and bamboo in construction

M. ASIF
Glasgow Caledonian University, UK

Abstract: Owing to its unique characteristics, wood has historically been a valuable and useful natural resource. It is also one of the most important construction materials mankind has ever come across. Wood is at the heart of modern construction owing to its versatility, abundance in nature and environmental friendliness. It comes in thousands of types and has a remarkably diverse range of applications. This chapter discusses the basic features of wood, i.e. chemical composition, growth and structure. Various aspects of wood, crucial to its role as a construction material – i.e. seasoning, preservation and repair – have also been highlighted. The status of wood as a sustainable construction material has been reflected upon with regard to different features such as environmental friendliness, durability, waste disposal and recycling. Towards the end of the chapter, bamboo, a family member of wood, has been discussed in detail in terms of its structure and properties, applications and sustainability.

Key words: timber, wood, bamboo, sustainability, softwood, hardwood, seasoning, composition, durability, preservation, recycling, engineered wood.

2.1 Introduction

Wood is one of the most versatile and ancient materials in human use. It is the material that forms the trunk and branches of a standing tree. It can be called timber (NB the terms 'wood' and 'timber' are synonymous in this chapter), when the tree has been cut and/or it has been processed for use. In the United States, it is also termed 'lumber'. Throughout recorded history, the unique characteristics and relative abundance of wood have made it one of mankind's most valuable and useful natural resources. It has numerous uses and is recognised as an environmentally friendly material. It is biological in nature and has widely different properties depending upon many factors such as species, geographic area of growth, growth conditions, age and size of tree at the time of harvest, sawing and other treatment processes. Wood has a remarkably diverse range of applications: it is one of the most versatile building materials; it is widely used as a traditional as well as modern biomass fuel; it is used in the manufacturing of furniture, decorative materials, sports equipment, musical instruments, and boats.

Bamboo is one of the fastest growing plants with a wide range of applications in

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Table 2.1 Regional distribution of softwood and hardwood forests in the world[1]

Region	Softwood forest (%)	Hardwood forest (%)
Africa	0.2	10.9
Asia	5	19.5
Central America	1.5	2.3
Europe	8.2	4.3
CIS*	53	13.6
North America	30.5	13.4
South America	0.8	32
Oceania	0.8	4
World (total)	100	100

*Confederation of the Independent States of the former Soviet Union.

different sectors. It is a tall, fast-growing hollow grass with an extensive root system that creates new bamboo shoots and requires no replanting.

2.2 Softwood and hardwood

Wood can be broadly classified into two main groups: softwoods and hardwoods. The terms 'softwood' and 'hardwood' do not indicate softness or hardness of particular timbers. Some hardwoods are actually softer and lighter than softwoods. Mountain-grown Douglas Fir, for example, produces an extremely hard wood although it is classified as a softwood, and Balsawood is classified as a hardwood although it is very soft. Softwood and hardwood normally differ from each other in terms of the botanic structure of the wood. The dominant feature separating hardwoods from softwoods is the presence of pores or vessels in the former. Softwood and hardwood forests are not uniformly distributed in the world – the Northern Hemisphere contains mostly softwood forests and the Southern Hemisphere mostly hardwoods as shown in Table 2.1.[1]

2.2.1 Softwood

Softwoods are conifers and normally have needle-like leaves. They generally have lower densities and are often light in colour. Softwoods usually grow quicker than hardwoods and are cheaper, softer and easier to work. Common examples of softwood include: pine, fir, spruce, larch and cedar.

2.2.2 Hardwood

Hardwoods generally have broad leaves and often have dark-coloured wood. They normally have higher densities and thicker cell walls than softwoods. There are a much greater number of hardwood species than there are softwoods. Some examples of hardwood include: oak, ash, elm, beech, birch and teak.

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Table 2.2 Basic chemical composition of wood

Element	Percentage of dry weight of wood
Carbon	49
Hydrogen	6
Oxygen	44
Nitrogen	Few traces

Table 2.3 Organic compounds in softwoods and hardwoods

Component	Softwood (%)	Hardwood (%)
Cellulose	40–50	40–50
Hemicellulose	20–30	25–35
Lignin	25–35	15–25
Extractives	1–5	1–15

2.3 Chemical composition

Wood is a fibrous substance primarily composed of three chemical elements: carbon, hydrogen and oxygen, as shown in Table 2.2. These basic elements are incorporated into a number of organic compounds, i.e. cellulose, hemicellulose, lignin and extractives formed into a cellular structure. The cellular structure and the characteristics and amounts of these components vary from species to species. Table 2.3 provides an overview of the breakdown of the organic compounds in softwoods and hardwoods. It is the combination of these components that determines the properties of wood – some woods are heavier, some lighter, some stiffer, some more flexible, some harder, some softer, and some easier to work with than others.

2.3.1 Cellulose

Cellulose is the main structural element and the principal constituent of the cell wall of trees. The glucose ($C_6H_{12}O_6$) units, produced during the process of photosynthesis, bond themselves together in the cambial zone into long chains to form a molecule of cellulose. Cellulose is thus a straight chain polymer with the empirical formula $(C_6H_{10}O_5)_n$ where n is the degree of polymerization. Cellulose is the most important component because of its effect on the properties of wood, it makes up around 50% of the dry weight of wood.

2.3.2 Hemicelluloses

Hemicelluloses, the second important constituent of wood, are also sugar polymers.

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Unlike cellulose, which is made only from glucose, hemicelluloses consist of glucose and several other water-soluble sugars produced during photosynthesis. In hemicelluloses the degree of polymerisation is lower – they are composed of shorter molecules than cellulose. They make up 20–35% of the dry weight of wood. There are many varieties of hemicelluloses and they markedly differ in composition in softwoods and hardwoods. Generally, hemicelluloses are in a relatively greater proportion in hardwoods than in softwoods.

2.3.3 Lignin

Lignin is a complex constituent that cements the wood (cellulose and hemicelluloses) together. It is a three-dimensional polymer without any sugar in it. It delivers rigidity to the cells, crucial for the growth of the tree. Lignin is thermoplastic, which means it becomes pliable at high temperatures and hard again when it cools. It makes up 15–35% of the dry weight of wood.

2.3.4 Extractives

Extractives are various organic and inorganic chemicals found in the cell walls and cell lumens that are not structural components of wood. These substances are called extractives because they can be removed from wood through extraction with various solvents. Extractives contribute to such properties of wood as colour, odour, taste, decay resistance, density, hygroscopicity (ability to absorb water) and flammability. Usually, they make up around 1–10% of the wood's dry weight.

2.4 Growth and structure of wood

A tree can be divided into three parts: roots, trunk and crown, as shown in Fig. 2.1.[2] Roots play a vital role in the growth of a tree. Water and nutrients are absorbed by roots and transported from the soil up to the leaves through hollow cells. Leaves carry out the crucial job of photosynthesis during which they absorb atmospheric carbon dioxide and process it in with help of chlorophyll (the green matter of leaves) and sunlight to manufacture food, in the form of various sugars, for the tree's use. A byproduct of this process is the release of oxygen. The nutrients produced by the leaves are conducted through the inner bark (or phloem cells) to the areas of a tree where growth takes place – the tips of branches and roots and the cambium layer. Newly grown wood is found on the outer side of a tree and the oldest wood is found on the inner side of a tree.

2.4.1 Cambium

The cambium is the layer of reproductive cells found between the inner bark (phloem) and sapwood portions of a tree, as shown in Fig. 2.2.[3] This very narrow

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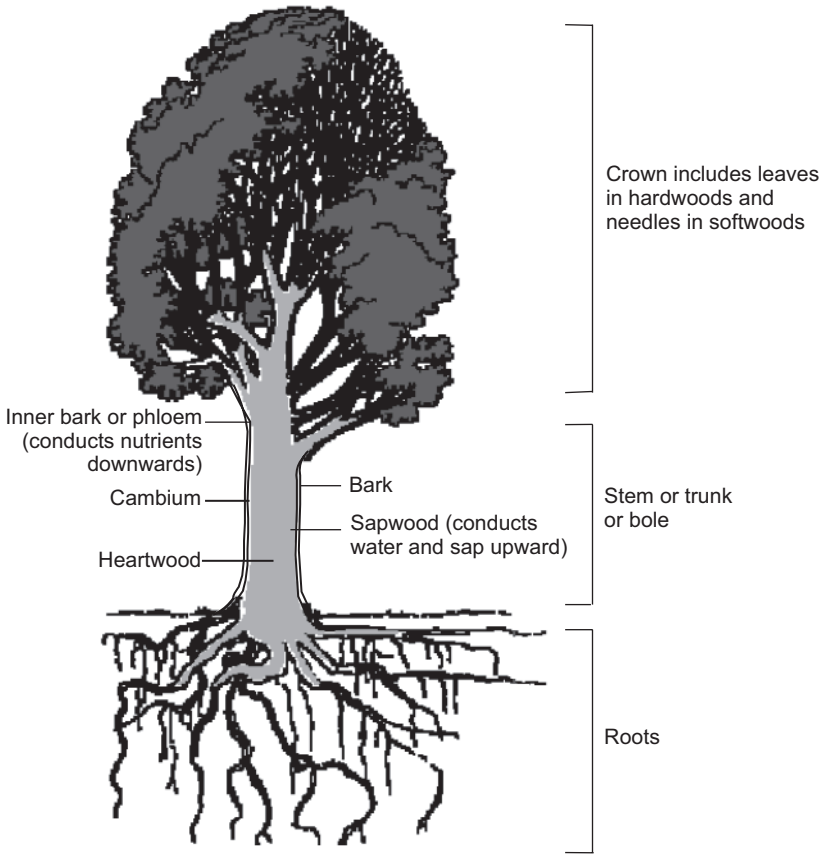

2.1 Main components of a tree.[2]

layer of cells creates new sapwood cells towards the inside and new phloem cells towards the outside of the cambium. Thus the cambium layer is responsible for a tree's outward growth in diameter and circumference.

2.4.2 Bark

As a tree gets bigger in circumference, phloem cells get older; they are pushed farther away from the cambium (toward the outside) and gradually die. Their water-transporting function is then taken over by younger phloem cells produced by the cambium. Dead phloem cells become part of the outer protective layer of trees that we call bark. Bark is important in protecting the tender cells in and near the cambium. Without bark, these cells would be under continual attack from insects, forest animals, fungi and birds, and would be susceptible to physical damage from frost, wind and fire.[4]

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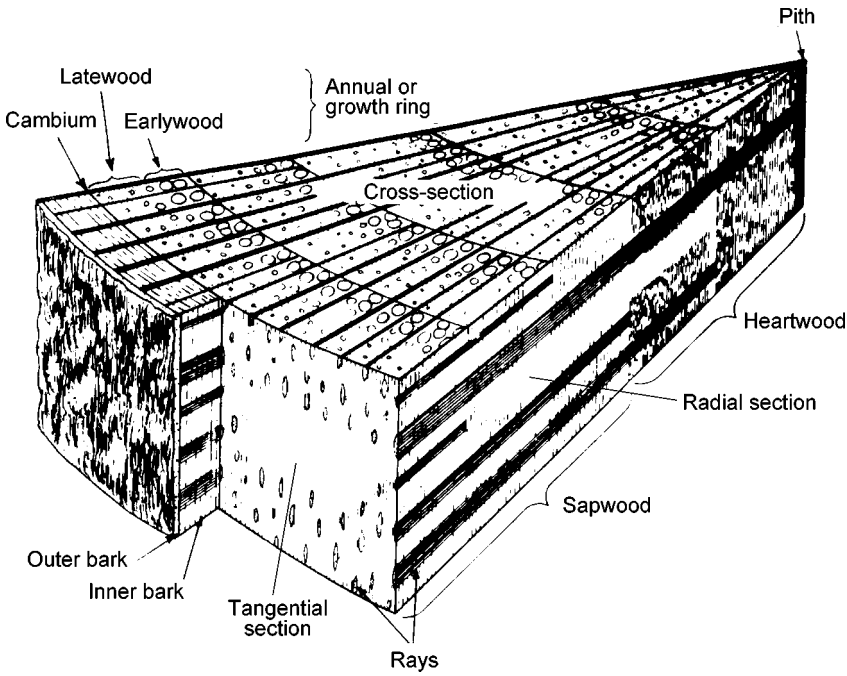

2.2 An overview of a cross-section of hardwood showing the main features of wood.[3]

2.4.3 Annual rings

An annual ring is the layer of wood that is formed during a single growing season. Normally in temperate zones trees make one growth ring each year, with the newest adjacent to the bark. Annual rings are highly visible in tree species that form less dense wood during favourable growing conditions early in the season and denser wood during less favourable conditions later in the year. In some tree species this differentiation does not occur and annual rings are difficult to see. In tropical species, where the environment is not seasonal, growth hardly ceases throughout the year and hence annual rings may not be apparent. In the tropical rain forest, relatively few species of trees, teak is one example, have visible annual rings. The annual rings appear like concentric bands and can be counted to age-date the tree.

2.4.4 Earlywood and latewood

In many species of wood each annual growth ring is divided into two distinct layers. The portion of the annual growth ring that is formed during the early part of the growing season – a period of more rapid growth – is called earlywood or

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springwood. The earlywood, formed in the spring, has an important role in the transportation of liquids in an upward direction. Earlywood is usually less dense (with thin walls of wood cells) and mechanically weaker than latewood.

Latewood is the portion of the annual growth ring that is formed after the earlywood formation has ceased. Normally, it is denser than earlywood and has thicker cell walls. It is mechanically stronger than earlywood and provides stiffness to the trunk. It is also termed as 'summer wood' since it is usually formed during the summer when growth has slowed. The transition from springwood may be gradual or abrupt, depending on the kind of wood and the growing conditions when it was formed.

2.4.5 Sapwood and heartwood

The woody portion of a tree is called xylem and includes two main parts. The outer part, consisting of a ring of wood around the tree just under the bark, is called sapwood and is lighter in colour. Within the sapwood ring is an inner core, darker in colour, called heartwood. All wood in a tree is first formed as sapwood. It is the living wood in a growing tree. Sapwood contains the living cells and takes part in the active life processes of the tree – it conducts water from roots to the leaves and stores up or gives back, according to the season, the food prepared in the leaves. The more leaves a tree bears and the more vigorous its growth, the larger the volume of sapwood required. Hence trees making rapid growth in the open have thicker sapwood for their size than trees of the same species growing in dense forests. The thickness of the sapwood ring also depends on the age and species of the tree.

Heartwood is wood that extends from the pith to the sapwood. Heartwood consists of inactive cells (which no longer participate in the life processes of the tree) and serves mainly to give strength to the tree. It is more resistant to decay than sapwood. As a tree grows older and larger, the inner layers of sapwood change to heartwood. Eventually the heartwood core forms the major part of the trunk and main branches.

2.5 Seasoning

The amount of water in wood is known as its moisture content and is expressed as a percentage of its dry weight.

$$\text{Moisture content (\%)} = (\text{wet weight} - \text{dry weight}) \times 100/\text{dry weight}$$

The moisture content of green wood (i.e. wood that is part of a tree) varies greatly from species to species. It also depends on the density of wood – in a dense wood there is very little space to hold water. Typically moisture contents could be up to 60% in hardwoods and up to 120% in softwoods. The moisture is classified into two types: chemically bound and free – representing moisture in cell walls and in cell voids, respectively.

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As soon as the wood is cut from a tree it starts losing water in a process called seasoning or drying. Wood changes its dimensions in direct relationship to its moisture content. Nearly 70–90% of the original moisture in the green wood needs to be removed before timber can be used. In construction applications, the required level of moisture content is normally 15%–25%. Some of the major reasons for seasoning wood are as follows:

- to minimize the amount of shrinkage during the service life of wood;
- to make it more resistant to fungal decay, staining and insect attack;
- to render it more absorbent of preservative fluids;
- to make it more receptive to surface finishes such as paints and varnishes;
- to reduce its weight before handling and transportation;
- to make it less corrosive to metals.[5]

Owing to the hygroscopic nature of wood, it has an intrinsic relationship with moisture. The ultimate moisture content of wood depends on the relative humidity and temperature of the air surrounding it. Even wood that has been seasoned to the desired level of moisture content, does respond to the relative humidity and temperature of the environment if it is exposed for a sufficiently long period of time. It will absorb or give up moisture depending upon the surrounding environment. The process will continue until the moisture equilibrium is established – i.e. the moisture content of the wood becomes equal to that of the environment.[6] The changes in size that occur in seasoned wood in response to the humidity of the environment, are called 'movement' of timber. Therefore, while seasoning the timber it is important to take into consideration the environmental conditions (i.e. humidity and temperature) in which the timber is to be used. Seasoning of wood can be classified into two main types: air seasoning and kiln seasoning.

2.5.1 Air seasoning

In air seasoning, wood is dried in an outdoor environment with the help of natural movement of air. In this method wood is stacked in open-sided covered sheds which protect the wood from rain while still allowing a free circulation of ambient air. The normal practice is to stack the wood boards on firm foundations around 18 inches (46 cm) off the ground, separating each layer of boards with piling sticks set at intervals along the boards. The key advantage of air seasoning is that it does not require any drying energy. The downside, however, is that it requires large areas to store the wood. In addition, it is a lengthy process – depending on species and weather conditions, air-dried wood may take from several weeks to several months (sometimes up to 2 years) to reach the dryness desired for its intended use.

2.5.2 Kiln seasoning

Kiln seasoning is an accelerated method of drying wood that was developed in the

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1920s. In this method, rapid and controlled drying is achieved by enclosing the wood in a building called a kiln and circulating heated air through the piles of timber. In order to avoid splitting the wood by drying it too fast (removing water too quickly), steam is often injected into the kiln to re-dampen the air. The circulation of heated air is controlled by baffles and fans to give uniform distribution in the kiln which is critical. The kiln drying schedule differs depending upon the type of wood and the required dryness. Kiln drying of softwoods, such as the southern yellow pines, will normally take 1–4 days to reach 15% moisture content. It takes longer to dry dense hardwoods if serious splitting, warping and other drying defects are to be avoided. The acceleration factors – i.e. temperature of heated air, air flow and humidity – are varied to achieve the optimum dryness. Unlike air seasoning, kiln seasoning is an energy-intensive process. Its main advantages include: precise control of the moisture content best suited for the application of wood; quicker drying, giving a rapid turnover of stock and reduction in capital investment; and avoidance of degradation due to fungal staining or insect attacks during storage for seasoning.

2.6 Sustainability

Wood can be regarded as a renewable material – it is environmentally friendly, widely available, abundant and through sustainable forest management it can be replenished continuously, delivering a plentiful and dependable supply. In sustainable forests the harvested tree is replaced by another tree, whether naturally grown or planted. Extraction is thus compensated for, unlike in the case of most other materials. Nearly one-third of the total land area of the planet is covered by forests, the source of wood.[7–9] The production of wood is ecologically sound – trees undertake the vital process of photosynthesis through which they absorb unhealthy carbon dioxide from the environment and release oxygen which is healthy. From a sustainability perspective, the role of forests is actually much wider. It is not just about quantity, but also about the ecological quality; regardless of the sustainable extraction of individual trees, the forest maintains its ecological functions relating to biodiversity, climate and water cycles. When compared with other building and construction materials, wood is by far the most sustainable choice.

Wood has distinctive environmental benefits compared with other competitor materials such as concrete, aluminium, steel, plastic and glass. Wood is the most efficient material, both in terms of embodied energy and environmental impacts, as shown in Table 2.4.[10–13] Processing a raw tree trunk to a usable wooden product requires very little energy as compared with competitor materials because its extraction and finishing do not involve any purification or melting stages. Almost 80% of global energy needs are being met by fossil fuels. These properties of wood imply that the lower the amount of energy needed to make a useable product, the less fossil fuels – such as oil, gas or coal – are burnt and the lower the emission of

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Table 2.4 Energy and environmental performance of timber compared with other common construction materials[10–13]

Material	Embodied energy	Environmental impacts		
	(GJ/m^3)	GWP (kg/m^3)	AP (kg/m^3)	POCP (kg/m^3)
Aluminium	497	29 975.4	162	321.3
Bricks	5.4	342	3.6	30.6
Ceramic tiles	16	1142	8	102
Concrete	4.8	156	2.4	0.72
Glass	19.2	1365.6	96	4.8
Plaster board	4.5	238.5	2.7	1.8
Roof tiles	2.2	288.2	2.2	2.2
PVC	116	1932	17.9	0.69
Steel	200	17 840	80	6720
Wood	1.65	63.8	0.55	0.55

GWP, global warming potential; AP, acidification potential; POCP, photochemical ozone creation potential; PVC, polyvinyl chloride.

greenhouse gases into the environment, contributing to global warming. The environmental performance of building and construction materials has been widely investigated by researchers using the parameters of embodied energy and environmental impacts. Environmental impacts are further measured on the basis of: global warming potential (GWP) in kg CO_2 equivalents; acidification potential (AP) in kg SO_2 equivalents; and photochemical ozone creation potential (POCP) in kg ethene equivalent. The versatile nature of wood draws different materials as competitors: concrete and brick in general construction applications such as walls, floors and roofs; steel, aluminium and polyvinyl chloride (PVC) in windows; concrete and steel in sheds; lino and vinyl in flooring products. In terms of environmental performance and sustainability, wood outweighs all its competitors by a clear margin.

2.7 Durability

The term 'natural durability' when applied to wood refers to its ability to endure, or resist deterioration, by virtue of its inherent properties. The natural durability of solid wood depends to a large extent upon the species and upon the presence of heartwood or sapwood. In appropriate conditions, timber has the ability to last for centuries. For example, the Horiuji temple in Japan, made of cypress, dates back to AD 607 and is among the most ancient timber structures in the world. Despite its highly integrated matrix of cellulose, hemicellulose and lignin, which gives wood superior strength properties and a marked resistance to chemical and microbial attack, it is subject to decay by a variety of organisms and processes. Decay may be considered as a reversal of the wood growing process. During decay, cellulose and starch are broken down by enzymes into sugars and eventually into carbon dioxide and water. Once decay has started in a piece of wood, the

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rate and extent of deterioration depend on the intensity and the duration of decaying conditions. The degradation of wood can be broadly classified into two types: biotic and abiotic.

2.7.1 Biotic degradation

Under particular conditions, wood is subject to attack and degradation by a variety of organisms, including fungi, bacteria, insects and marine bores. These organisms attack wood in a variety of ways: some utilise it for food; some use it for shelter; and others for food and shelter. Fungi are among the most important wood-degrading organisms and require a suitable combination of moisture, temperature and air to grow. The optimum temperature conditions for fungi to grow in wood range from 22–30 °C. Wood is virtually safe from fungi and other biotic elements at temperatures below 0 °C and above 40 °C. Different species of fungi have slightly different moisture requirements but, in general, wood is at risk of decay when the moisture content exceeds around 20% for a prolonged period of time. Most decay fungi will become inactive and eventually die if the wood moisture content drops below this for extended periods.[5] The natural durability of wood against fungal attack has been classified into five types according to the requirements for preservative treatment.[14]

There are a number of insects that attack wood, such as termites, beetles, ants and bees. Some of these insects use wood as a source of food, while others use wood primarily for shelter. In tropical regions termites are the cause of a great deal of damage to timber structures, but in temperate regions damage by insects causes less economic loss than does fungal decay. The decay caused by fungi is different to that caused by insects. In order to control the biological decay of wood properly, it is crucial to understand the source of the damage. Some of the distinguishing features of damage caused by fungi and insects are given in Table 2.5

2.7.2 Abiotic degradation

Climate has an important bearing on the durability of wood in terms of abiotic degradation. A number of environmental factors such as heat, oxygen, moisture (rain, humidity and snow), polluting elements and chemicals, and sunlight (ultra-violet) have the tendency to affect the service life of wood adversely, especially in outdoor applications. This degradation process, also called weathering, starts at the surface of the wood through photo-oxidation of the surface catalysed by heat and ultraviolet radiation in sunlight. It is augmented by other processes such as washing by rain, abrasion by wind-blown particles, changes in temperature and moisture, and reaction with the chemicals in air. Although the degradation process can take many forms depending upon the wood and the intensity of the exposure conditions, in general it begins with a colour change followed by slow erosion from the surface. The surface initially develops slight checking that leads to

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Table 2.5 Distinguishing features of fungal and insect decay[5]

Fungal decay	Insect decay
Wood crumbles into square-edged pieces or into a whitish, lint-like substance	Narrow tunnels are bored in the wood
Toadstools, brackets, or skins or fungal growth appear on the surface	Small, round or oval exit holes can be seen on the surface
Wood is discoloured, sometimes with narrow dark lines through it	Little discolouration
There is often a mushroomy or fungal smell	No noticeable smell
Occurs in situations that are, or have been, damp	Occurs in relatively dry situations

cracking. All of the four components of wood – cellulose, hemicelluloses, lignin and extractives – are affected by this form of degradation. For example, extractives undergo changes upon exposure to sunlight and lighten or darken in colour. Lignin, the polymeric substance cementing the cellulose together, is affected more by photodegration than is cellulose. The breakdown of lignin results in a loss of contact of the celluloses with the surface of wood. If the process continues, cellulose will be lost from the surface (a process called erosion).[12]

2.8 Preservation

Different timber species have varying degrees of permeability to moisture and this also affects their service life. In some cases natural durability may not be sufficient for the particular situation, and improved durability may need to be conferred on solid wood. The durability of wood can be improved through preservation and finishing treatments. Wood can be impregnated with certain poisonous chemicals to protect it from fungi and insects. Surface deterioration through weathering can also be prevented by applying paints and other surface coatings. Treatment is particularly important for non-durable wood. For any given sample of wood, it is of the utmost importance to select the most suitable preservative and the correct method of treatment. The selection should be based upon a thorough understanding of the scope and limitations of the available preservation treatments. For optimum results, before any preservation treatment is carried out the wood should be duly prepared, i.e. it should be dry, clean and free of dirt. The treatment of wood can be broadly classified into two main types: finishing treatments (to protect from weathering) and preservative treatments (to protect from biological attack by fungi, insects and marine borers). Sometimes wood is also treated to improve its resistance to fire.

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2.8.1 Finishing treatments

Wood can be protected from the weathering elements (i.e. sunlight, moisture, wind abrasives) by applying a physical barrier. The common treatments used for this purpose include paints and other transparent coatings. They prevent the destructive weathering elements from reaching the surface of the wood. Application of paints is a well-established phenomenon. Paint gives sound protection against weathering elements as long as it is renewed at regular intervals, normally every 6 years for outdoor wood application. Transparent surface finishes are used when the natural appearance of wood is required to be maintained. The clear, transparent finishes are of two types: varnishes and water-repellent solutions. Varnish is a blend of oils and resins that coats the surface of wood and gives a transparent, protective coating, allowing the beauty of the wood to show through. Depending on its formulation, it can leave a gloss, semi-gloss or satin finish. Water-repellent finishes penetrate the surface of the wood, allowing the natural pattern of the grain to remain visible, but not forming a glossy surface film. Transparent surface finishes are less durable than paints, requiring more frequent renewal.

2.8.2 Chemical preservative treatments

These preservatives protect wood against decaying organisms by virtue of their toxicity. Some of the desirable characteristics a good preservative should possess include;

- sufficiently toxic (poisonous) but only to the organisms to which the treated wood is likely to be exposed, i.e. fungi, insects or marine borers; it should not cause any threat to human health;
- capable of penetrating wood to a reasonable depth;
- actively persistent in the treated wood for many years;
- not harmful to the timber itself ;
- not liable to increase the flammability of wood in service (preferably it should reduce flammability);
- reasonably inexpensive and readily available;
- non-corrosive to metals or other materials.

Chemical preservatives can be broadly classified into three categories as follows.

1 *Tar oil preservatives*. The principal representative of this type of preservatives is creosote. It is a complex mixture of organic compounds distilled from coal tar at a temperature range of 200–400 °C. Creosote is the oldest and one of the most effective industrial preservatives for protecting wood from deterioration and decay caused by fungi, insects and marine organisms. Its effectiveness not only relies on its natural toxicity but also on its water-repellent qualities. It is used primarily for railway ties, telephone and electricity poles, marine piling and highway construction.

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2 *Water-borne preservatives*. There are numerous types of water-borne preservatives. The most common formulations are based on copper, chromate and arsenic (CCA) compounds, but combinations of copper–chromium and copper–chromium–boron are also used. These preservatives are used both for indoor and outdoor applications. They produce a clean and odourless wood, which can be painted after treatment once water has dried out. They are not a fire hazard and are preferred for applications where there is close human or animal contact. They also help reduce the effects of weathering on wood in use, thereby reducing checking and the rate at which the wood turns grey.
3 *Organic solvent preservatives*. These consist of a substance toxic to fungi and insects dissolved in a petroleum distillate (organic solvent). Compared with tar oils and water-borne preservatives, they are relatively new and more expensive. They penetrate readily and are therefore suitable for application by brushing, spraying or dipping.

2.8.3 Application of preservatives

A number of methods are practiced for the application of wood preservatives. These can be broadly classified into two types: superficial treatments and impregnation.

1 *Superficial treatments*. These include application of preservative through brushing, spraying, dipping and steeping. Brushing and spraying are the least effective techniques. Dipping and steeping are relatively better approaches since a total immersion in the preservative bath ensures that every part of the surface is completely coated. However, in these treatments only the surface layers are penetrated leaving a risk of splits occurring during service. Thus, over a period of time untreated timber may be exposed to the deteriorative organisms. Superficial treatments are suitable only when the exposed surface can be regularly retreated.
2 *Impregnation treatment.* For lasting protection of timber, deep penetration of preservatives is essential and this is accomplished through impregnation treatment. There are a number of techniques available, for example: high-pressure/vacuum impregnation, injection treatment and open tank treatment. These techniques provide a deep and uniform penetration ensuring a long-term effective protection. Such treatment is particularly suited to high-risk applications such as where wood is embedded in the ground.

2.8.4 European standards

The European and British standards dealing with wood preservatives are as listed below.[13]

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BS EN 350-1	Durability of wood and wood-based products. Natural durability of solid wood
Part 1	Principles of testing and classification of the natural durability of wood
Part 2	Guide to natural durability and treatability of selected wood species of importance in Europe
BS EN 351-1	Durability of wood and wood-based products. Preservative treated solid wood
Part 1	Classification of preservative penetration and retention
Part 2	Guidance on sampling for the analysis of preservative treated solid wood
BS EN 355-1	Hazard classes of wood and wood-based products against biological attacks
Part 1	Classification of hazard classes
BS EN 355-3	Durability of wood and wood-based products. Definition of hazard classes of biological attacks
Part 3	Application to wood-based panels
BS EN 460	Durability of wood and wood-based products. Natural durabil ity of solid wood
Part 3	Guide to the durability requirements for wood to be used in hazard classes
BS EN 599-1	Durability of wood and wood-based products. Performance of wood preservatives as determined by biological tests
Part 1	Specification according to hazard class

European Standard BS EN 460:1994 broadly integrates the different timber durability specification practices throughout Europe and provides a general introduction to the determination by hazard classes of the need for natural durability.

2.9 Repair

Timber, like other organic materials, is prone to decay caused by biological and non-biological factors as discussed earlier. It may also experience accidental wear and tear requiring it to be repaired in order to remain functional. Some of the common problems in timber that may require repair are as follows:

- rot;
- insect infestation;
- joint movements and distortion;
- fissure;
- deflection;
- deliberate or accidental removal of timber;
- incipient fractures;
- fire damage.

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Timber can be repaired to maintain or reinstate its structural function through systematic control of the decaying process and/or restoration of the damaged part. Timber repairs may be broadly classified into three types: traditional methods, mechanically fastened methods and adhesive methods.

2.9.1 Traditional methods

Traditional methods include the use of scarf, tenon and dovetail joints of various designs, capable of being compared with the types of original joint found in ancient buildings.[15]

Advantages

- Replaces timber with timber.
- Repairs may be made, representative of a specific period.
- Maintains the historical visual image.
- Does not detract from the nature of the building.

Disadvantages

- Limited structural performance.
- Requires skilled craft labour.
- Some original material lost.
- May give misleading information on the age of the structure to future generations.

2.9.2 Mechanically fastened methods

These methods may be defined as repairs to timber that use a combination of timber, timber connectors and other structurally defined materials, in a manner accepted by present engineering practice.

Advantages

- Calculable by current engineering recommendations.
- Straightforward techniques, whose function is readily apparent.
- Reversible.

Disadvantages

- May be visually unattractive.
- May or may not reduce the amount of original timber cut away.

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2.9.3 Adhesive methods

These methods chiefly entail repairs using various epoxy resin formulations, together with metallic or non-metallic reinforcement. They are particularly useful where access to the timber is limited and structural disturbance must be minimised. Careful design and material specification and good preparation and site practice are all essential in ensuring good quality adhesive repairs.

Advantages

- Low structural or fabric disruption.
- Adaptable techniques allow custom application.
- High-strength materials used.

Disadvantages

- Additional structural weight added.
- Specialist knowledge required.
- Non-reversibility.
- Unknown long-term performance.

2.10 Waste disposal and recycling

Waste is produced at a number of stages during the life cycle of a wood product. Firstly, during harvesting and extraction a small amount of waste is generated. Secondly, during the primary processing (sawmilling) a substantial amount of waste, typically 40–50%, is produced. Thirdly, the majority of the wood undergoes secondary processing to be transformed into the finished product; this also results into a considerable amount of waste production. In the manufacture of furniture, for example, up to 40–50% of the sawn timber is typically wasted where hardwoods are used, approximately 30% with softwoods and 10–15% with panel products. The manufacture of joinery products such as windows and doors generates similar levels of waste.[16] In principle, the waste generated during the harvesting and processing stages depends on the effectiveness of operation and the efficiency of the technologies involved. In many countries the generated waste is regarded as a co-product since it finds numerous applications, for example as raw materials for the panel board and paper industries. Lastly, at the end of the service life, all timber products become waste. A considerable amount of this type of timber waste is generated by the construction sector. A significant proportion of this waste is reclaimed while the rest is disposed of, mostly to landfill or by being burnt.

Timber is a recyclable material. Recycled timber is an environmentally friendly product – it is easy to sort and does not require complicated reprocessing. Major sources of recycled timber include: demolished houses, old buildings, sheds and

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factories, warehouses, wharves and boats. In many places in the world – for example in France, Belgium and the Netherlands – old (recycled) timber is substantially cheaper than new wood. Recycled wood is becoming increasingly sought after in a number of applications. One of the main applications of recycled wood is in the production of chipboard and particleboard. Chipboard and related panel products are progressively replacing solid timber in a number of applications, making a potentially useful contribution to the efficient use of timber. Wood is also used as a biomass fuel – whether in the form of pellets or chips from waste wood, logs for stoves, or willow coppice for co-firing power stations. Recycled wood is also being used in flooring, panelling, beams and railway sleepers.

2.11 Wood composites

The diverse characteristics of wood enable it to be blended with other materials into a wide range of composites in order to improve its performance and to broaden its applications. The commonly used wood composites can be broadly classified into three types: composite wood; wood–cement composites; and wood–polymer composites.

2.11.1 Composite wood

Wood is a natural material that can be used in its original or sawn form. It can also be converted into particles and fibres that can be combined with other adhesive materials to form wood composite products. Since the composite wood is engineered to precise design specifications according to national or international standards, it is also called engineered wood. Some of the advantages that composite wood offers include:

- composite wood can be designed to meet application-specific performance requirements;
- composite wood can transcend the dimensional limitations of sawn timber – larger panels of composite wood may be manufactured from fibres and particles than would otherwise be possible using natural wood;
- in composite wood, the anisotropic strength properties of solid wood can be transformed into uniform properties, and the influence of growth features and defects on strength can be greatly lessened.;
- boards can be produced from young trees grown on short forestry rotation and from timber of relatively poor quality.

The downside of composite wood products is their higher embodied energy as compared with those made from natural wood. Composite wood products may also include toxic adhesives; for example, the release of formaldehyde from urea–formaldehyde-bonded composites.

The composite wood products can be broadly classified into two types:

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materials that consist of layers of wood glued together to form a solid piece of much greater thickness than the individual layers, i.e. laminated beams and plywood; and products made from wood disintegrated mechanically into chips or shavings and then bonded together under high pressure after the addition of a small amount of a synthetic resin adhesive, i.e. chipboard.[5]

Plywood

Plywood is made from thin sheets (veneers) of wood glued together, each with its grain in perpendicular directions in alternating layers to improve the strength and to minimise movement in the plane of the board. There are usually an odd number of veneers, so that the grain on the outside plies runs in the same direction and so that the properties are balanced about the central veneer or core. The quality and durability of plywood depends on both the timber species and the adhesive used to bond it. Plywood also comes in decorative finishes. Common applications of plywood are found in roof sheathing, siding, floor underlayment and structural diaphragms. Plywood grading is carried out according to the appearance and finish of the exposed (face and back) faces and it varies from country to country.

Chipboard

Chipboard is made by binding dried and graded wood shavings or chips under heat and pressure with the help of an adhesive material (i.e. urea–formaldehyde) to form a rigid board with a relatively smooth surface. Chipboards normally come in thicknesses ranging from 6 to 25 mm. Their densities also vary depending on applications. Chipboard grades are defined in terms of their suitability for particular applications and their resistance to moisture. Chipboards are commonly used in flooring, cladding, panelling and shelving. They can be used pre-painted or faced with decorative wood veneers, melamine foils or other surface treatments.

2.11.2 Wood–cement composites

Wood–cement composites have been used in the fabrication of building materials since the early 1900s.[17] Wood–cement composites are generally placed into two categories: wood particle-cement composites and wood fibre-reinforced cement products. Wood particle–cement composites have been in use as architectural, fire-resistant and acoustic panels. Wood fibre-reinforced cement products were developed primarily as a substitute for asbestos cement and are relatively new, developed and promoted mostly in the last 25–30 years.[18]

Wood can serve as a low-cost reinforcing material to improve significantly the stiffness, fracture toughness, strength-to-weight ratio, creep deflection and thermal and acoustic resistance of cement when incorporated into a composite bonded with cement. The mechanical properties of wood–cement composites are also a

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direct function of the interface bonding between the reinforcing wood and the matrix and are greatly affected by the type, content, geometry and arrangement of the wood. Bond strength in wood–cement composites is largely dependent on hydrogen bonding between the wood surface and the cement matrix.[19]

Wood–cement composites have a much higher resistance to both decay (i.e. mould, rot, borers and termites) and combustion than resin-bonded boards or solid wood.[20,21]

Wood–cement composites are popular in Europe, the United States and Russia, mainly for roofs, floors and walls. Other typical external applications include agricultural buildings, pre-fabricated and mobile buildings, flat roofing, industrial and exterior domestic cladding, tunnel linings, highway sound-barriers, fire-barriers and paving tiles.[22]

2.11.3 Wood–polymer composites

Polymers can be used as the composite material to enhance specific properties of wood. Wood–polymer composites are produced by impregnating wood with monomers that are then polymerised in wood to tailor the material for specific applications.[23] The properties of wood–polymer composites depend on a number of factors, such as the volume fraction of wood in the composite, as well as processing temperature, additives, and type of polymer used.[24] In principle, wood–polymer composites should display superior mechanical properties, greater dimensional stability, greater resistance to chemical and biological degradation, and less moisture absorption than non-impregnated wood.[25]

Blending of polymers with the wood materials may require the use of different types of additives. Compatibilisers to improve the dispersion, flow and mechanical properties of the composite are used when increased performance is required. Many of the applications of wood–polymers do not require a compatibiliser to improve mechanical properties but other chemicals may be added, for example: stabilisers against ultraviolet radiation, heat and antimicrobials; antioxidants; and colorants. Processing aids or lubricants are almost always used. Foaming agents can also be added to reduce the density of the final product.[24]

The wood–polymer composites market is now regarded as one of the most dynamic and fast-growing areas of the wood industry. Over the last couple of decades, wood–polymer composites have been extensively used for a number of applications such as building products, and for automotive and packaging materials. Owing to their strong wood base, wood–polymer composites are still prone to fungal and termite attacks. Research has shown that more of the wood content in wood–polymer composites is accessible to the fungi on the faces of the composite and in composites produced with large particle size; decay susceptibility also increased with wood content and particle size.[26]

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2.12 Bamboo

Bamboos are tall, tree-like, fast-growing grasses with durable woody or branched stems. There are about 1000 species of bamboo and they are normally found in tropical and subtropical to mild temperate regions. The main regions of distribution are Australia, South Asia, China, Japan, Africa, South America, and Northern and Central America. Bamboos are normally classified into two main types: clumping (monopodial) and running (sympodial). Clumping bamboos are more versatile in their nature and applications than running ones.

2.12.1 Structure and properties

The main structure of bamboo consists of rhizomes (root), culms (stem) and branches. They are all formed of an alternating series of nodes and internodes. Culms are hollow stems with a cylindrical shape and with rigid internal internodes. Bamboo does not grow in width, like trees; when the young shoots emerge from the ground they maintain their original diameter throughout their life. However, young developing clumps of bamboo produce progressively thicker and taller culms each year.[28] The culm is divided at intervals by raised nodes from where branches arise. The cavities of adjacent internodes are totally separated at the node by a transverse diaphragm. Each shoot pushing out of the soil already contains, in miniature, all the nodes and diaphragms that the fully grown culm will possess later. The segment closest to the ground increases in size first, and the one at the top last.

The diameters of culms range from 2 to 30 cm and the lengths from 3 cm to 35 m. The wall thickness of the culms also increases in accordance with the circumferential and longitudinal dimension of the culm. After attaining maximum growth, the process of maturation of the cells starts, with concomitant increase in rigidity. The culms reach their maturity after 3–5 years, depending on species. The physical dimensions of the culm – such as its strength, diameter and wall thickness – are dependent on the species and maturity of the culm.[29] Bamboo is distinguished by its longitudinal growth and is regarded as one of the fastest growing plants. Some species of bamboo grow as much as 90 cm in a single day. It reaches full height in one growth spurt of about 10–12 weeks.

Bamboo possesses excellent strength properties, especially tensile strength. The strength and mechanical properties of bamboo are influenced by a number of factors such as the type of species, harvesting age, climatic and soil conditions, moisture content, location of the sample with respect to the length of the culm, and the presence or absence of nodes. The chemical constituents present in bamboo do not have enough toxicity to impart any natural resistance to fungal or insect attack. In addition, the presence of a large amount of starch makes bamboo highly susceptible to attack by staining fungi and powder post beetles.[30] Bamboo has a strong interaction with moisture, and can have moisture

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levels of 100–300% (compared with its dry weight). It is crucial to remove the moisture as far as possible before application. Upon drying, bamboo shrinks more than wood. In addition, to protect the bamboo from fungi and mould, the moisture must be kept away. If untreated, the life span of bamboo is normally just over 2 years, but if appropriate preservation measures are adopted, it can last up to 10 years. Preservation measures could vary depending on species and environment; common preservation treatments include: smoking, heating, water immersion and impregnation coatings. In order to achieve optimum performance from bamboo, culms must be at least 3 years old, must be only harvested in the dry season and must be properly handled, cured and stored before being used.

2.12.2 Applications

Bamboo is a light yet very hard substance and is widely used as a construction material. In particular, after treatment against rot and insect infestation it forms a hard wood which is both light and exceptionally tough. Bamboo houses are strong, lightweight and elastic, and have a high degree of resistance against earthquakes. Bamboos not only have the technical advantages for use as construction materials but they are also economical – bamboos are among the cheapest building materials. Other key advantages that bamboo construction offers include: easy assembly, pre-fabrication, simple replacement of structural parts – the bamboo elements can be easily dismantled and reused.

Bamboo possesses strength, flexibility and versatility and therefore it finds a wide range of applications within the construction sector. The favourable characteristics of bamboos make them a suitable material for practically every part of a house (i.e. foundation, flooring, walls and roofs) when treated and used properly (http:// www.bambooliving.com/bamboo.html). Bamboo houses are quite common in many countries including China, India, Bangladesh, Indonesia, Philippines, Costa Rica and Ecuador. Bamboos are also used in fences, bridges, furniture, ropes, scaffolding and as a substitute for steel reinforcing rods in concrete construction. Owing to its favourable characteristics such as low cost, easy availability and reasonably high strength, bamboo can also be used to reinforce cement matrices replacing conventional, relatively scarce materials such as mild steel and galvanised steel mesh, or fibres such as asbestos. Thus, bamboo could be used to reinforce cement concrete flexural and compression members, and soil–cement elements. Meshes made of bamboo splints could be used to reinforce cement mortar to obtain thin, ferrocement-like material. As with other vegetable fibres, bamboo fibre could also be used to reinforce cement concretes and mortars.[31]

Other applications of bamboos include: food, medicine, decoration products, paper pulp, biomass fuel, conventional weapons (i.e. bows, arrows and spears) and musical instruments (i.e. flutes and pipes).

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2.12.3 Sustainability

Bamboo can be regarded as a renewable construction material. It can be harvested and replenished sustainably with virtually no impact on the environment. Compared with other construction materials – e.g. concrete, steel and plastic – it has lower embodied energy. In addition to helping local climates through photosynthesis, bamboos also help to control erosion and flooding. The bamboo crop is cultivated on a yearly basis in such a way that only ripe and mature culms are cut and younger ones are left. When bamboo is harvested, the root system is unharmed and healthy, ready to produce more shoots, as with grass. For the micro-climate, as well as for the economy of the population, this yearly crop is better than that of wood, where sometimes an equivalent-sized plot is cut only once in decades.[29] Bamboos can also be regarded as a recyclable material since their products can be incinerated or digested in sewage.

2.13 References

1 Williamson T. G., *APA Engineered Wood Handbook*, McGraw-Hill, USA, 2002.
2 Hoadley R. B., *Identifying Wood*, The Taunton Press, Connecticut, USA, 1990.
3 Dinwoodie J. M., *Timber: its Nature and Behavior*, 2nd edition, BRE, E & FN Spon, New York, 2000.
4 Milton F. T., *The preservation of wood: a self study manual for wood treaters*, University of Minnesota, College of Natural Resources, 1995.
5 Findlay W. P. K., *Timber: Properties and Uses*, Granada Publishing Limited, London, 1978.
6 Simpson W. T., *Equilibrium Moisture Content of Wood in Outdoor Locations in the United States and Worldwide*, United States Department of Agriculture, Washington, DC, 1998.
7 UN Environment Programme, *Global Environment Outlook 3*, United Nations Environment Programme, Nairobi, Kenya, 2002.
8 Townsend P. and Wagner C., *Timber as a building material – an environmental comparison against synthetic building materials*, National Association of Forest Industries Ltd, Germany, 2002.
9 Berge B., *The Ecology of Building Materials*, Architectural Press, Oxford, UK, 2001.
10 Asif M., Muneer T. and Kubie J., Sustainability analysis of window frames, *Building Services Engineering Research & Technology*, 2005, **26**, 1.
11 National Timber Development program, *Environmental benefits of building with timber*, Technical Report, Issue 2, National Timber Development Program, Australia, March 2003.
12 Williams R. S., Jourdain C., Daisey G. and Springate R., Wood properties affecting finish service life, *Journal of Coatings Technology*, 2000, **72**, 35–42.
13 Desch H. and Dinwoodie J., *Timber: Structure, Properties, Conversion and Use*, 7th edition, Palgrave Macmillan, Hampshire, UK, 1996.
14 The Scottish Executives, *The durability of timber cladding*, The Scottish Executive, Scotland, http://www.scotland.gov.uk/Publications/2002/03/15098/8738 (accessed April 2008)
15 TRADA Technology, *Assessment and repair of structural timber*, TRADA, High Wycombe, UK, 1992.

www.EngineeringEBooksPdf.com

16 Mickleburgh S. and Magin G., *Timber Recycling Opportunities in the UK*, Fauna & Flora International, Cambridge, UK, 2003.
17 Wolfe R. W. and Gjinolli A., Durability and strength of cement-bonded wood particle composites made from construction waste. *Forest Products Journal* **49**(2), 24–31, 1999.
18 Wolfe, R.W. and Gjinolli, A., Cement-bonded wood composites as an engineering material. In *The Use of Recycled Wood and Paper in Building Applications*, USDA Forest Service and Forest Products Society Proceedings No. 7286, pp. 84–91, 1997.
19 Semple K. E. and PEvans P. D., *Wood-cement composites–Suitability of Western Australian mallee eucalypt, blue gum and melaleucas*, A report for the RIRDC/Land & Water Australia, Canberra, ACT, 2004.
20 Goodell B., Daniel G., Liu J., Mott L. and Frank R., Decay resistance and microscopic analysis of wood-cement composites, *Forest Products Journal*, 1997, **47**(11/12), 75–80.
21 Del Menezzi C. H. S., de Castro V. G., de Souza M. R., Production and properties of a medium density wood-cement boards produced with oriented strands and silica fume, *Ciencia y tecnología*, 2007, **9**(2), 105–115.
22 Van Elten G. J., Production, properties and world wide application of various wood-cement products. In Proceedings of the 34th International Particleboard and Composite Materials Symposium, eds Wolcott M. P., Tichy R. J. and Bender D. A., Washington State University, Pullman, Washington, pp. 169–174, 2000.
23 Ellis W. D. and Sanadi A. R., Expanding the limits of wood polymer composites: studies using dynamic mechanical thermal analysis, in Proceedings of the 18th Risø International Symposium on *Materials Science: Polymeric Composites – Expanding the Limits*, Roskilde, Denmark, pp. 307–312, 1997.
24 Rowell R. M., Advances and challenges of wood polymer composites. In Proceedings of the 8th Pacific Rim Bio-based Composites Symposium *Advances and Challenges in Biocomposites*, 20–23 November 2006, Kuala Lumpur, Malaysia, pp. 2–11 (http://www.fpl.fs.fed.us/documnts/pdf2006/fpl_2006_rowell001.pdf).
25 Stolf D. O. and Lahr F. A. R., Wood-polymer composite: physical and mechanical properties of some wood species impregnated with styrene and methyl methacrylate, *Materials Research*, 2004, **7** (4), 611–617.
26 Duan X., Lu J. Z., Wu Q. and Lian K., Mechanical properties and decay resistance of wood-polymer composites modified with chitosan copper complexes. In Proceedings of 7th Pacific Rim Bio-based Composite Symposium, 31 October–2 November, 2004, Nanjing, China (http://www.rnr.lsu.edu/wu/PDFFiles/ChitosanCCC-NANJING-Duan04-6-28.pdf).
27 BBC, *Bamboo, Edited guide entry, Guide to life, the universe and everything*, http://www.bbc.co.uk/dna/h2g2/A2175851#footnote3 (accessed April 2008).
28 *Bamboo as a building material*, http://www.bambus.com/new/eng/reports/buildingmaterial/buildingmaterial.html (accessed April 2008).
29 Janssen J., *Bamboo in building structures*, PhD thesis, Eindhoven University of Technology, The Netherlands, 1981.
30 Sattar M. A., *Traditional bamboo housing in Asia: present status and future prospects*. In *Bamboo, People and the Environment*, Proceedings of the Vth International Bamboo Workshop and the IV International Bamboo Congress, 19–22 June 1995, Ubud, Bali, Indonesia.
31 Swami R. N., *New Reinforced Concretes*, Surrey University Press, UK, 1984.

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3

Sustainability of vegetable fibres in construction

H. SAVASTANO JR, S. F. SANTOS
and V. AGOPYAN
Universidade de São Paulo, Brazil

Abstract: This chapter discusses the performance of vegetable fibres that are important in international trade and are of interest as construction materials. The chapter is focused on fibres extracted from non-wood plants and their wastes such as sisal, coconut, bamboo, sugar cane bagasse, banana and jute. The availability of the fibres and their extraction depends on manufacturing and processing these fibrous raw materials for different uses. General applications of vegetable fibres as reinforcing elements are connected to both polymeric and cementitious matrices. The chapter also contains an example of the application of vegetable fibres as reinforcement in cement-based composites for building and infrastructure constructiion. The mechanical and physical performances of non-conventional composites are evaluated in both the newly formed state and after exposure to weathering conditions.

Key words: composite, fibre cement, general applications, mechanical performance, physical characteristics, processing, vegetable fibre.

3.1 Introduction

Sustainability is a concept of increasing concern all over the world in view of the shortage of natural resources and energy, the generation of several types of solid wastes and gas emissions from various sources. The rational use of vegetable fibre can be an alternative solution for the production of durable and more sustainable goods. Fibres obtained from the various parts of plants are known as vegetable fibres. These fibres are classified into three categories depending on the part of the plant from which they are extracted: bast or stem fibres (jute, malva, banana, flax); leaf fibres (sisal, pineapple, screw pine) and fruit fibres (cotton, coir, oil palm) (Wood, 1997).

Fibre resources such as bamboo, sisal, coir and banana, and those from agricultural residues are called natural non-wood fibre resources. The four main fibre material resources from plants are: (a) natural non-wood fibre resources; (b) bamboo; (c) agricultural residues and (d) recycled fibre (waste paper). These fibres have been used to produce clothing, ropes and cordage, sacks, canvas, fishing nets, brushes and sewing thread; and also pulp, paper and building products such as plaster products, fibre-cement sheeting, fibre-reinforced concretes, fibre-reinforced plastics and insulating materials.

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The traditional non-wood fibres can be used to produce high-quality writing and specialty papers. Global paper use has increased more than six times over the latter half of the twentieth century, and has doubled since the mid-1970s. About 93% of today's paper comes from trees, and paper production is responsible for about one-fifth of the total wood harvest worldwide. A sheet of writing paper might contain fibres from hundreds of different trees that have collectively travelled thousands of kilometres from forest to consumer.

In recent years, vegetable fibres have been increasingly used as reinforcement in polymer composites. With their low cost and high specific mechanical properties, they can represent a good, renewable and biodegradable alternative to the most common synthetic reinforcement, i.e. glass fibres (Li *et al*., 2000; Herrera-Franco and Valadez-González, 2005; Doan *et al*., 2007; Tomczak *et al*., 2007; Zini *et al*., 2007).

The fibre reinforcement of building materials has been practised since early ages and its application in the civil construction industry took a large leap forward, with the introduction of asbestos cement in the world market, at the beginning of the twentieth century; however, the durability and mechanical properties of fibre reinforced composites are still not fully understood. Materials based on vegetable plants and alternative cements are well known and should be more intensely used as local building materials. Advantages can include low cost, energy efficiency, control of residues and contamination, thermal comfort and principally the achievement of eco-friendly materials (Agopyan, 1988; Coutts, 1988; Agopyan *et al*., 2005; Coutts, 2005; Savastano and Warden, 2005).

There is also substantial knowledge regarding the materials and techniques required for the construction of earth buildings containing vegetable plants (non-wood and wood fibres). Unfortunately, current performance codes are much more focused on modern materials and in several cases construction materials based on natural earth are found to be out of conformity in relation to these performance codes, even for special uses in rural areas (Agopyan, 1988; Coutts, 1988; Plessis, 2001).

The main objective of the present chapter is to discuss the performance of the vegetable fibres relevant to civil construction applications. The availability of the fibres and their extraction are closely related to the manufacturing and processing of the fibrous raw materials for different uses. The chapter also contains an example of the application of vegetable fibres as reinforcement in cement-based composites for building and infrastructure construction.

3.2 Availability and extraction

There are three basic procedures for extracting vegetable fibres (for example, jute, malva, banana, sisal): retting, chemical treatment and mechanical decortication. The fibre bundles have traditionally been extracted by a microbiological process known as retting, in which the combined action of microbial enzymes and water

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decomposes the non-fibrous material surrounding the fibre bundles, enabling them to be loosened for manual extraction (Wood, 1997). The fibres produced by the retting process are still encrusted with high amounts of lignin and hemicellulose which affect the quality of the fibre. For the production of textiles, the fibres are often subjected to chemical treatment to remove these adhering compounds. Decortication is a process where the fleshy leaves are first trimmed to remove the spines and then passed through decortication machines that crush them between rollers and scrape them against a bladed drum. During the scraping stages water is sprayed on to the leaves to assist in the separation of fleshy material from the fibre. For some purposes the bast fibres can be extracted from green or dried stem material simply by mechanical means with no pre-treatment required (Wood, 1997).

Some advantages and disadvantages of vegetable fibres for building components can be highlighted as follows.

The advantages of vegetable fibres include:

- low specific weight, which results in higher specific strength and stiffness than glass; this is particularly beneficial in components designed for bending stiffness;
- they are a renewable resource, the production requires little energy and carbon dioxide is used while oxygen is given back to the environment;
- can be produced with low investment at low cost, which makes the material an interesting product for developing countries;
- good thermal and acoustic insulating properties in building applications.

The disadvantages of vegetable fibres are:

- variable quality, depending on unpredictable influences such as weather;
- moisture absorption, which causes swelling of the fibres;
- restricted maximum processing temperature;
- lower durability, which can be considerably improved by fibre treatments;
- price can fluctuate depending on harvest yield or agricultural politics.

Many researchers are working to mitigate the disadvantages of vegetable fibres and to modify their characteristics in order to optimize their performance as reinforcement in composite technology. Table 3.1 gives details of some commercially available vegetable fibres. The selection was made based on physical and mechanical properties, cost, durability in natural wet environments and production. As they are natural products, the fibres are heterogeneous and therefore the coefficients of variation in some properties are very high. The characteristics of E-glass and polypropylene fibres are included in Table 3.1 for comparison purposes.

3.3 Manufacturing and processing of raw materials

Treatment is required to turn just-harvested plants into fibres suitable for composite processing. For example, in the case of flax, the first step is retting (as described

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Table 3.1 Physical and mechanical properties of vegetable, E-glass and polypropylene fibres

Fibres	Properties				
	Density (g/cm³)	Tensile strength* (MPa)	MOE (GPa)	Elongation at failure (%)	Water absorption (%)
Jute (*Corchorus capsularis*)[a]	1.36	400–500	17.4	1.1	250
Coir (*Cocos nucifera*)[b]	1.17	95–118	2.8[d]	15–51	93.8
Sisal (*Agave sisalana*)[b]	1.27	458	15.2	4	239
Banana (*Musa cavendishii*)[a]	1.3	110–130	–	1.8–3.5	400
Bamboo (*Bambusa vulgaris*)[b]	1.16	575	28.8	3.2	145
E-glass[c]	2.5	2500	74	2–5	–
Polypropylene[c]	0.91	350–500	5–8	8–20	–

*Tensile strength strongly depends on type of fibre, being a bundle or a single filament.
[a]Rehsi (1988), [b]Agopyan (1988), [c]Fordos (1988), [d]Guimarães (1984).
MOE, Modulus of elasticity.

in Section 3.2); this is a controlled retting process to get rid of the pectin that connects the fibre bundles to the wood core of the stem. During harvesting, pre-treatments and processing, the handling of the material plays an important role in fibre quality. Failure spots on the fibres can be induced, which cause a reduction of the tensile strength. This section describes the manufacturing and processing methods that are widely available and commonly used for vegetable fibres.

3.3.1 Sisal fibres

The sisal plant and its products have proved, over centuries of natural and commercial production, that they can serve mankind as a sustainable renewable resource; the plant is used for cordage and for woven, pharmaceutical and building products. Figure 3.1 shows some production stages in the cordage industry that generate residues of sisal. The sisal (*Agave sisalana*) fibres are easily obtained from the leaves of the Agave plants. Sisal is produced in South America (e.g. Brazil and Venezuela), Africa (e.g. Tanzania, Kenya and Madagascar) and Mexico, where it originated. Central American countries also produce small amounts of this fibre. In 2004, the annual production of fibre in Brazil was about 139 700 tonnes, making it the largest producer of sisal in the world. The Brazilian production is concentrated in the states of Bahia (87%) and Paraiba (7.4%), both located in the northeast region of the country (Andrade, 2006). Nowadays, sisal leaves are also being used by the pulp and paper industry and there have been many attempts to use it in cementitious (Savastano *et al*., 2005) and polymeric (Fung *et al*., 2003; Chand and Jain, 2005) materials.

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(a)

(b)

(c)

(d)

3.1 (a) Sun drying of sisal; (b) separation of sisal bundles for cleaning; (c) weighting of sisal; (d) residues of sisal obtained from the cordage industry.

The procedure of decortication of the sisal fibre is very crude and it can be dangerous for the workers if they do not use proper procedures for this operation. Thousands of simple machines powered by diesel engines are spread throughout the sisal plantations. These machines mechanically separate the fibres from the mucilage, but about 40% of the fibres, the short ones, remain in the mucilage residues. The acidity of the fibres is neutralized simply by washing in water; the fibres are bleached in the sun. During processing, a further 10% of the fibres are lost as residues. Therefore only 3%, by weight of leaves, is recovered as long fibres.

The global market for sisal fibres has remained strong, after improving through 2003 and 2006. Brazil has benefited from China's growing import demand. There is a high demand for African sisal for various non-traditional applications. In Africa the prices increased from around US$750 per tonne in early 2003 to stabilize at around US$1010 through 2006. In Brazil, the price increased from US$400 during 2002 to around US$780 in the second half of 2006 (FAO, 2006).

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3.3.2 Coir fibres

Coconut is a tall cylindrical-stalked palm tree, reaching 30 m in height and 60–70 cm in diameter. It is a tropical plant for low altitudes. It needs sunshine and a soil rich in calcium and phosphorus and is thus generally suitable for cultivation in sandy, sea-shore areas (Agopyan, 1988; FAO, 2002). Although coconut cultivation is concentrated in the tropical belts of Asia and East Africa, it is also found in Latin America on a smaller scale; coconut is cultivated on a commercial basis in Brazil (Tomczak *et al*., 2007). The most important part of the tree is its fruit, which is egg-shaped and about 30 cm long and 25 cm in diameter. The more external layer of the fruit is thin and smooth: its fibrous mesocarp is 3–5 cm thick and the endocarp is very hard. The fruit has a large central cavity that contains a sweet liquid (coconut water). The number of fruits per tree varies, depending strongly on soil conditions (Agopyan, 1988).

Brazil produces about 1.5 billion coconuts (*Cocos nucifera* L.) annually, mainly in the northeast region, in a cultivated area of 273 810 ha. Coconut fibres (coir) can be extracted from either immature or mature fruits (Fig. 3.2). They are lignocellulose fibres obtained from the mesocarp of the coconut fruit, which constitutes about 25% of the nuts. They are one of the least expensive of the various natural fibres available in the world. They are not brittle like glass fibres, they are responsive to chemical modification and are non-toxic. However, the waste from their disposal causes environmental problems (Tomczak *et al*., 2007).

Coir fibre production is normally rudimentary; old-fashioned equipment crushes the husk and separates the fibres. Some industries have modern equipment that can separate long fibres (of more than 110 mm in length) suitable for brushes and threads. Asasutjarit *et al*. (2007) carried out research into the development of coir-based, lightweight cement boards. They were used as building components for energy conservation. John *et al*. (2005) also conducted a comparative study on the microstructure of both new and in-use aged blast-furnace slag cement reinforced with coir fibre. Aged samples came from the internal and external walls of a 12-year-old house built in São Paulo, Brazil that remained in an acceptable condition after this period under normal utilization. The panels of the house were produced using 1:1.5 : 0.504 (binder:sand:water, by mass) mortar reinforced with 2% of coir fibre by volume. After 12 years, the cement was fully carbonated. Fibres removed from the old samples seem to be undamaged when examined using scanning electron microscopy. Qualitative determination of lignin content by Wiesner reaction suggested that the old samples had a lower content of guaiacyl lignin units. Nevertheless, the total lignin content of the old fibres when measured by the acetyl bromide method was comparable with that reported in literature. No significant difference was found in the lignin content of fibres removed from external walls and those removed from internal walls.

As a by-product generated in the fabrication of other coconut products, coir fibre production is largely determined by demand. Abundant quantities of coconut husk

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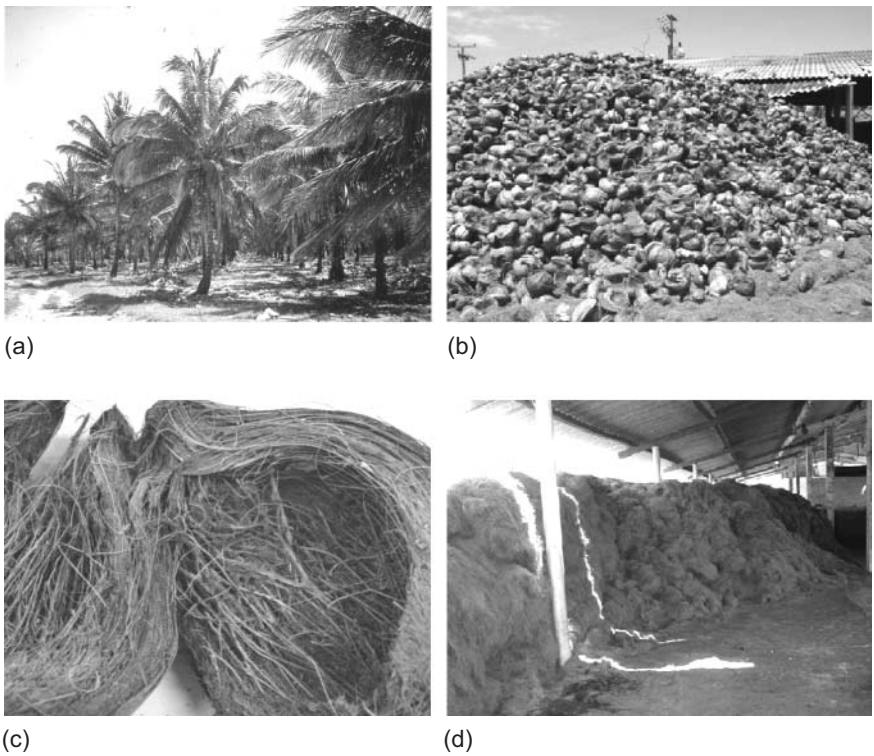

*3.2 (*a) Coconut plantation in the northeast region of Brazil; (b) deposits of coconut husk; (c) detail of the fibres in the coconut husk; and (d) extracted coir fibre.

imply that, given the availability of labour and other inputs, coir fibre producers can adjust relatively rapidly to market conditions and prices. It is estimated that approximately 10% of husks are utilized for fibre extraction, satisfying a growing demand for fibre and coir products. Production of coir fibre takes place in small- or medium-sized units, mainly in India, Sri Lanka and Thailand. During the 1990s, production in India expanded by 8.2% annually in order to meet domestic demand, while in Sri Lanka, a major exporter of coir fibre, production contracted due to weakening export and domestic demand. In the medium term it is projected that global production will increase from an average of 534 000 tonnes in 1998–2000 to 640 000 tonnes in 2010. Most of the expansion in production is likely to take place in India, with some modest growth in Sri Lanka (FAO, 2002; FAO, 2003a).

3.3.3 Bamboo fibres

Throughout wide areas of the world, bamboo plants serve many purposes. The bamboo culture in the Americas and Asia is ancient. In these areas the largest, most

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pure and densest bamboo forests and the best and largest number of giant species were found. The natives of this area also developed the best constructions technologies for bamboo houses and bridges and became skilled builders. Nowadays, there are many applications for bamboo in different fields of aeronautical, chemical, civil, electrical, hydraulic, nautical and mechanical engineering (Hidalgo-Lopez, 2003; Ghavami, 2005; Yamashita *et al.*, 2007; Lo *et al.*, 2008).

Sixteen countries in Asia reported a total of 24 million ha of bamboo resources, while five African countries reported 2.8 million ha. It is estimated that ten Latin American countries may have over 10 million ha of bamboo resources, taking the world total to some 37 million ha or roughly 1% of the global forest area. However, the figures represent only rough estimates and include pure bamboo forests, bamboo mixed with other species (in which bamboo is not necessarily predominant) and bamboo on other land (also pure or mixed with other trees or crops) (FAO, 2005). National and local trade is probably a few times higher. There are numerous other examples of the importance of bamboo for national economies and international trade; however, reliable statistics are still lacking. Most of the economic activities related to bamboo are not recorded officially. They are site-specific, highly diverse and present challenges for official data collection.

The growing industrial and environmental importance of bamboo requires the development of more comprehensive statistics on bamboo resources, utilization and trade. In 2005, the World Customs Organization (WCO) approved the Food and Agriculture Organization of the United Nations (FAO) proposal to introduce 16 new harmonized system codes, including bamboo pulp, panels, furniture and shoots. The new codes will have a profound long-term effect on bamboo statistics and will facilitate bamboo trade and development (FAO, 2005).

About 75 genera and 1250 species of bamboo are found in different countries of the world. *Bambusa vulgaris* is the best known and most widely used species in Asia. For building, *Guadua angustitifolia* Kunth is also used and is a common plant in Latin America, especially in Colombia, Peru and Ecuador (Agopyan, 1988; Hidalgo-Lopez, 2003). Bamboo is the most important non-wood forest product and in India it is known as the 'poor man's timber'. In China, it is the valuable raw material for the booming bamboo industry (FAO, 2005).

Over the last 15–20 years, bamboo has developed as an exceptionally valuable and often superior substitute for wood. Bamboo-based panels and boards are hard and durable and may successfully substitute the hardwood products. Bamboo may replace wood in many industrial applications and thereby contribute to the saving and restoration of the world's forests. Pulp and paper manufacture from bamboo is expanding (Hidalgo-Lopez, 2003; FAO, 2005). Fig. 3.3 shows some steps in the production of bamboo paper.

Fresh bamboo materials softened by high temperature can be manufactured into fibres for textile production. Bamboo fibre is hollow inside and, thus, it results in breathable fabrics. The texture of bamboo fibre and hemp, silk or wool fibres results in fabrics with better performances than those made from other commonly

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3.3 (a) Bamboo seedlings; (b) nursery; (c) minced raw material; (d) bamboo paper depot.

used fibres. As China is one of the biggest bamboo producers in the world, bamboo utilization is significant to the development of China's pulp industry. Bamboo is the second most important fibre material for pulp making in China, and its production is estimated at approximately 177 000 tonnes (Dhamodaran *et al.*, 2003; INBAR, 2004).

The length of bamboo fibre is much longer than the length of hardwood (e.g. eucalyptus) fibre and this also results in a stronger pulp. However, as pulping conditions are very similar for both eucalyptus and bamboo, they can be pulped together. This mixed pulping (for example in a chemical process) gives a stronger pulp than if the hardwood is pulped separately (Stig Andtbacka, 2005).

3.3.4 Sugar cane bagasse fibres

Sugar cane bagasse is a lignocellolusic fibre residue obtained from sugar cane culm (Fig. 3.4), after the culm is milled and the juice is extracted. The average composition of sugar cane is 65–75% water, 11–18% sugars, 8–14% fibres and 12–23% soluble solids. The cane basically consists of juice and fibre (Santaella,

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3.4 Sugar cane plantation (photograph by Loan T. Le).

2007). The sugar cane bagasse has the following composition (by weight): cellulose, 41.8%; hemicellulose (as pentosan), 28.0%; lignin, 21.8% (Bilba *et al.*, 2003).

There are roughly 130 countries that are responsible for between 74 and 77% of the global sugar cane production; about 191 countries are registered as producers. Developing countries currently account for about 67% of world production (1998–2000). In addition, production is becoming more concentrated in certain countries. In 1980, the top ten producers accounted for 56% of global production; by 2004, they accounted for 69%. World sugar consumption is expanding, reflecting rising incomes and shifts in food consumption patterns. Developing countries account for more than 67% of current global sugar consumption – particularly in Asia – and are expected to be the primary source of future demand growth. Brazil is the major player and the most competitive supplier in the world sugar market, with the lowest production costs both in field and factory. The country has significantly increased its exports over the last 5 years, driven by record production and by deregulation of the sugar and ethanol sectors (FAO, 2007).

Other applications for parts of the sugar cane and its residues are being studied with the objective of generating a sustainable life cycle of production. There are successful examples of cement-based materials reinforced with plant fibres produced at very low cost and with high potential as building materials in poor areas. In Cuba, the Technical Centre for Construction and Materials, with the help of the Cuban Institute for the Research of Sugar Cane By-products, has developed sugar cane husk–cement panels, similar to those produced from chip wood bonded with cement. Panels of up to 1.20 m^2 have been produced and have been found to be

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useful for construction purposes. Agopyan (1988) has presented several propositions involving the use of pressed sugar cane bagasse for the production of panels and sheets. In the future it is possible that the availability of bagasse will increase due to the general interest in the production of bio fuels based on sugar cane.

3.3.5 Banana fibres

Bananas are grown in all tropical regions and play a key role in the economies of many developing countries. Banana plantations were cultivated over an area of some 9 million ha in 2000. World production averaged 92 million tonnes per annum in 1998–2000 and it was estimated at 99 million tonnes in 2001. The bulk of world banana production (almost 85%) comes from relatively small plots or backyard gardens (FAO, 2003c). In many developing countries, the bulk of the banana production is self-consumed or locally traded (FAO, 2003a; FAO, 2003c).

World banana exports are projected to reach almost 15 million tonnes in 2010, rising by approximately 28% with respect to the volume exported in the base period 1998–2000 (FAO, 2003). The average annual increase was predicted to be between 1 and 2% from 2001 to 2005. The opening of the European Community market in 2006 was expected to be reflected by a rise in exports of some 5% that year. In subsequent years the growth was predicted to return to a more moderate rate of 2% per annum. The projected growth of exports in the 2000–2010 decade is lower than the expansion observed in the previous decade. Global exports rose by 48% from an annual average of 7.8 million tonnes in 1988–1990 to some 11.7 million tonnes in 1998–2000. The slower rate of growth projected for 2000–2010 can be explained by both supply and demand. On the supply side, structural adjustments have been made by banana producers in the wake of low prices at the end of the 1990s (FAO, 2003a). The three leading exporting countries are Ecuador, Costa Rica and Colombia. In Asia, the main exporter is the Philippines; in Africa, Cameroon and Côte d'Ivoire; and in the Caribbean, the Dominican Republic and the Windward Islands (FAO, 2003b; FAO, 2003c).

Banana is perennial crop that grows quickly and can be harvested all year round and its plants reproduce asexually by shooting suckers from a subterranean stem. The shoots have vigorous growth and can produce a ready-for-harvest bunch in less than 1 year. Suckers continue to emerge from a single mat year after year, making bananas a perennial crop. The importance of bananas as a food crop in tropical areas cannot be underestimated. Bananas fall into two categories:

(a) cooking bananas, including plantains and other sub-groups of varieties such as Pisang Awak in Asia;
(b) dessert or sweet bananas, where the Cavendish cultivars are prominent with a 47% share of global banana production; almost all bananas traded worldwide are Cavendish (Fig. 3.5).

Approximately 26% of the total Cavendish crop is exported, and 8 out of 10 bananas exported originate from Latin America.

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3.5 Banana Cavendish fruit.

The banana plant has long been a source of fibre for high-quality textiles. In Japan, the cultivation of banana for clothing and household use dates back to at least the thirteenth century. In the Japanese system, leaves and shoots are cut from the plant periodically to ensure softness. The harvested shoots must first be boiled in lye to prepare the fibres for the making of the yarn. These banana shoots produce fibres of varying degrees of softness and yielding yarns. Textiles can be produced with differing qualities for specific uses. For example, the softest, innermost fibres are desirable for kimono and kamishimo clothing; this traditional Japanese banana cloth-making process requires many steps, all performed by hand (Kijoka Banana Fiber Cloth Association, http://www.kougei.or.jp/english/crafts/0130/f0130.html, 2007).

Banana fibre is also used in the production of banana cellulose and paper. Soffner (2001) compared two different types of pulping processes applied to wastes from the banana stem, the grain stalk that supports the banana fruits. For banana stem pulping, a CaO process can be considered a technical alternative for pulp production, with delignification rates similar to the NaOH process.

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The use of banana fibres as a reinforcement in cement composites has shown enormous potential in the field of recycled materials and supports their utilization in the sustainable production of building components for civil construction (Coutts, 1990; Savastano *et al*., 2005).

Banana fibres can be used with man-made or natural polymers to provide a wide range of useful composites in textiles (including geotextiles and non-wovens), particle and other boards, chemical and thermosetting polymer-containing goods, and filters; as well as having several uses in transportation, building industry and agriculture. These applications are of increasing interest as in the future all biocomposites will have to be recyclable and fully biodegradable (Kozlowski, 2000).

3.3.6 Jute fibres

Jute is a long, soft, shiny vegetable fibre that can be spun into coarse, strong threads. It is produced from plants in the genus *Corchorus*, family Malvaceae (Agopyan, 1988). Jute is one of the cheapest vegetable fibres and it is second only to cotton in the amount produced and the variety of its uses. Jute fibres are composed primarily of the plant materials cellulose (major component of plant fibre) and lignin (major component of wood fibre). It falls into the bast fibre category (fibre collected from the bast or skin of the plant) along with kenaf, industrial hemp, flax (linen) and ramie. The industrial term for jute fibre is 'raw jute'. The fibres are off-white to brown and 1–4 m long.

Jute was growth for many centuries in Bengal before it became known to the West in the eighteenth century (Fig. 3.6). Small quantities were imported into Europe and America, but it was only in the nineteenth century that serious attention was given to jute as a textile fibre (Wood, 1997). Although, jute is not a typical American plant, Brazil is producing it on a large scale, mainly in the Amazon region. The plant grows quite easily in wet and warm areas, and it is harvested 130 days after planting. The average productivity varies from 1500 to 2000 kg/ha (Agopyan, 1988).

The fibres are separated by maceration or decortication. However, for large-scale production only mechanical decortication is suitable, and this kind of equipment is not available in Latin American countries. The fibres are used alone or blended with other types of fibres (cotton, for example) to make twine and rope (Sreenath *et al*., 1996). Jute butts, the coarse ends of the plants, are used to make inexpensive cloth. Conversely, very fine threads of jute can be separated out and made into imitation silk. As jute fibres are also being used to make pulp and paper, and with increasing concern over forest destruction to obtain the wood pulp used to make most paper, the importance of jute for this purpose may increase. Jute has a long history of use in the sackings, carpets, wrapping fabrics (cotton bale) and construction fabric manufacturing industries.

Ramakrishna and Sundararajan (2005) reported experimental investigations

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3.6 Jute plant details.

into the resistance to impact loading of cement mortar slabs reinforced with jute; four different fibre contents (0.5, 1.0, 1.5 and 2.5% by weight of cement) and three fibre lengths (20, 30 and 40 mm) were investigated. Ordinary Portland cement was used as the binder. The results obtained showed that the addition of the cellulose fibres increased the impact resistance to 3–18 times that of the reference (i.e. plain) mortar slab.

Jute is predominantly a rain-fed annual crop. Its cultivation is labour-intensive, but it requires relatively small quantities of other inputs, such as fertilizer and pesticides, and can be carried out on smallholdings. For all these reasons, jute production is increasingly concentrated in Bangladesh, India, China and Thailand, which between 1998 and 2000 together accounted for more than 95% of the world production, compared with a share of 90% in the early 1970s (FAO, 2003a).

3.4 General uses of vegetable fibres

In most developing countries in Africa, Asia and Latin America, the sustainable production of vegetable fibres fulfils a major economic role which is confirmed by its large contribution to the gross domestic product (GDP) and to the employment rate.

When determining the properties of vegetable fibres, it is advisable to keep in mind that one is dealing with natural products with properties that are strongly

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influenced by their growing environment. Temperature, humidity and the composition of the soil and of the air affect the height of the plant, the mechanical properties and the density of its fibres. In addition, the way in which the plants are harvested and processed results in a variation of properties. For this reason it is very difficult to use vegetable fibres, but due to their low costs they are being widely applied in many areas of the economy.

Nowadays, vegetable fibres form an interesting alternative to the glass fibres that are the most widely applied fibre in the composite technology industry. The use of fibres such as coir, hemp, jute or sisal in this industry so far is small since the availability of a durable semi-finished product with constant quality is often a problem. Recent research and development have shown that these aspects can be improved considerably. The knowledge that vegetable fibres are cheap and have a better stiffness per weight than glass fibres, which results in lighter components, has resulted in a growing interest in vegetable fibres.

Secondly, the environmental impact of these fibres is smaller since the vegetable fibre can come from a renewable resource. The main drawback of using hydrophilic vegetable fibres as reinforcement in polymer composites is the lack of adhesion with most common thermoplastic matrices which have an intrinsic hydrophobic character. Several methods have been applied to overcome this inconvenience. Typically, physical and chemical modifications of fibres and matrices have been performed in order to obtain similar surface properties for the composite constituents.

Hemp, sisal, jute and flax are the fibres most commonly used to reinforce polymers such as polyolefins, polystyrene, epoxy resins and unsaturated polyesters (Li *et al*., 2000; Arbelaiz *et al*., 2005; Bourmaud and Baley, 2007; Doan *et al*., 2007; Yuanjian and Isaac, 2007). Most of the present applications are in the automotive sector and include composite parts produced by means of thermoforming or thermo-compression moulding techniques. The vegetable fibres are in the form of mats and the matrix is a thermoset or thermoplastic polymer. Recent developments in natural fibre-reinforced composites point – for economic reasons – towards the use of the more versatile and faster injection-moulding techniques. The main disadvantage associated with processing through extrusion/injection moulding is the drastic decrease of fibre length (caused by the high mixing energy applied) and the consequent reduction of reinforcing effect.

In several industrialized and developing countries, cellulose fibres derived from hardwood or softwood are used for the production of cement composites by adaptation of the former asbestos-cement production processes. Asbestos cement still represents around 74% of the approximately 200 million m^2 of fibre–cement composites produced yearly in Central and South America, mostly as corrugated roofing elements, as estimated by Heinricks *et al*. (2000). In the case of developing countries, there is an enormous need for houses, schools, hospitals and public service buildings. Therefore, even in periods of economic difficulty, there is a

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Table 3.2 General prices for E-glass and vegetable fibres (Brouwer, 2001)

Fibre	Price/kg (US$), raw
E-glass	1.3
Flax	1.5
Hemp	0.6–1.8
Jute	0.35
Ramie	1.5–2.5
Coir	0.25–0.5
Sisal	0.6–0.7

major need for the application of these vegetable fibres to accelerate the production of composites with adequate performance (Agopyan, 1988).

Vegetable fibres are low cost (Table 3.2). When consideration is given to the variety and abundance of vegetable fibres, of adequate length, available in developing regions, including residues (such as those from agro-industries), the challenge is to facilitate the application of these fibres in civil construction. However, it is first necessary to improve their durability in composites (Mohr *et al*., 2004).

Changes in the fibre and fibre–cement interfacial region due to environmental interactions can affect the long-term performance of cement-based composites reinforced with natural fibres. A significant cause of changes in composite properties is pulp fibre degradation as a result of environmental interactions or changes in the fibres themselves due to their presence in the strongly alkaline matrix (Mohr *et al*., 2004).

According to Savastano and Pimentel (2000), there is a considerable range of short-length fibre residues that can not be used for textile or cordage industries, but which are still adequate for the reinforcement of composites. These authors proposed the following steps for the use of these residues based on information collected in technical visits: (a) general identification of the agricultural production; (b) identification of residues, including correlation with main products and production processes; (c) amount of residues available and other possible uses with actual demands; (d) local availability and requirements for transportation or processing; (e) market value of the residue; (f) physical and mechanical properties of composites and components.

3.5 Case study: vegetable fibre in cement-based composites

The main objective of the present section is to discuss the performance of several non-conventional materials based on cementitious matrices with emphasis on vegetable fibre-cement studies. Construction materials and elements are evaluated

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Table 3.3 Physical properties of sisal chemi-thermomechanical pulp and fibre

Property	Value
Kappa number[a]	32
Canadian standard freeness (mL)[b]	650
Fibre length (length weighted)[c] (mm)	1.65
Fibre width average (μm)[d]	13.5
Aspect ratio	122

[a]Appita P201 m-86 (Appita,1986). [b]AS 1301.206s-88 (Australian Standards,1988).
[c]Kajaani FS-200 fibre length analyzer.
[d] Average of 20 determinations by scanning electron microscopy.

by their mechanical, physical and microstructural properties and also their durability in the environment where these materials are to be used.

Savastano *et al*. (2001) carried out a collaborative work between Universidade de São Paulo (USP), Brazil and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia. The main objective of the study was to develop asbestos-free fibre cements based on residues from agriculture and pig iron fabrication in Brazil. The processing of these construction materials was based on technologies previously developed in CSIRO in collaboration with industrial partners in Australia.

3.5.1 Raw materials

Ground granulated blast furnace slag (GGBS) was employed as the main component of an alternative binder. Ground agricultural gypsum and construction-grade hydrated lime were used as activators in the proportions of 0.88:0.10:0.02 (GGBS:gypsum:lime) by mass as previously discussed (Oliveira *et al.*, 1999). Sisal (*Agave sisalana*) field by-product was selected from a variety of Brazilian fibrous residues on the basis of availability and the relatively low levels of contamination. Chemi-thermomechanical (CTM) pulping procedures, based on the suggestions of Higgins (1996), were employed in the preparation of the sisal fibres. The main physical attributes of the sisal CTM pulps are summarized in Table 3.3.

3.5.2 Composite preparation

Cement-composite pads reinforced with 8% sisal CTM pulp, were prepared in the laboratory using a slurry vacuum dewatering technique. The selection of fibre contents was based on the optimum levels found in a similar study published by Savastano *et al*. (2000). Pads were pressed simultaneously at 3.2 MPa for 5 min.

On completion of the initial saturated air cure for the period of 7 days, pads were then allowed to air cure in a laboratory environment at 23 ± 2 °C and 50 ± 5%

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Table 3.4 Climate averages

Location	Temperature (°C)		Relative humidity (%)		Average
	Av. max (month)	Av. min. (month)	Av. max. (month)	Av. min. (month)	rainfall (mm/year)
Melbourne, Victoria, Australia[a]	25.8 (Jan)	5.9 (July)	82 (June)	60 (Jan–Dec)	654
Pirassununga, São Paulo, Brazil[b]	30.1 (Jan–Feb)	9.5 (July)	77 (Jan–Feb)	63 (Aug)	1363

Source: [a]Bureau of Meteorology, Australia (www.bom.gov.au); [b]Air Force Academy, Defence Ministry, Brazil (www.afa.aer.mil.br).

relative humidity prior to the performance of mechanical and physical tests at a total age of 28 days. Additional pads were allocated for exposure for up to 60-month periods of weathering in temperate Australian and tropical Brazilian environments (Table 3.4). Corresponding sets of pads were stored continuously in the laboratory over the same periods to provide specimens for the determination of reference properties at the different ages.

3.5.3 Test methods

Three-point bending tests were performed for the determination of modulus of rupture (MOR), modulus of elasticity (MOE) and toughness. A span of 100 mm and a deflection rate of 0.5 mm/min were used for all tests in an Instron model 1185 testing machine. Fracture energy was calculated by integration of the load–deflection curve to the point corresponding to a reduction in load carrying capacity to 50% of the maximum observed. For the purpose of this study, the toughness was measured as the fracture energy divided by specimen width and depth at the failure location. The mechanical test procedures employed are described in greater detail by Savastano *et al.* (2000). Water absorption and bulk density values were obtained from tested flexural specimens following the procedures specified in ASTM C 948–81 (ASTM, 2000).

The experimental data were subjected to one-way analysis of variance using Tukey's multiple comparison method to determine the significance of observed differences between sample means at the 95% confidence level ($\alpha = 0.05$).

3.5.4 Weathering conditions

After 28 days, composites of each formulation were placed in a rack facing the Equator at an angle of inclination of 45° to age naturally in the temperate environment of Melbourne, Victoria, Australia (37° 49' S latitude). Corresponding

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Table 3.5 Mechanical and physical properties (± standard deviation) of composites at 28 days

Fibre type	Fibre content (% by mass)	MOR (MPa)	Toughness (kJ/m^2)	MOE (GPa)	Water absorption (% by mass)	Bulk density (g/cm^3)
Nil	–	8.1 ± 2.2	0.03 ± 0.01	11.6 ± 1.7	17.6 ± 0.9	1.84 ± 0.03
Sisal	8	18.4 ± 1.4	0.85 ± 0.10	5.9 ± 0.5	32.9 ± 0.6	1.33 ± 0.01

series of composites were exposed in a similar manner to the tropical environment of rural Pirassununga, São Paulo state, Brazil (21° 59' S latitude). Exposure of these series started in July 1999. Table 3.4 lists the main long-term climate averages for the Australian and Brazilian exposure sites.

3.5.5 Mechanical and physical properties

Table 3.5 presents some mechanical and physical properties of the composites with their standard deviations. Figures 3.7 and 3.8 show the mechanical properties of the composites. Non-aged composites presented flexural strengths of about 18 MPa, representing a 120% improvement over a plain GGBS matrix ('Nil' in Table 3.5) of similar formulation. Non-aged GGBS-based composites possessed MOE values of 5.9 GPa, approximately 50% of that of the plain GGBS matrix. The reduction is associated with the low modulus of the cellulose fibres employed and the additional porosity resulting from their inclusion. Toughness is the property of the composite most often enhanced by the presence of fibres, which in this material produced a 28-fold increase.

The short-term water absorption and bulk density values of the composites with sisal pulp were 33% by mass and 1.3 g/cm^3 respectively (Table 3.5). The plain GGBS matrix, produced using a process analogous to that reported in the present study for composites, was found to have a water absorption of 18% and bulk density of 1.8 g/cm^3, confirming the influence of the cellulose fibres on the volume of capillary voids in fibre cements.

Figures 3.7 and 3.8 show decreasing strength and increasing toughness with time for the composites maintained in laboratory environment. There was a tendency of stabilization of the mechanical properties after the first four initial.

As shown in Fig. 3.7, the external exposure of fibre cement to temperate weather resulted in considerable reduction in flexural strength, which dropped to 4 MPa after 60 months. In the case of tropical weather, the same formulation presented a strength of 1.5 MPa after the same period of time due to even more severe degradation. Both flexural strength and toughness (Figs 3.7 and 3.8) measurements indicated that tropical weather (São Paulo, Brazil) affected the microstructure of the composites more intensely than temperate weather (Victoria, Australia) after the fourth month of exposure. The loss in mechanical strength of composites

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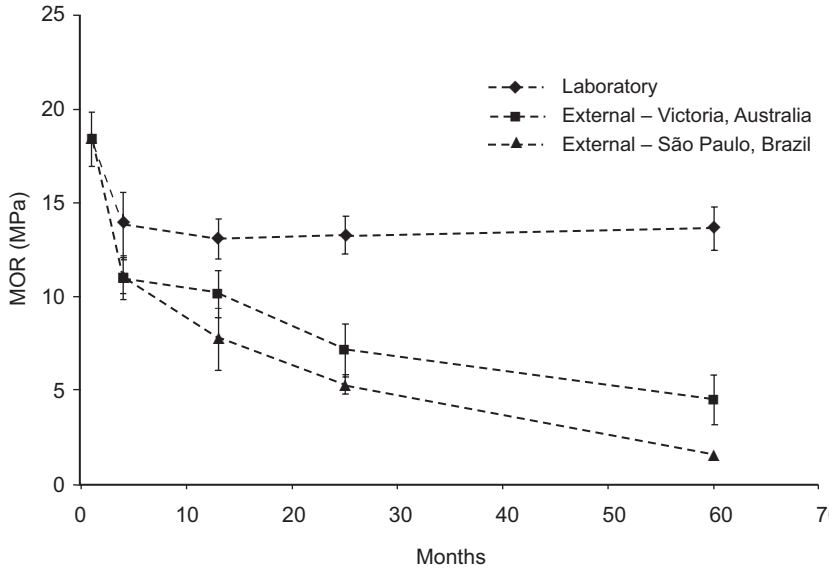
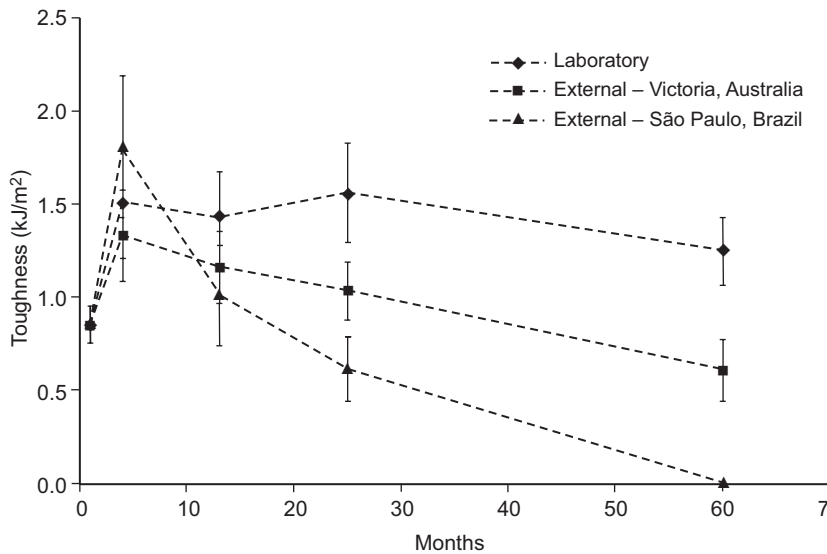


3.7 Sisal CTM pulp in GGBS. Variation in composite modulus of rupture (MOR) with age and conditions of exposure.



3.8 Sisal CTM pulp in GGBS. Variation in composite toughness with age and conditions of exposure.

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subjected to either natural weathering or ageing under a controlled environment is attributable to matrix carbonation. Such a mechanism (Wang *et al*., 1995; Taylor, 1997) consumes calcium ions from hydration products and hence causes weakening of the composites.

Qualitative evaluation using an indicator solution of 2% phenolphthalein in anhydrous ethanol revealed that the aged composites were completely carbonated. The greater severity of the effect of the natural environment on composite properties can be attributed to interfacial damage resulting from volume changes of the porous and hygroscopic vegetable fibres inside the cement matrix (Savastano and Agopyan, 1999).

As shown in Fig. 3.8, the composites aged for 60 months in laboratory conditions demonstrated toughness values similar to or even higher than composites tested at 28 days. In general, the improvement in toughness can be linked to the reduction in MOR and MOE, according to the expected compromise between strength and ductility in such composites. Values of toughness after 60 months of weathering in external environments indicate that the integrity of the fibres within the GGBS matrix has been significantly reduced by decomposition. In a previous study of sisal, malva and coir strands in ordinary Portland cement (OPC) matrix, Savastano and Agopyan (1999) reported reductions of at least 50% in toughness after only 6 months in a laboratory environment. Tolêdo Filho *et al*. (2000) and Bentur and Akers (1989) noted similar embrittlement in aged vegetable fibre–OPC composites and found that it could be directly attributed to the petrifaction of the reinforcement through the migration of hydration products to the fibre lumens and pores.

3.5.6 Production of roofing tiles using vegetable fibre cement

Savastano *et al*. (1999) and Roma *et al*. (2008) developed roofing tiles, reinforced with sisal pulps, based on the Parry Associates process (United Kingdom) for moulding by densification and vibration, with intensive use of labour. Undulate roof tiles were produced with dimensions of approximately 500 × 275 mm, thickness between 8 and 10 mm, and format similar to ceramic roofing tiles (Fig. 3.9).

Roma *et al*. (2008) reported that the exposure to a tropical climate caused a severe reduction in the mechanical properties of the composites. This behaviour can be attributed to alkaline attack and petrifaction of the natural fibre and progressive micro-cracking of the cement matrix. The toughness of the vegetable fibre-cement fell to between 53 and 68% of that of non-aged composites after approximately 4 months under natural tropical weathering. The high porosity associated with water absorption of at least 30% by mass is expected to play a significant role in this undesirable behaviour. The refinement of pore structure or the combined use of vegetable and synthetic fibres for reinforcement may be effective approaches to material optimization.

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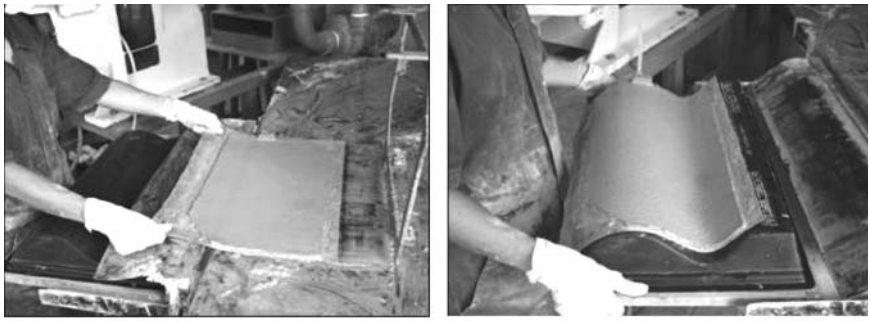

(a) (b)

3.9 (a) Transference of a newly manufactured flat pad for the mould with corrugated format. (b) Corrugated roofing tile on mould. (Courtesy of Luiz Carlos Roma Jr.)

The small roofing tiles reinforced with sisal pulp can be made by an alternative process of sucking and pressing, as patented by Savastano (2002) (Fig. 3.10(a)). In this process the mixture with the cement raw materials can be prepared with approximately 40% solids. The slurry is transferred to the storage container located in the upper part of the equipment shown in Fig. 3.10(a). This container is moved by an automated system for the transference of the mixture to a casting chamber with approximate dimensions of 500 mm long, 275 mm wide and 8 mm thick. The dewatering system in the lower part of the chamber is applied for 30 s to drain the excess water while the undulate tile is formed and pressed by pneumatic pistons (Fig. 3.10(a), arrows 1 and 2). Afterwards, negative pressure is applied to the upper device for an additional 30 s (Fig. 3.10(b), arrow 3). This device, after horizontal displacement, puts the roofing tile in a mould (Fig. 3.10(c), arrow 5) and the formed roofing tile can be transferred from the moulding chamber to the undulate mould conferring its final shape (Figs 3.10(c) and 3.10(d)).

The results show that maximum load for roofing tiles reinforced with sisal pulp, and prepared by the process of sucking and pressing, is approximately 50% higher than the maximum load associated with tiles produced by the Parry Associates process. This result suggests that the roofing tiles formed by the process of sucking and pressing present better densification and consequently lower porosity.

3.6 Conclusions

In 2006, the UN General Assembly declared 2009 the International Year of Natural Fibres. This decision will contribute to the Millennium Development Goals by further developing the efficiency and sustainability of these agricultural industries that employ millions of people in some of the world's poorest countries, according to the FAO.

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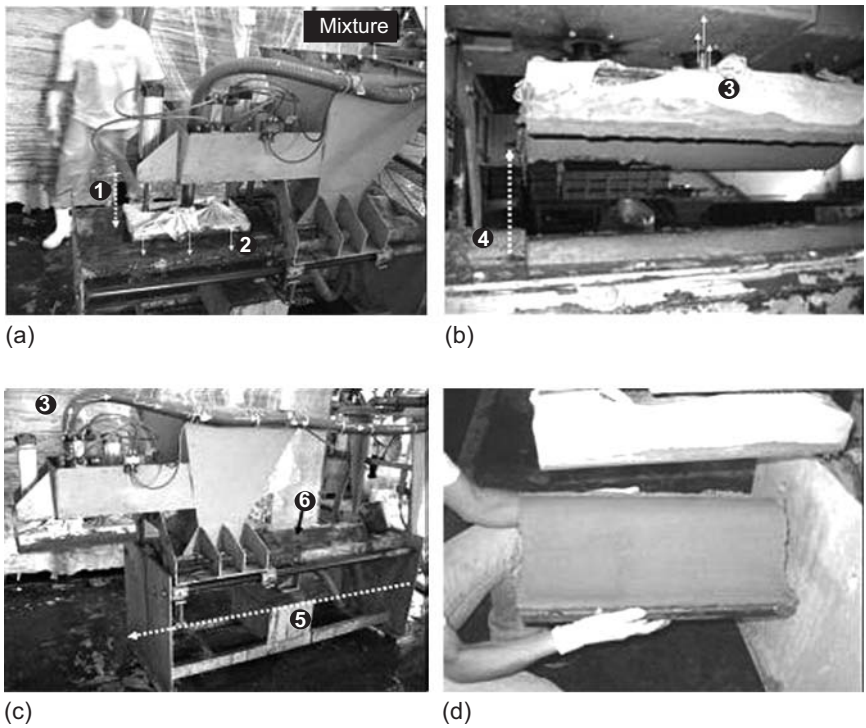

3.10 (a) Process of sucking and pressing (arrow 1) and dewatering to withdraw the excess water through the moulding chamber (arrow 2); (b) inverted suction using the upper device (arrow 3) and withdrawal of the roofing tile from the moulding chamber (arrow 4); (c) horizontal displacement of the equipment (arrow 5) and refilling the chamber with a mixture (arrow 6); (d) formed roofing tile on the undulate mould (Tonoli, 2006).

The use of vegetable fibres is increasing throughout the world but mostly in developing countries situated in tropical and subtropical climates. The fibres are used primarily for the production of bags, ropes, baskets and mats, in newer bio-based composites and as a source for paper making. Vegetable fibres offer several advantages – their renewable origin, worldwide availability, low costs, low production energy requirements, reduced equipment wear, biodegradability – over man-made fibres such as glass, carbon and aramid.

The use of vegetable fibres as a source of raw material in polymer and cement-based materials not only provides a renewable resource, but also generates a non-food source of economic development for farming and rural areas and brings new trends in composite materials. However, knowledge, durability, and suitable cost-effective design and fabrication techniques for manufacture should be developed.

The consumption of building components made of hybrid fibre cement

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reinforced with vegetable and synthetic fibres is increasing rapidly, especially in developing countries. Vegetable fibres, which are widely available, can be used as convenient materials for the reinforcement of a brittle matrix. In addition, different types of building components can be produced as low-cost, lightweight products for non-load-bearing, hollowed walls panels, ceiling plates and roofing tiles (Agopyan *et al*., 2005).

The scientific research has demonstrated that vegetable fibres can be a useful material in the transformation of recycling waste. In particular, the use of alternative materials for the complete (e.g. GGBS) or partial replacement of conventional OPC-based composites can be a helpful approach for appropriate solutions in rural construction. The result can be the production of cost-efficient building elements, with low consumption of energy, that are suitable for developing areas. Potential solutions to housing and rural infrastructure demand can be achieved through the adaptation of already known technologies to overcome the problem of durability, which is the main drawback of these composites.

3.7 References

Agopyan V (1988), 'Vegetable fibre reinforced building materials – developments in Brazil and other Latin American countries', in Swamy R N (Ed.), *Natural Fibre Reinforced Cement and Concrete (Concrete Technology and Design 5),* Glasgow, Blackie, pp. 208–242.

Agopyan V, Savastano Jr H, John V M and Cincotto M A (2005), 'Developments in vegetable fibre–cement based materials in São Paulo, Brazil: an overview', *Cement and Concrete Composites*, **27**(5), 527–536.

Andrade W (2006), *Brazilian Sisal*, Salvador, Apex-Brasil.

Appita (The Australian Pulp and Paper Industry Technical Association) (1986), P201 m-86, *Kappa number of pulp*, endorsed as part of AS 1301 by the Standards Association of Australia , February 1986.

Arbelaiz B, Fernández G, Cantero R, Llano-Ponte V A and Mondragon I (2005), 'Mechanical properties of flax fibre/polypropylene composites. Influence of fibre/matrix modification and glass fibre hybridization', *Composites Part A: Applied Science and Manufacturing*, **36**(12), 1637–1644.

Australian Standards (1988), AS-1301.206s-1988, *Methods of test for pulp and paper (metric units) – freeness of pulp*, North Sydney, Australian Standards.

Asasutjarit C, Hirunlabh J, Khedari J, Charoenvai S, Zeghmati B and Cheul Shin U (2007), 'Development of coconut coir-based lightweight cement board', *Construction and Building Materials*, **21**(2), 277–288.

ASTM (American Society for Testing and Materials) (2000), ASTM C948-81 (2000), *Standard test method for dry and wet bulk density, water absorption, and apparent porosity of thin sections of glass-fiber reinforced concrete*, West Conshohocken, USA, ASTM.

Bentur A S and Akers A S (1989), 'The microstructure and ageing of cellulose fibre reinforced cement composites cured in a normal environment', *International Journal of Cement Composites and Lightweight Concrete*, **11**(2), 99–109.

Bilba K, Arsene M-A and Ouensanga A (2003), 'Sugar cane bagasse fibre reinforced cement

www.EngineeringEBooksPdf.com

composites. Part I. Influence of the botanical components of bagasse on the setting of bagasse/cement composite', *Cement and Concrete Composites*, **25**(1), 91–96.

Bourmaud A and Baley C (2007), 'Investigations on the recycling of hemp and sisal fibre reinforced polypropylene composites', *Polymer Degradation and Stability*, **92**(6), 1034–1045.

Brouwer W D (2001), '*Natural Fibre Composites in Structural Components: Alternative Applications for Sisal*', seminar held by the Food and Agriculture Organization of the UN (FAO) and the Common Fund for Commodities (CFC), Rome, FAO.

Chand N and Jain D (2005), 'Effect of sisal fibre orientation on electrical properties of sisal fibre reinforced epoxy composites', *Composites Part A: Applied Science and Manufacturing*, **36**(5), 594–602.

Coutts R S P (1988), 'Wood fibre reinforced cement composites', in Swamy R N (Ed.), *Natural Fibre Reinforced Cement and Concrete (Concrete Technology and Design 5)*, Glasgow, Blackie, pp. 1–62.

Coutts R S P (1990) 'Banana fibres as reinforcement for building products', *Journal of Materials Science Letters*, **9**(10), 1235–1236.

Coutts R S P (2005), 'A review of Australian research into natural fibre cement composites', *Cement and Concrete Composites*, **27**(5), 518–526.

Dhamodaran T K, Gnanaharan R and Sankara Pillai K (2003), *Bamboo for Pulp and Paper – A State of the Art Review*, Beijing, INBAR.

Doan T T L, Brodowsky H and Mäder E (2007), 'Jute fibre/polypropylene composites II. Thermal, hydrothermal and dynamic mechanical behaviour', *Composites Science and Technology*, **67**(13), 2707–2714.

FAO (Food and Agriculture Organization of the United Nations) (2002), *Coir processing technologies, improvement of drying, softening, bleaching and dyeing coir fibre/yarn and printing coir floor coverings*, Rome, FAO.

FAO (Food and Agriculture Organization of the United Nations) (2003a), *Medium-term prospects for agricultural commodities, projections to the year 2010*, Rome, FAO.

FAO (Food and Agriculture Organization of the United Nations) (2003b), *Raw materials, tropical and horticultural products service*, Rome, FAO.

FAO (Food and Agriculture Organization of the United Nations) (2003c), *The world banana economy*, Rome, FAO.

FAO (Food and Agriculture Organization of the United Nations) (2005), *World bamboo resources – a thematic study prepared in the framework of the global forest resources assessment*, Rome, FAO.

FAO (Food and Agriculture Organization of the United Nations) (2006), *Jute, kenaf, sisal, abaca, coir and allied fibres statistics*, Rome, FAO.

FAO (Food and Agriculture Organization of the United Nations) (2007), *Trade policy briefs on issues related to the WTO negotiations on agriculture,* n 6*, sugar: policy insights from analysis of sugar sector reform,* Rome, FAO.

Fordos Z (1988), 'Natural or modified cellulose fibres as reinforcement in cement composites', in Swamy R N (Ed.), *Natural Fibre Reinforced Cement and Concrete (Concrete Technology and Design 5)*, Glasgow, Blackie, pp. 173–207.

Fung K L, Xing X S, Li R K Y, Tjong S C and Mai Y–W (2003), 'An investigation on the processing of sisal fibre reinforced polypropylene composites', *Composites Science and Technology*, **63**(9), 1255–1258.

Ghavami K (2005), ´Bamboo as reinforcement in structural concrete elements´, *Cement and Concrete Composites*, **27**(6), 637–649.

Guimarães S S (1984), 'Experimental mixing and moulding with vegetable fibre reinforced

www.EngineeringEBooksPdf.com

cement composites', in *Proceedings of the International Conference on Development of Low-Cost and Energy Saving Construction Materials and Applications*, Rio de Janeiro, Envo, vol. 1, pp. 37–51.

Heinricks H, Berkenkamp R, Lempfer K and Ferchland H-J (2000), 'Global review of technologies and markets for building materials', in *Proceedings of the 7th International Inorganic-Bonded Wood and Fiber Composite Materials Conference,* Moscow, Moslemi A A (Ed.), University of Idaho (SHS report).

Herrera-Franco P J and Valadez-González A (2005), 'A study of the mechanical properties of short natural-fiber reinforced composites', *Composites Part B: Engineering*, **36**(8), 597–608.

Hidalgo-Lopez O (2003), *Bamboo: The Gift of the Gods*, Bogota, Oscar Hidalgo-Lopez.

Higgins H G (1996), *Paper Physics in Australia*, Melbourne, CSIRO Division of Forestry and Forest Products.

INBAR (The International Network for Bamboo and Rattan) (2004), *International Workshop on Bamboo Industrial Utilization in Xianning*, Hubei, Xuhe C, Yiping L and Ying H (Eds).

John V M, Cincotto M A, Sjöström C, Agopyan V and Oliveira C T A (2005), 'Durability of slag mortar reinforced with coconut fibre', *Cement and Concrete Composites*, **27**(5), 565–574.

Kozlowski R (2000), 'Potential and diversified uses of green fibres', in *Proceedings of the 3rd International Wood and Natural Fibre Composites Symposium*, Kassel, Germany, pp. 2–14.

Li Y, Mai Y-W and Ye L (2000), 'Sisal fibre and its composites: a review of recent developments', *Composites Science and Technology*, **60**(11), 2037–2055.

Lo T Y, Cui H Z, Tang P W C and Leung H C (2008), 'Strength analysis of bamboo by microscopic investigation of bamboo fibre', *Construction and Building Materials*, **22**(7), 1532–1535.

Mohr B J, El-Ashkar N H and Kurtis K E (2004), 'Fiber-cement composites for housing construction: State-of-the-art review', in *NSF Housing Research Agenda Workshop*, Orlando, Florida, Syal M, Mullins M and Hastak M V (Eds).

Oliveira T A, John V M and Agopyan V (1999), 'Pore water composition of activated granulated blast furnace slag cements pastes', in *Proceedings of the 2nd International Conference on Alkaline Cements and Concretes*, Kiev State Technical University of Construction and Architecture, Kiev.

Plessis C D (2001), 'Doing more, better, with less – A developing country perspective on sustainability through performance (plenary session)', in *CIB World Building Congress: Performance in Product and Practice*, Wellington, New Zealand, Duncan J (Ed.).

Ramakrishna G and Sundararajan T (2005), 'Impact strength of a few natural fibre reinforced cement mortar slabs: a comparative study', *Cement and Concrete Composites*, **27**(5), 547–553.

Rehsi S S (1988), 'Use of natural fibre concrete in India', in Swamy R N (Ed.), *Natural Fibre Reinforced Cement and Concrete (Concrete Technology and Design 5)*, Glasgow, Blackie, pp. 243–255.

Roma Jr L C, Martello L S and Savastano Jr H (2008), 'Evaluation of mechanical, physical and thermal performance of cement-based tiles reinforced with vegetable fibers', *Construction and Building Materials*, **22**(4), 668–674.

Santaella J (2007), 'The sugarcane agribusiness – An energy focused vision', Bulletin published by Technische Universität Berlin – *TU International*, **60**(8), 3.

Savastano Jr H (2002), Process to obtain roofing tiles of fibre cement composites reinforced

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with cellulosic pulp by process of sucking and pressing, Privilégio e Inovação no. 0201204–9, 'Invenção de processo e produto obtido' (Patent deposited in Brazil).
Savastano Jr H and Agopyan V (1999), 'Transition zone studies of vegetable fibre-cement paste composites', *Cement and Concrete Composites*, **21**(1), 49–57.
Savastano Jr H, Agopyan V, Nolasco A M and Pimentel L (1999), 'Plant fibre reinforced cement components for roofing', *Construction and Building Materials*, **13**(8), 433–438.
Savastano Jr H and Pimentel L L (2000), 'Viabilidade do aproveitamento de resíduos de fibras vegetais para fins de obtenção de material de construção', *Brazilian Journal of Agricultural and Environmental Engineering*, **4**(1), 103–110 (Technical communication, in Portuguese).
Savastano Jr H and Warden P G (2005), 'Special theme issue: Natural fibre reinforced cement composites', *Cement and Concrete Composites*, **27**(5), 517.
Savastano Jr H, Warden P G and Coutts R S P (2000), 'Brazilian waste fibre as reinforcement for cement based composites', *Cement and Concrete Composites*, **22**(5), 379–384.
Savastano Jr H, Warden P G and Coutts R S P (2001), 'Performance of low-cost vegetable fibre-cement composites under weathering', in *CIB World Building Congress: Performance in Product and Practice*, Wellington, New Zealand, Duncan J (Ed.), pp. 1–11.
Savastano Jr H, Warden P G and Coutts R S P (2005), 'Microstructure and mechanical properties of waste fibre–cement composites', *Cement and Concrete Composites*, **27**(5), 583–592.
Soffner M L A P (2001), *Pulp production from banana stem,* Piracicaba, Escola Superior de Agricultura 'Luiz de Queiroz' (MSc Dissertation, in Portuguese).
Sreenath H K, Shah A B, Yang V W, Gharia M M and Jeffries T W (1996), 'Enzymatic polishing of jute/cotton blended fabrics', *Journal of Fermentation and Bioengineering*, **81**(1), 18–20.
Stig Andtbacka K (2005), 'A fibre line designed for bamboo pulping', *TAPPSA Journal*, November.
Taylor H F W (1997), *Cement Chemistry*, 2nd edition, London, Thomas Telford.
Tolêdo Filho R D, Scrivener K L, England G and Ghavami K (2000), 'Durability of alkali-sensitive sisal and coconut fibres in cement mortar composites', *Cement and Concrete Composites*, **22**(2), 127–143.
Tomczak F, Sydenstricker T H D and Satyanarayana K G (2007), 'Studies on lignocellulosic fibers of Brazil. Part II: Morphology and properties of Brazilian coconut fibers', *Composites Part A: Applied Science and Manufacturing*, **38**(7), 1710–1721.
Tonoli G H D (2006), *Productive aspects and performance of fibre cement without asbestos in the development of technology for undulate roofing tiles*, Universidade de São Paulo, Pirassununga, Faculdade de Zootecnia e Engenharia de Alimentos (Thesis, in Portuguese).
Wang S-D, Pu X-C, Scrivener K L and Pratt P L (1995), 'Alkali-activated slag cement and concrete: A review of properties and problems', *Advances in Cement Research*, **7**(27), 93–102.
Wood I M (1997), *Fibre Crops: New Opportunities for Australian Agriculture*, Queensland, National Library of Australia.
Yamashita O, Yokochi H, Imanishi H and Kanayama K (2007), 'Transfer molding of bamboo', *Journal of Materials Processing Technology*, **192–193**(10), 259–264.
Yuanjian T and Isaac D H (2007), 'Impact and fatigue behaviour of hemp fibre composites', *Composites Science and Technology*, **67**(15/16), 3300–3307.
Zini E, Focarete M L, Noda I and Scandola M (2007), 'Bio-composite of bacterial poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) reinforced with vegetable fibers', *Composites Science and Technology*, **67**(10), 2085–2094.

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4

Sustainability of masonry in construction

P. BINGEL and A. BOWN
Leeds Metropolitan University, UK

Abstract: The chapter provides an overview of masonry as a sustainable construction material. It deals primarily with clay brickwork and concrete blockwork and describes their manufacture and principal properties with regards to sustainability. The broader issues associated with sustainability are briefly discussed and the current methods for quantifying the whole life environmental performance of masonry walling used in residential and commercial buildings within the UK are examined. Examples of masonry buildings that are 'more sustainable' in terms of their operational energy and/or material usage are given, together with a brief outline of possible future developments in the masonry area.

Key words: masonry, sustainability, environmental impacts, whole life performance.

4.1 Introduction

This chapter provides an overview of masonry as a sustainable construction material. It deals primarily with clay brickwork and concrete blockwork, these being the main types of masonry used in the UK. The chapter describes their manufacture and principal properties with regard to sustainability. The historical use of masonry is briefly reviewed and recent changes in the use and forms of masonry construction are highlighted.

The broader issues associated with sustainability are discussed and current methods for quantifying the whole life environmental performance of masonry walling used in residential and commercial buildings within the UK are examined. Examples of masonry buildings that are 'more sustainable' in terms of their operational energy and/or material usage are given, together with a brief outline of possible future developments in the masonry area.

4.2 Additional sources of information

In view of the limitations on size, much detail has necessarily had to be left out of this chapter. For additional background information on the engineering properties of brick and block masonry the reader should consult books such as *Civil Engineering Materials,* 5th Edition (Jackson and Dhir, 1997) and *Construction*

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Materials: Their Nature and Behaviour (Illston and Domone, 2001). Information is also available from the websites of the UK manufacturers of masonry products and the various trade associations within the UK masonry industry. The latter include:

- Aircrete Products Association;
- Brick Development Association;
- British Lime Association;
- British Precast Concrete Federation;
- Concrete Block Association;
- Hemplime Construction Products Association;
- Mortar Industry Association;
- Quarry Products Association;
- Stone Federation Great Britain;
- Traditional Housing Bureau.

The British Masonry Society also publishes papers on all aspects of masonry construction and performance.

The history of brick masonry and brick manufacturing in the UK, and the different mortars used in brick and stone masonry, is comprehensively described by Lynch (1994). Other useful sources of information include the *Chilterns Buildings Design Guide – Chilterns Brick, Supplementary Technical Note* (Chilterns Conservation Board, 2005) as well as the Internet generally. Pevsner Architectural Guides and The Buildings Books Trust also give numerous examples of historically significant brick and stone masonry buildings throughout Great Britain.

Further details of the environmental performance of UK construction materials and forms of construction, including masonry, are available from the Building Research Establishment (BRE) website (http://www.bre.co.uk) and their associated publications and software packages. Useful introductions to life cycle assessment (LCA) – the generic process that underpins environmental sustainability, are available from the SimaPro 7 webpage of PRé Consultants (SimaPro7, 2007) and the ISO 14040 series of voluntary standards dealing with LCA (International Organization for Standardization, 2006).

4.3 Definitions

Masonry is the generic term used to describe an assemblage of pre-formed 'units' laid in a bed of mortar. In the UK a range of units are available including clay bricks (both fired and unfired), concrete bricks, dense and lightweight aggregate concrete blocks, aerated concrete blocks, and natural and reconstituted stone. Although previously available, calcium silicate (sand-lime) bricks are no longer marketed in the UK and are not considered here.

Mortar is essentially a mixture of fine sand, water and a binding agent. Hydrated

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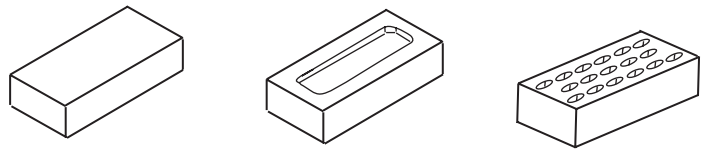

(a) Solid unit (b) Frogged unit (c) Vertically perforated unit

4.1 Common types of UK brick.

lime or a plasticising agent (either in powdered or liquid form) is often added to improve the physical properties of the mortar in its fresh or hardened states. A colouring agent may also be included to improve the overall appearance of the masonry. Essentially, mortar bonds the individual units together and provides a degree of weatherproofing to the structure being built. In modern forms of masonry construction the binding agent in mortar is normally based on Portland cement (CEM I) whereas in older masonry structures some form of lime would have been used, possibly with added ash as a colorant.

In the UK bricks have traditionally been defined in terms of unit size. Since 1969 this has been standardised at 215 mm long × 102.5 mm wide (thick) × 65 mm high, although the new European standards for masonry no longer limit the size or shape of bricks or blocks; instead, bricks or blocks are now both referred to as masonry units. The UK tradition of differentiating blocks and bricks by face size is, however, likely to continue (British Standards Institution, 2003b). Typical types of bricks used in the UK are shown in Fig. 4.1(a), (b) and (c).

Blocks may be solid, cellular or hollow (Fig. 4.2). They are produced in a number of face sizes from 390 mm long × 190 mm high up to 610 mm long × 270 mm high, in the case of aerated blocks. The thickness of blocks ranges from 75 to 300 mm. Reconstituted and natural stone products are produced in various sizes depending on the finish required, e.g. random or coursed. The thickness of the mortar joint for masonry construction has now been standardised at 10 mm apart from thin-joint blockwork, where it is 3 mm.

4.4 Facts and figures

Approximately 2.5 billion fired-clay bricks are produced annually in the UK. This accounts for 95% of all those sold, with the remaining 5% being concrete bricks. The current market value of clay bricks is about £550 million per annum with some 1200 varieties of clay brick available (Brick Development Association, 2007). Facing bricks, which account for over 90% of UK sales, are used primarily in the domestic housing market. Engineering bricks, with their higher strengths and lower porosity, are used for load-bearing masonry structures and in more aggressive environments generally.

The UK brick industry consumes 8 million tonnes of clay each year and is

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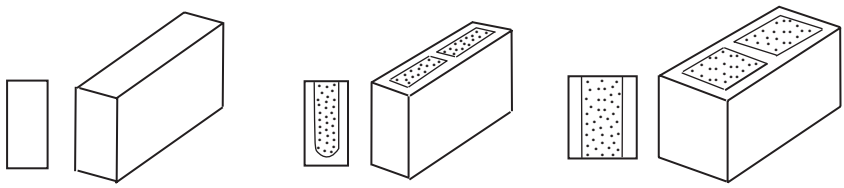

4.2 Common types of UK block.

energy intensive, its total annual energy consumption being around 6.3 terawatt hours of primary energy. This is, however, less than 1.5% of the total energy consumed by the UK manufacturing industry (Brick Development Association, 2007).

Concrete block sales are reported in terms of square metres of blockwork; in the UK this is currently around 90 million m^2 per annum (Department of Trade and Industry, 2006). Aggregate concrete blocks account for around two-thirds of sales, the remainder being aerated blocks. No precise figures appear to exist regarding the primary energy consumed in block manufacturing or stone production. In relation to the latter it should be noted, however, that approximately 30% of the natural stone used in the UK is now imported from countries as far away as India and Brazil (personal communication with the Stone Federation of Great Britain, 2007).

4.5 Manufacture of masonry units and mortar

4.5.1 Fired-clay bricks

Three basic techniques are used for the initial shaping of fired-clay bricks (Hammett, 2004).

1 *The soft-mud process.* The clay is thrown into moulds either by hand or by machine. The bricks are then removed from the moulds, dried and fired. Bricks made by this process contain 25–30% water and are known as 'stock bricks'.
2 *The extruded, wire-cut process.* The clay is mixed with approximately 18% water to a stiff plastic consistency and forced through a die with dimensions slightly greater than the length and width of the brick. Taut wires then cut this continuous 'sausage' of clay into individual bricks. This is the principal method of brick forming and accounts for approximately 65% of UK production.
3 *Semi-dry pressing.* This method uses hydraulic presses to push semi-dry clay into steel moulds and is reserved for Fletton bricks produced in the Bedfordshire area.

After shaping, the 'green' bricks are allowed to dry for up to 5 days and then

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fired at temperatures of between 900 and 1050 °C, depending on the type of clay. The chemical and physical changes occurring during the firing process are complex and involve the breakdown of the original clay minerals and the formation of new crystalline materials and glass phases (British Geological Survey, 2007). These give the brick its mechanical strength and durability. The firing process and subsequent cooling of the bricks takes between 40 and 150 hours, depending upon the type of clay and the kiln used. Four types of kiln are available: intermittent, clamp, continuous multi-chamber and continuous tunnel. In practice, the tunnel kiln is used in most large-scale works as it is more efficient, with a complete firing cycle typically taking between 2 and 3 days.

For many years recycled waste materials from other industries have been utilised in the manufacture of clay bricks. These include pulverised fuel ash (PFA), blast furnace slag, coke breeze and coal slurry, ground glass (cullet), sewage sludge, paper ash, bone ash and sawdust. Some of these are used to improve or modify specific properties of the brick, for example its frost resistance or colour, while others that are combustible may simply act as a source of fuel, reducing the amount of external energy required during the firing stage. Waste materials such as ground glass also act as fluxing agents, reducing firing temperatures and times, as well as emissions to air. Recent research has shown that when ground glass is used in brick manufacturing, energy savings of up to 20% are possible (WRAP, 2006).

In practice, the greater use of recycled waste materials in brick manufacturing is currently somewhat limited by handling, supply and quality issues, as often only small quantities of these materials, which potentially may be hazardous, are available. Nevertheless, the ability of the clay brick industry to utilise waste products that would otherwise go to landfill is extremely beneficial from a sustainability viewpoint.

4.5.2 Unfired-clay bricks

Although available in Europe for a number of years, unfired bricks have only recently been introduced to the UK and are still at the developmental stage. Essentially, they consist of raw clay mixed with sand and sawdust which, after shaping, is artificially air-dried for approximately 2 days and then used in construction. As they are not kiln-fired their embodied energy (the quantity of energy required to manufacture a material or product) is very low. For example, the unfired brickwork in a test house had embodied energy of 146 kwh/tonne and embodied carbon of 44.6 kg CO_2/tonne. This is about 14% of the value for comparable fired-clay brickwork and 24% of that for lightweight blockwork (Morton, 2006). Unfired bricks are normally used for internal non-load-bearing walls and are laid in weak clay, rather than cement-based, mortars (Errol Brick, 2007).

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4.5.3 Concrete blocks

Two basic types of blocks are available in the UK: aggregate and autoclaved aerated concrete blocks (Aircrete).

Aggregate blocks

Two types of aggregate block are produced: dense and lightweight. Both consist of a binder, which is normally a form of Portland cement (CEM I), together with water and graded aggregates of 10–14 mm maximum size. In addition, PFA may sometimes be used as a partial cement replacement. For lightweight blocks, furnace bottom ash and some type of lightweight aggregate such as Leca or Lytag are used, whereas natural aggregates are used for dense blocks. The manufacture of both dense and lightweight blocks involves the compaction of a very dry concrete mix into individual moulds, after which the 'green' blocks are immediately pushed out on to a pallet and taken away for curing.

Autoclaved aerated concrete blocks (Aircrete)

The materials used in the manufacture of Aircrete blocks are PFA, sand, cement, lime and water. The PFA, sand and water are initially mixed to form a slurry which is heated and mixed with cement and lime. A small quantity of aluminium powder is then evenly dispersed through the mixture before it is poured into moulds.

The aluminium initiates a chemical reaction, generating minute bubbles which form the characteristic Aircrete structure. When the mixture has partially set the resultant 'cakes' are wire-cut into blocks of predetermined size, and transferred to autoclaves for high-pressure steam curing. During this process the ingredients combine to form the calcium silicate hydrates that provide the mechanical strength of the finished blocks.

Aircrete production is environmentally friendly when compared with many other construction materials as a large proportion of the block is PFA, a product that would otherwise be used in landfill. The process is also highly efficient with most waste material and energy being recycled back into the production process itself (H+H Celcon, 2007).

4.5.4 Mortar

The sand usually used in masonry mortars is 'fine sand', the grain size being smaller than that of the 'coarse sand' used for the manufacture of concrete. In addition, in masonry mortars the shape of the sand grains is essentially rounded or 'soft'. This is in contrast to the sand used in concrete, where the individual grains are more angular, or 'sharp'. A range of mortar mixes are available for use in masonry construction (Table 4.1). Traditionally these have been specified in

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Table 4.1 Mortar compressive strength classes, composition and designation (adapted from UK National Annex to BS EN 1996-1-1:2005 (British Standards Institution, 2005a))

Compressive strength class*	Prescribed mortars (proportion of materials by volume)		Traditional mortar designation
	Cement:lime:sand with or without air entrainment	Cement:sand with or without air entrainment	
M12	1:0 to ¼:3	1:3	(i)
M6	1:½:4 to 4½	1:3 to 4	(ii)
M4	1:1:5 to 6	1:5 to 6	(iii)
M2	1:2:8 to 9	1:7 to 8	(iv)

*The number following the M is the compressive strength for the class at 28 days (in N/mm^2).

volume terms, with sufficient water being added to the mix to achieve the desired workability. Weak mortars are more able to accommodate brick or block movement whereas high-strength mortars will provide a better bond, higher lateral walls strengths and increased frost resistance. Mortar mix selection depends upon the types of units being laid and the degree of exposure, with higher strength mixes required in more exposed situations generally (see Table 4.4 later).

Although once common practice, less than 25% of the mortar used in the British market each year is now mixed on site using traditional cement mixers (Beningfield, 2002). Instead, most mortars are weigh-batched in factories under controlled conditions and then delivered to site. Two main types of factory-produced mixes are available; lime–sand mixes to which cement and water is added on site to produce a masonry mortar, and ready-to-use mortar.

Ready-to-use mortars have guaranteed mix proportions and overcome any potential problems relating to site mixing. Two types of ready-to-use mortar are available: wet and dry. Wet ready-to-use mortars incorporate a retarding agent and are stored in tubs on site. They require no further mixing and are fully useable for a specific period – typically 36 hours. Dry ready-to-use mortars are stored in silos or bags. The silos are delivered to site complete with integral mixers and require only power and water supplies to be connected in order to mix the mortar (Mortar Industry Association, 2005).

The mixes shown in Table 4.1 contain Portland cement and should not be confused with traditional lime mortars. These are occasionally specified for new masonry construction and use hydraulic lime, rather than cement, as the binding agent. Traditional lime mortars are considered to be more environmentally friendly than cement-based mortars, although they may be slower to set and gain strength. The stability of modern forms of thin masonry walling built with traditional lime mortars may therefore be an issue during the construction phase and care should be taken with their use. Further information on traditional lime mortars is available from both the UK Brick Development Association Ltd

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Table 4.2 New standards for masonry

	New standard
Masonry units	
Clay masonry units	BS EN 771-1:2003
Calcium silicate masonry units	BS EN 771-2:2003
Aggregates concrete masonry units (dense and lightweight aggregates)	BS EN 771-3:2003
Autoclaved aerated concrete masonry units	BS EN 771-4:2003
Manufactured stone masonry units	BS EN 771-5:2003
Natural stone masonry units	BS EN 771-6:2005
Mortar	
Rendering and plastering mortar	BS EN 998-1:2003
Masonry mortar	BS EN 998-2:2003
Design of masonry structures	
Design of masonry structures. General rules for reinforced and unreinforced masonry structures	BS EN 1996-1-1:2005
Design of masonry structures. General rules. Structural fire design	BS EN 1996-1-2:2005

(Brick Development Association, 2001a) and Limetechnology (Limetechnology, 2007).

Mortars for use in thin-joint blockwork are normally cement–sand mixes that contain additional polymer reinforcement as well as specialist shrinkage or plasticising agents to produce a workable mortar at low water:cement ratios (Building Research Establishment, 1998).

4.6 Standards for masonry

As part of the move towards a single European market, new European Standards for construction materials and products, including masonry, are being introduced. Where already adopted, these have the status of a British Standard and are referred to as a BS EN. In addition, a new series of European structural design codes (Eurocodes) is gradually being introduced for all materials. Table 4.2 shows some of the new standards for masonry. It should be noted that the manner in which masonry products are specified and tested in these new standards may be different from previous British Standards. A useful summary of the main differences for clay bricks and concrete blocks is provided by Ibstock (2003) and the Concrete Block Association (2006), respectively.

4.7 Properties of masonry

This section briefly describes some of the principal properties of masonry and masonry units. For further details the reader should consult the relevant standard(s) listed in Table 4.2.

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4.7.1 Compressive strength

The strength of masonry units can vary considerably. Typical values are shown below (Institution of Structural Engineers, 1996):

- clay bricks, 15–150 N/mm^2;
- lightweight aggregate blocks, 2.9–25 N/mm^2;
- dense aggregate blocks, 2.9–40 N/mm^2;
- aerated blocks, 2.9–7.3 N/mm^2;
- natural stone, 16–250 N/mm^2;

In practice, the strength of a brick, block or stone masonry wall is considerably lower than the compressive strength of the individual masonry units from which it is made. This is due to the presence of the weaker mortar joints in which the units are laid. In addition, the load-bearing capacity of masonry walls decreases with increasing slenderness, i.e. the ratio of (effective) wall height to (effective) wall thickness (Curtin *et al.*, 2006).

4.7.2 Density

Two types of fired-clay masonry units are specified in BS EN 771-1 (British Standards Institution, 2003a), namely, low density (LD) for use in protected masonry (gross dry density ≤ 1000 kg/m^3) and high density (HD). The majority of UK bricks are classified as high density. Owing to the presence of perforations and frogs, the weight of UK bricks may vary from around 1.7 to 3.6 kg. The net dry density of aggregate concrete blocks (i.e. allowing for the volume of voids) ranges from 650–2400 kg/m^3 with aerated blocks normally within the range 300–1000 kg/m^3.

4.7.3 Configuration

Masonry units in BS EN 1996-1-1 (British Standards Institution, 2005a) are grouped in one of four specific categories depending upon factors such as volume of voids present and direction of the voids, i.e. horizontal or vertical, etc. In the case of aggregate concrete blocks, for example, the groups are:

- Group 1 <25% formed voids;
- Group 2 >25% and <60% formed vertical voids;
- Group 3 >25% and <70% formed vertical voids;
- Group 4 >25% and <50% formed horizontal voids.

Most aggregate concrete block units manufactured in the UK fall within Groups 1 and 2.

4.7.4 Movements in masonry

Movement in masonry is considered here under the following headings: elastic movement, moisture movement, thermal movement and creep.

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Elastic movement

The movement of brick and block masonry under short-term load is a function of the movement of the individual bricks, blocks and mortar that together form the masonry. As such, it can vary considerably depending upon the type of unit and mortar used. For example, the elastic modulus of clay bricks ranges from 3.5 to 35 kN/mm^2 while that of mortar can vary between 0.6 and 25 kN/mm^2 (Jackson and Dhir, 1997). The elastic modulus of brick or block masonry is consequently also very variable, typically being in the range 1–30 kN/mm^2.

Moisture movement

Clay bricks expand or contract with increases or decreases in moisture content. In addition, they undergo long-term irreversible expansion due to adsorption of water vapour from the atmosphere. The rate of irreversible expansion is initially high but decreases with age. Concrete blocks, stone and mortar expand or contract with changes in moisture content but, unlike clay bricks, they undergo long-term drying shrinkage.

Moisture movement of brick, block or stone masonry is therefore the composite effect of short-term changes in moisture content and irreversible expansion/drying shrinkage of the masonry units and mortar in the joints. The net effect is generally considered to be a gradual expansion in most types of clay brickwork (although an initial shrinkage may occur) whereas concrete blockwork and stone masonry contract with time.

The age of the units at the time of laying influences the amount of movement in the masonry – the longer bricks/blocks are left to stand the smaller the ultimate moisture expansion/drying shrinkage of the brickwork and blockwork, respectively. In order to avoid in-service problems, the use of kiln-fresh clay bricks for new masonry construction should, in particular, be avoided.

Thermal movement

Masonry units and mortar expand or contract in response to short-term changes in ambient temperature. In the case of clay brickwork, movement in the vertical direction may be 50% higher than in the horizontal direction due to the greater proportion of mortar, which has a higher coefficient of expansion than brick.

In order to accommodate thermal and moisture movements, soft vertical joints are usually incorporated in masonry walls at regular intervals – typically every 12–15 metres in the case of clay brickwork, and every 6–9 metres for blockwork.

Creep

When subject to a sustained load, masonry undergoes an initial elastic deformation followed by a long-term, time-dependent, deformation. The latter consists of creep

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Table 4.3 Ranges of coefficients of creep, moisture expansion or shrinkage, and thermal properties of masonry (adapted from BS EN 1996-1-1:2005 (British Standards Institution, 2005a))

Type of masonry unit	Final creep coefficient[a] Φ_∞	Long-term moisture expansion or shrinkage[b]	Coefficient of thermal expansion, α_t (10^{-6}/K)
Clay	0,5 to 1,5 (1,5)	–0,2 to +1,0 (0,5)	4 to 8 (6)
Dense aggregate concrete and manufactured stone	1,0 to 2,0 (1,5)	–0,6 to –0,1 (–0,2)	6 to 12 (10)
Lightweight aggregate concrete	1,0 to 3,0 (1,5)	–1,0 to –0,2 (–0,4)	6 to 12 (10)
Autoclaved aerated concrete	0,5 to 1,5 (1,5)	–0,4 to +0,2 (–0,2)	7 to 9 (10)
Natural stone			
Magmatic			5 to 9 (10)
Sedimentary	[c]	–0,4 to +0,7 (0,1)	2 to 7 (10)
Metamorphic			1 to 18 (10)

[a]The final creep coefficient $\Phi_\infty = \varepsilon_{c\infty}/\varepsilon_{el}$, where $\varepsilon_{c\infty}$ is the final creep strain and $\varepsilon_{el} = \sigma/E$.
[b]Where the long-term value of moisture expansion or shrinkage is shown as a negative number, this indicates shortening; a positive number indicates expansion.
[c]These values are normally very low.
Values shown in parentheses are the values adopted in UK National Annex to BS EN 1996-1-1:2005.

together with drying shrinkage or moisture expansion, according to the type of masonry unit. Creep is important as it relieves stresses in restrained masonry and reduces the tendency for tensile shrinkage cracks to develop in restrained blockwork panels, for example.

Table 4.3 shows the ranges of values for long-term moisture movement, coefficients of thermal expansion and creep coefficients for different types of masonry. (The reader should note the use of a comma rather than a full stop to represent the decimal point, this being the European convention).

4.7.5 Durability

The durability of masonry products is normally expressed in terms of their resistance to freeze/thaw and, in the case of clay bricks, their active soluble salt content.

Freeze/thaw resistance

1 *Clay bricks.* BS EN 771-1 specifies that bricks should comply with one of three categories according to their degree of exposure to saturation and

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freezing, i.e. frost resistant (F2), moderately frost resistant (F1), not frost resistant (F0).

2 *Concrete blocks*. For extreme exposure conditions and frost attack, aggregate blocks with a strength in excess of 7.3 N/mm^2 or Aircrete blocks may be used.

3 *Natural stone*. Within the UK, physical damage due to frost is considered to be relatively rare except in conditions of extreme exposure (Institution of Structural Engineers, 1996).

Category of active soluble salts

Fired-clay bricks, in particular, may contain water-soluble salts (especially those of sodium, potassium and magnesium) that can attack the mortar, or migrate to the surface of the brickwork causing efflorescence. BS EN 771-1 specifies that bricks should comply with one of three categories according to the degree of exposure: S0, suitable for completely dry applications; S1, suitable for normal exposure applications; S2, suitable for prolonged saturation applications. These limits ensure that, under the particular service conditions, damage will not occur to the masonry units, mortar, or render (if any).

Table 4.4, adapted from BS 5628: Part 3 (British Standards Institution, 2005b), shows the quality of masonry units and mortar designations necessary to achieve durable masonry construction for specific exposure conditions.

4.7.6 Water absorption

Water absorption is important in relation to whether clay brickwork in particular should act as a *raincoat* or an *overcoat* on buildings. Bricks with high absorption, for example, may act as an overcoat, soaking up large amounts of rain which is then slowly released back to the atmosphere. Low absorption bricks, on the other hand, tend to shed rain water. This can lead to unsightly streak marks down the face of the brickwork as well as water penetrating the brickwork through incompletely filled mortar joints. A low water absorption figure is specified for engineering bricks (Table 4.5), which are frost resistant, and for bricks used as damp-proof courses although water absorption, in itself, is not a reliable indicator of a brick's resistance to frost attack (British Standards Institution, 2005b).

4.7.7 Fire resistance

Most masonry products are inherently resistant to fire, as they contain a mass or volume fraction of ≤1.0% of homogeneously distributed organic materials. They are categorised as Class A1 in terms of BS EN 13501-1:2007 (British Standards Institution, 2007), i.e. they will not contribute in any stage of the fire. Masonry walls consequently perform well in fire with, for example, 100 mm solid clay brickwork walls having 120 minutes fire resistance (British Standards Institution, 2005c).

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Table 4.4 Quality of units and mortar for durable masonry (adapted from BS 5628: Part 3(2005) (British Standards Institution, 2005b))

Masonry condition or situation	Quality of masonry units and appropriate mortar designations			Remarks
	Clay units	Aggregate concrete bricks	Aggregate concrete blocks	
(A) Work below or near external ground level				
A1. Low risk of saturation		Without or with freezing	Without or with freezing	
Without freezing	LD – F0 and S0 or HD – FO, F1 or F2 and SO, S1 or S2 in (i), (ii) or (iii)	Compressive strength 16.5 N/mm^2 or above in (iii)	(a) of net density ≥1500 kg/m^3 or (b) made with dense aggregate conforming to BS EN 12620; or	Some types of autoclaved aerated concrete block may not be suitable. The manufacturer should be consulted
With freezing	HD – F1 or F2 and S0, S1 or S2 in (i), (ii) or (iii)		(c) having a compressive strength of 7.3 N/mm^2; or (d) most types of auto-claved aerated block (see remarks) All in (iii) or (iv) (see remarks)	In sulphate-bearing ground conditions, the recommendations in 5.6.4 should be followed. Where designation (iv) mortar is used it is essential to ensure that all masonry units, mortar and masonry under construction are protected fully from saturation and freezing (see A.4.1.3.2 and A.5.1.1)

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(E) Internal walls and inner leaves of cavity walls above DPC level				
Internal walls and inner leaves of cavity walls	LD – F0 and S0 or HD – F0, F1 or F2 and S0, S1 or S2 in (i), (ii), (iii) or (iv) (see remarks)	Compressive strength 7.3 N/mm^2 or above in (iii) or (iv)(see remarks)	Any in (iii) or (iv) (see remarks)	Where designation (iv) mortar is used it is essential to ensure that all masonry units, mortar and masonry under construction are protected fully from saturation and freezing (see A.4.1.3.2 and A.5.1.1)

LD = low density; HD = high density.

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Table 4.5 Specification for UK engineering and DPC bricks (BS EN 771-1:2003 (British Standards Institution, 2003a))

Performance characteristic	Clay engineering bricks	
	Class A	Class B
Compressive strength (N/mm^2)	125	75
Water absorption (% by mass) and also when used as DPC units	4,5 (and DPC1)	7,0 (and DPC2)
Freeze/thaw resistance category	F2	F2
Active soluble salts category	S2	S2

DPC1 bricks are required for buildings.
DPC1 or 2 may be used in external works.

4.8 Historical use of masonry

Stone masonry, as a form of construction, has existed since the beginnings of civilisation. The ancient pyramids in Egypt were built during the second and third millennia BC using stone laid in gypsum mortar. Sun-dried bricks first appeared in Southern Turkey *c*. 8000 BC while fired-clay bricks were used in the third millennium BC (Lynch, 1994). Fig. 4.3 shows brick and stone masonry from the second century AD.

The Romans introduced fired bricks to England although, after the fall of the Roman Empire, the use of masonry effectively ceased. Stone masonry construction began again in Europe during the ninth and tenth centuries and thousands of churches and cathedrals were built in masonry during the Middle Ages. Bricks were reintroduced to the UK from the Netherlands in the twelfth and thirteenth centuries, and UK brick manufacturing recommenced at this time. Examples of brickwork from this period still exist (Fig. 4.4).

The demand for bricks increased rapidly following the Great Fire of London and again during the Industrial Revolution in the nineteenth century when brick became the dominant construction material with an annual production in excess of nine billion units. The move to a unified metric size for UK bricks took place in 1969, although some manufacturers still produce imperial-size bricks for renovation work and extensions to existing buildings.

The market for masonry, and the manner in which it is used, has changed greatly during the last hundred or so years. This is due to the introduction of materials such as reinforced concrete and structural steel which, unlike masonry, are able to resist tensile bending stresses. This has allowed new types of bridges, for example, to be built and has led to an overall decline in the use of masonry for traditional civil engineering structures such as arches, retaining walls and sewers.

The development of steel and concrete structural frames during the early part of the twentieth century has also meant that clay brick masonry no longer performs its traditional function as a load-bearing material in buildings (Sutherland, 1993).

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4.3 The Roman Library of Celsus at Ephesus.

4.4 The north side of the chancel at Holy Trinity Church, Hull, UK.

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4.5 Comparison of wall thicknesses in (a) eighteenth, nineteenth and (b) twentieth centuries in relation to overall areas of buildings (Sutherland, 1993) (© British Masonry Society). Each plan is approximately to scale within itself but the plans are not all reproduced to exactly the same scale.

Instead, its function is now essentially limited to that of a decorative cladding, insulating and weatherproofing the interior.

The introduction of structural design codes for masonry, in particular, has enabled the thickness of walling to be greatly reduced during the last century (Fig. 4.5) and cavity wall construction, with its unloaded outer leaf, has become the norm for masonry buildings in the UK and other European countries with similar, i.e. wet, climates. In addition, traditional lime mortars have been replaced by quick-setting cement-based mortars which, although usually stronger, are more prone to cracking generally. Efforts to promote the increased use of lime mortars in masonry, with their greater ability to accommodate movements, are nevertheless underway (Sumacon, 2007).

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A particular feature of masonry construction over the past 60 or so years has been the introduction of concrete blocks. These are more thermally efficient than clay bricks and, due to their size, enable increased rates of production to be achieved on site. The introduction of higher standards of thermal performance for buildings has led to the almost universal use of blockwork for the inner leaf of cavity walls, replacing the common clay brickwork used previously. More recently, thin-joint aerated blockwork has been introduced. As well as high levels of thermal insulation, this form of masonry offers increased resistance to lateral wind loadings, reducing the need for wind posts in cladding panels, for example.

Modern thin-skin forms of cavity wall construction, with their relatively low embodied energies and high thermal efficiencies, are more environmentally friendly than the thicker types of solid masonry walling used in the past. They are, however, more complicated to construct due to the large amount of metalwork fixings they normally contain, and tolerances are often critical (Sutherland, 1988). In addition, thin cavity walls are more prone to thermal and moisture expansion/contraction than traditional, thicker, forms of masonry. In order to accommodate movements, soft vertical and horizontal joints are now installed at regular intervals in brick, block and stone masonry walling. These, together with the almost universal use of stretcher bond for facing brickwork, tend to reduce the aesthetic appeal of masonry as a solid facing material.

4.9 Sustainability

Prior to discussing the 'sustainability' of masonry materials and forms of masonry construction, it is useful in the first instance to consider what is actually meant by sustainability and to explain the importance of the construction industry to sustainable development, i.e. the process by which sustainability is achieved.

4.9.1 Introduction to sustainability

Sustainability is a relatively recent concept that has arisen out of concerns about anthropogenic, i.e. man-made, changes to the climate and the profligate use of the earth's limited resources by the developed nations in particular. In essence, sustainability is concerned with promoting the most efficient use of resources, the protection of the environment and ecosystems, and the development of a more equitable world society generally. The different aspects of sustainability are often illustrated by means of a simple Venn diagram (Fig. 4.6).

As sustainability encompasses a wide range of complex yet inter-related issues, it is difficult to define in precise terms. Consequently, no single universally agreed definition has to date been adopted; instead, numerous definitions have been proposed, all of which are essentially vague in nature (Global Development Research Center, 2007). Probably the most commonly used definition is that of the Brundtland Commission in their 1987 report *Our common future* (Brundtland,

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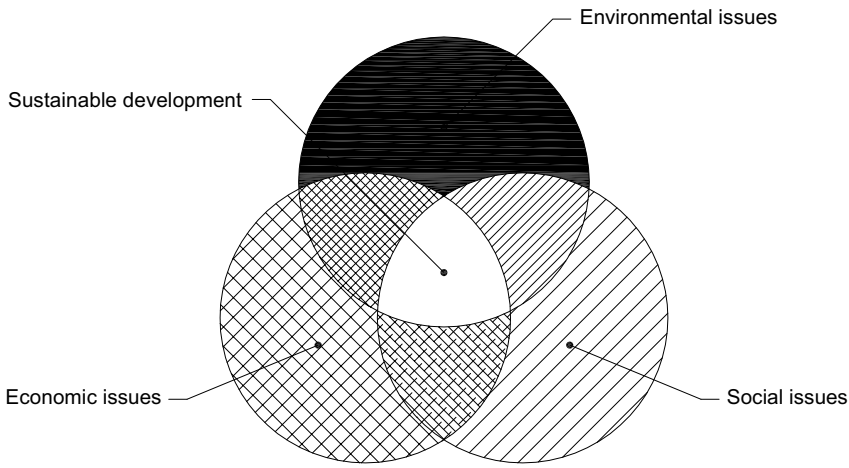

4.6 Venn diagram to represent sustainability.

1987), i.e. 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.'

While the economic and environmental issues associated with sustainability can often be quantified in terms of the different sciences involved (albeit often in a very crude manner due to the complexities of the processes involved), the less tangible social aspects of sustainability, such as fairness and 'justice for all', are essentially qualitative in nature and cannot be quantified in the same manner.

Certain decisions relating to sustainability can, therefore, be made on the basis of quantitative scientific data. Others, however, may have to be based upon *value–choice* judgments: for example, as a mark of a civilised society, we expect to live in a house or apartment even though cave dwelling may well be less damaging to the environment. The selection of sustainable products or processes therefore involves 'trade-offs' between competing environmental, economic and social issues and no perfect solution is usually possible. In addition, an accurate determination of what is truly sustainable, in an absolute sense, is usually not possible due to the current lack of understanding of the complex issues involved.

In practice, therefore, products or processes may simply be selected on the basis of environmental impacts (burdens) or economic costs (or some combination of these) over a specified lifespan – the product or process with the lowest overall impact, or cost, being considered the 'most sustainable' option. As such, sustainability reduces to a simple comparative exercise between alternatives, all of which may actually be unsustainable in absolute terms. In this respect, it should be noted that relative sustainability is not a valid concept, with terms such as 'more sustainable' and 'less sustainable' being considered essentially meaningless (Sutton, 2000). They are, nevertheless, still widely used.

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On a more general note, it should be noted that most of the current tools for evaluating the environmental performance of construction materials and buildings are commercial in nature. This has led to the 'black box' situation, where it is often not possible for the client to verify the results obtained from these tools because data on the whole life performance of materials and their costs, for example, may not be available for inspection.

4.9.2 Sustainability and the construction industry

Sustainability is, as already noted, concerned with the more prudent use of natural resources and the protection of the environment. These are issues of direct relevance to the global construction industry – a consumer of large quantities of natural resources in the forms of energy, water, materials and land. In the UK alone, for example, the construction industry consumes over 420 million tonnes of raw material annually and generates over 90 million tonnes of waste, much of which is disposed of in landfill sites (Environment Agency, 2007). In addition, the energy consumed in building services, i.e. lighting, heating and cooling of buildings, etc. accounts for approximately half of the UK's current emissions of carbon dioxide, while around 10% of UK energy consumption is used for the production and transport of construction products and materials (Thistlethwaite, 2004).

In order to promote more sustainable practices within the UK construction industry, legislation is gradually being introduced to improve the thermal efficiency of buildings, to reduce waste and to encourage the use of recycled and more environmentally friendly materials generally.

4.9.3 Masonry as a sustainable construction material

Buildings and civil engineering structures such as arch bridges built in stone or brick masonry are usually capable of lasting centuries with minimal maintenance. These are important criteria in relation to the environmental and economic aspects of sustainability (Your Home, 2005). In the UK, for example, there are approximately 40 000 masonry arch bridges in daily use on highways, railways and canals; most are over 100 years old, while some are over 500 years old (Mabon, 2002). In terms of their whole life maintenance, masonry arch bridges probably perform better than those built in reinforced concrete or steel. Work by Steele *et al.* (2002), in particular, has shown that maintenance of the brickwork in masonry arch bridges represents less than 0.5% of the environmental impacts of initial bridge construction over a typical 120-year design life.

In relation to buildings, around 25% of the 23 million residential properties in the UK are more than 160 years old (Department of Communities and Local Government, 2006a). Most of these are built out of brick or stone, or some combination of these materials. Despite their age, the vast majority of these older

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properties continue to satisfactorily perform the functions for which they were originally built.

The highly sustainable nature of the traditional materials used in UK housing is recognised by the Royal Town Planning Institute (Royal Town Planning Institute, 2004), who note that:

> With the exception of the 'system' building of the 1960s, there is little evidence that the traditional materials used in house building in the UK – brick, stone, tiles, slates, etc – are not sustainable. The large numbers of 19th century houses that are still in good structural condition show that, with a responsible level of maintenance, the traditional materials are capable of lasting well over 100 years. Where major demolition has taken place – such as inter-war, peripheral council estates – this has been primarily for social reasons rather than a lack of building integrity.

Masonry also performs well in relation to the less tangible aspects of a building's sustainability. These include its adaptability, 'loveability' (Sayce, 2002) and overall robustness. Masonry also has excellent resistance to fire and will not ignite, burn or emit toxic fumes when exposed to extreme heat.

The principal use for masonry in buildings is as external and internal walling. Typically, these account for only 5–15% of the total environmental impacts from materials over a 60-year period (Fig. 4.7). Floor finishes and upper floors, on the other hand, are responsible for 40–45%, i.e. they are significantly more damaging to the environment than the masonry used in a building.

Houses built of masonry also retain value, with the UK housing stock being worth £4000 billion in 2006. This is equivalent to around 60% of the country's net worth, making housing, and by implication 'bricks and mortar', its most valuable asset (Office for National Statistics, 2006). In relation to the social aspects of sustainability, brick and stone masonry in particular are visually attractive materials and buildings clad with an external skin of brick or stone contribute to the aesthetic sustainability of the urban fabric generally. In addition, an insurer may charge more for buildings insurance for a timber-framed property than for one built with masonry (Hall, 2007).

Overall, masonry cavity walling with a brick or stone external leaf and a thermally efficient aerated or aggregate blockwork inner leaf can be considered to be a highly sustainable form of building construction.

4.9.4 Quantifying the sustainability of masonry

In the UK most of the work on the sustainability of construction materials, including that of masonry and the different types of masonry wall construction, has been undertaken by the Building Research Establishment (BRE). Their Environmental Profiles Methodology (Howard *et al.*, 1999), originally developed in the late 1990s and subsequently updated, provides a means of comparing the

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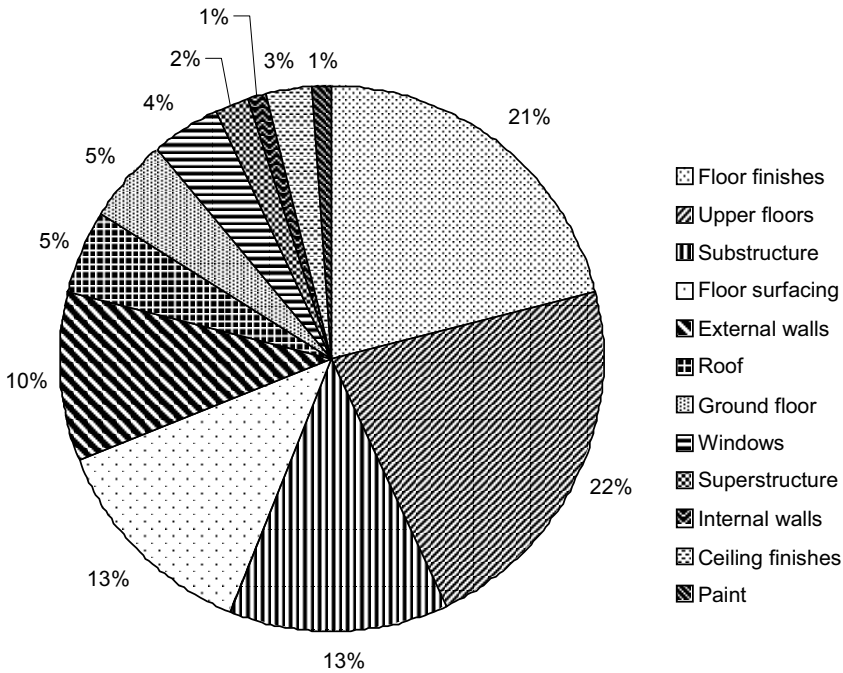

4.7 Contribution of building elements to the whole life (60-year) environmental impacts of a typical building (Bown, 2007).

environmental performance (impacts, or burdens) of over 250 materials and components used specifically in buildings. (NB, by themselves most construction materials do not have a specific function. It is only possible to quantify their sustainability when they form part of a component within a building, e.g. an internal or external wall, or a roof.)

Environmental impacts were quantified in relation to a pre-defined set of 13 issues, including:

- climate change;
- ozone depletion;
- air pollution;
- fossil fuel depletion and extraction;
- mineral and water extraction;
- waste disposal;
- transport pollution and congestion: freight.

Three types of profile were developed.

1 'Cradle to factory gate', performed for a standard mass of a product or material, e.g. 1 tonne of bricks, without any concern for their eventual use.

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2 'Cradle to installed-on-site' for walls, floors, ceilings, etc. performed on a per-square-metre basis.
3 'Cradle to grave' for building elements with a 60-year lifetime only, taking into account maintenance, replacements and disposal, again on a per-square-metre basis.

The profiles were then used in range of BRE publications and tools for assessing the environmental and economic performance of different types of buildings. These include:

- The Green Guide(s) to Specification (different versions are available);
- ENVEST software package;
- The BREEAM suite of assessment methods and tools;
- The Code for Sustainable Homes.

Green Guide(s) to Specification

Here the principal elements within buildings – i.e. floors, walls, roofs – are assessed in terms of a simple A–B–C rating system, with an 'A' having the least environmental impact. (NB, The revised 2007 version of the Green Guide, yet to be published, adopts an A* – E rating system.) Table 4.6 shows the ratings for a variety of external masonry walls. It can be seen that the brickwork and blockwork cavity walls listed achieve an 'A' summary rating, whereas the cavity wall with a reconstituted stone outer leaf receives a 'B' rating. It should be noted that the Green Guides are a simplistic tool for enabling comparative assessments between pre-selected elements of construction only, as an 'A' rating for one form of construction or element may not be equivalent to an 'A' rating in another element for the same environmental impact.

ENVEST software package

A more comprehensive assessment of the whole life environmental and economic performance of buildings is provided by the BRE's ENVEST software package (Building Research Establishment, 2007a). This gives an indication of a building's operational energy and whole life costs, and allows designers to investigate the trade-off between the environmental impacts of the different elements in a building and operational energy.

ENVEST expresses environmental performance in terms of 'ecopoints' (notional units, in which 100 ecopoints represent the environmental impact of one UK citizen over a period of 1 year). The validity of this simplified approach to environmental performance – i.e. reducing the 13 impact categories to a single point 'score' – is, however, questionable as it involves the subjective process of weighting (International Organization for Standardization, 2006).

Figure 4.8 shows the results of a recent ENVEST analysis to quantify the total

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Table 4.6 Extract from a rating table in the *Green Guide to Specification* (Anderson *et al.*, 2002) (© BRE, reproduced with permission)

Traditional forms of cavity wall construction Element	**Summary rating**	Climate change	Fossil fuel depletion	Ozone depletion	Human toxicity to air and water	Waste disposal	Water extraction	Acid deposition	Ecotoxicity	Eutrophication	Summer smog	Minerals extraction	Cost (£/m²)	Typical replacement interval	Recycled input	Recyclability	Recycled currently	Energy saved by recycling
Brickwork outer leaf, insulation, aerated blockwork inner leaf, plasterboard/plaster	**A**	A	A	A	A	B	A	A	A	A	A	A	55–105	60	C	A	B	A
Brickwork outer leaf, insulation, dense blockwork inner leaf, plasterboard/plaster	**A**	A	A	A	A	C	A	A	A	A	A	A	55–105	60	C	A	B	A
Fair-faced reconstituted stone outer leaf, insulation, dense blockwork inner leaf, plasterboard/plaster	**B**	A	A	A	A	C	A	A	C	B	A	B	125–150	60	C	A	B	A

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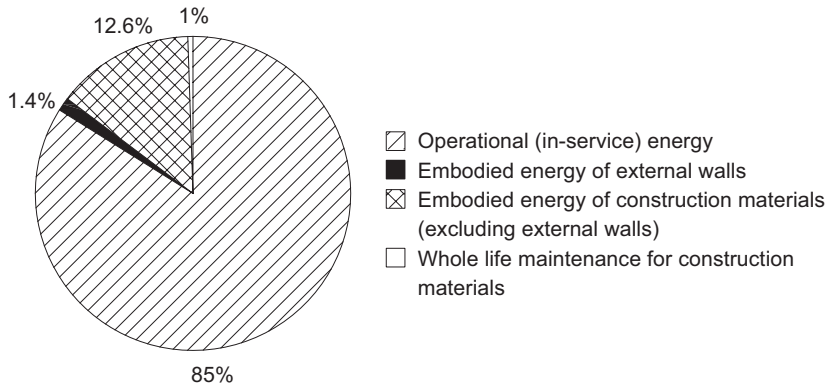

4.8 Comparison of embodied energy of the construction materials and operational (in-service) energy for a four-bedroom residential property at 100 years, according to ENVEST (Bown, 2007).

energy consumption of a typical four-bedroom residential property in the UK over a 100-year lifespan. The external walls were of brick/block cavity construction and all main elements – i.e. walls, roof, etc. – complied with the 2005 UK Building Regulations governing thermal performance. It can be seen that the embodied energies of all the materials used in the building are low in relation to the operational energy, with external masonry walls accounting for less than 2% of total energy.

BREEAM and the Code for Sustainable Homes

In addition to the environmental impacts of the materials used in the fabric of buildings, the BREEAM suite of assessment methods (Building Research Establishment, 2007b) and the recently introduced Code for Sustainable Homes (Department of Communities and Local Government, 2007) assess building performance across a range of other categories. These include management, operational energy, health and well-being, pollution, land and water use, and ecology. Credits are awarded according to performance, with minimum standards specified in each category. Using a set of environmental weighting factors these are converted to produce a single overall score. In the case of BREEAM, buildings are rated on a scale of Pass, Good, Very Good or Excellent, and a certificate awarded. The Code for Sustainable Homes, on the other hand, has six levels of award – Level 1 to Level 6 – the latter being an aspirational standard based on zero carbon emissions for a dwelling.

Table 4.7 shows the environmental impact categories and associated weighting factors considered in the Code for Sustainable Homes. It can be seen that operational energy/CO_2 has the largest weighting (36.4%), with that for materials being relatively low (7.2%). Although these weighting factors are essentially

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Table 4.7 Environmental weighting factors in the Code for Sustainable Homes (Department of Communities and Local Government, 2007)

Environmental impact categories	No. of credits in each category	Environmental weighting factor (as % of total possible points score available)	Points score for each credit in category
Category 1 – Energy and CO_2 emissions	29	36.4%	1.26
Category 2 – Water	6	9.0%	1.50
Category 3 – Materials	24	7.2%	0.30
Category 4 – Surface water run-off	4	2.2%	0.55
Category 5 – Waste	7	6.4%	0.91
Category 6 – Pollution	4	2.8%	0.70
Category 7 – Health and well-being	12	14.0%	1.17
Category 8 – Management	9	10.0%	1.11
Category 9 – Ecology	9	12.0%	1.33
Total	104	100.0%	–

subjective in nature they do nevertheless illustrate that reducing the operational energy of a building over its lifespan is considered to be significantly more important, in terms of sustainability, than the environmental impacts of the materials used in the fabric of the building itself.

4.9.5 Masonry and the design life of buildings

The BRE Green Guides assume a design life of only 60 years when evaluating the whole life environmental performance of buildings. After this, the buildings are assumed to be demolished and the various materials are disposed of as landfill, or recycled/re-used to some degree. This approach is overly simplistic, however, as it fails to recognise that buildings may have different lifespans depending on their use and, indeed, re-use. It has been suggested, for example, that new housing should be designed to last a minimum of 200 years (Green Guide Update, 2006). Masonry would appear to be an ideal material in this respect as it is capable of lasting centuries. Finally, it is of interest to note that some of the lightweight modular designs in the recent UK Design for Manufacture £60 000 Home Competition (Department of Communities and Local Government, 2006b) may have lifespans of only 30 years (Building Products Magazine, 2007).

4.9.6 Whole life costs of masonry

Whole life costing considers the cost of a building over its entire life and includes initial build costs, maintenance and eventual demolition. In practice, durable, long life buildings that require little maintenance may be better value and more

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4.9 Example of replacement brickwork.

Table 4.8 Whole life economic performance of masonry walling (2005 base prices) (Bown, 2007)

	Initial cost (£/m²)	60 years (£/m²)	100 years (£/m²)	150 years (£/m²)	300 years (£/m²)	500 years (£/m²)
225 mm solid brickwork	81.41	162.17	191.96	260.93	455.54	697.28
102.5 mm brick/100 mm block cavity wall	96.73	179.09	221.78	324.78	–	1124.93

sustainable overall than designs that are cheaper to construct but have maintenance costs. Structures built in masonry perform well in this respect as they require minimal maintenance. Typically, this only involves repointing or replacement of brickwork or stonework (Fig. 4.9). Examples of the whole life costs of two types of masonry walling for different lifespans are shown in Table 4.8.

4.9.7 Reclamation and reycling of masonry

Reclamation and recycling of construction materials from demolition sites is an important aspect of sustainability. Data on the amount of masonry that is reclaimed or recycled in the UK are, however, limited. A 1998 survey estimated that

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147 million reclaimed bricks were sold each year, with a value of £80–160 million (Salvonews, 2006). The quality of reclaimed bricks was, however, poor with only 5% having any frost resistance guarantee. The survey also found that between 600 and 1200 million bricks were crushed and used annually as low-quality hardcore fill or capping layers in road construction. Table 4.6, from the *Green Guide to Specification*, gives a broad indication of the recyclability and energy saved by recycling masonry walling while the issues associated with the use of reclaimed bricks are discussed in more detail by the UK Brick Development Association Ltd (Brick Development Association, 2001b).

A thriving market exists for reclaimed stone products in areas of the UK where these have traditionally been used for building work, e.g. the Cotswolds and parts of Yorkshire. Much of the reclaimed stone is used for small extensions to existing residential properties, with its cost invariably being higher than that of newly quarried stone.

In practice, while soft lime mortars may readily be removed from bricks and stone, cement-based mortars cannot be so easily, or effectively, cleaned off. The reclamation of bricks that have been laid in cement-based mortar is consequently more problematic and may not be feasible in terms of its cost-effectiveness or environmental impacts at the present time.

Brick, block and stone masonry from demolition sites may be processed and re-used (usually in combination with crushed concrete) as a coarse aggregate for making new concrete. Its use in this way within the UK has, however, been very limited to date due to concerns about the variable composition of recycled demolition and excavation wastes and the possible presence within these wastes of undesirable substances such as plastics, wood, ferrous metals and gypsum. Careful separation of the different materials is therefore essential at recycling centres, together with adequate washing to remove soil, silt and clays (WRAP, 2007). Ideally, wastes should be sorted into colour-coded stockpiles:

- black – asphalt;
- white – concrete;
- red – mixed waste, but generally composed of brick.

In general, the strength of concrete containing recycled aggregates (RA) is lower than that of concrete made with natural aggregates. When used at moderate levels, i.e. up to 20% replacement by mass of natural coarse aggregate, the effects of RA on the overall performance of concrete, and the proportion of brick within the RA, are not considered significant (WRAP, 2007). When the coarse aggregate consists entirely of RA the strength of concrete decreases with increasing brick content, with concretes containing 100% crushed brick having strengths approximately 20–25% lower than those made entirely with recycled concrete aggregate (RCA). The general effects of RA, and the brick content of RA, on the strength of concrete is shown in Fig. 4.10 for different classes of concrete exposure. In practice, to achieve the same cube strength and consistence as concrete made with

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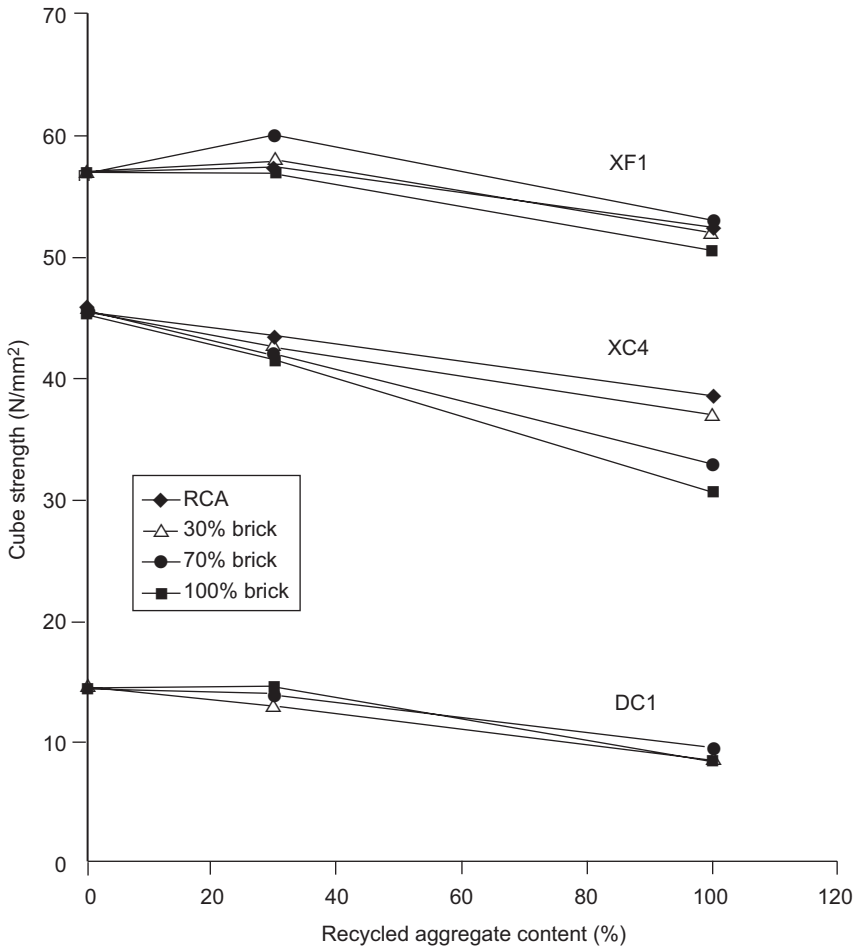

4.10 Effect of RA, and the brick content of RA, on the strength of concrete for different classes of exposure (courtesy of WRAP (2007)). [XF1, freeze/thaw attack – moderate water saturation without de-icing agent); XC4, carbonation – moderate humidity or cyclic wet and dry; DC1, design chemical class 1 (British Standards Institution, 2006).]

natural aggregates it may be necessary to increase the cement content of RA concretes or to use large dosages of admixtures, both of which are undesirable in terms of their environmental impacts (Hansen, 1992; WRAP, 2007).

Crushed brick can also be used as a fine aggregate in concrete. In practice, however, this can significantly increase water demand, leading to low-strength concrete (WRAP, 2003). The effect on the performance of concrete is similar to when brick is used as a coarse aggregate, i.e. the 28-day strength of concrete

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decreases with increasing brick content (Khatib, 2005). At later ages, however, the rates of gain of strength can be higher in concretes containing crushed brick fine aggregate, due possibly to pozzolanic action between the crushed brick and the products of cement hydration (Wild *et al*., 1996).

When ground to a very fine powder, clay bricks exhibit pozzolanic properties. Waste bricks, in particular, have the potential to be used as a partial replacement for cement in mortars and concretes, in a similar manner to fly ash (PFA) or silica fume. The benefits of this include reduced permeability and greater resistance to sulphate attack and alkali–aggregate reactivity (Gupta, 1992). Replacement of 10% cement by ground brick was found to have no effect on the compressive strength of mortar while tests on concrete showed that up to 20% replacement of cement was possible with no detrimental long-term effects (Golaszewski *et al*., 1999).

Further details of the performance of concretes containing recycled masonry materials, and proposed classes of RA, are available from WRAP (WRAP, 2007).

4.9.8 Thermal mass

Clay bricks, dense aggregate blocks and stone units have high thermal mass. Buildings containing these types of masonry take a long time to heat up and a long time to cool down. As a result they have a relatively steady internal temperature, which reduces the amount of external heating or cooling they require. Recent research has, in fact, shown that medium-weight and heavyweight masonry and concrete homes should have lower total energy consumption and CO_2 emissions over an assumed 100 year life than lightweight timber homes (Concrete Centre, 2006). This is due to the thermal mass of the blockwork walls and concrete floors, which restricts overheating during the summer months and captures solar gains on winter days.

4.10 Examples of sustainable masonry construction

4.10.1 BedZED, south London

The Beddington Zero (Fossil) Energy Development (BedZED) is a mixed-use scheme in south London consisting of 82 homes and 3000 m^2 of commercial or live/work space that was completed in 2002. It was initiated by the BioRegional Development Group and Bill Dunster Architects and was developed by London's largest housing association, the Peabody Trust. BedZED was designed as a carbon neutral development, i.e. one that produces at least as much energy from renewable sources as it consumes – with no net addition of carbon dioxide to the atmosphere. A particular aspect of the development is that it employs proven materials, including brick and block, and relatively low-tech methods of construction (Fig. 4.11)

In order to maximise solar gain, the terraced properties face south and have

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4.11 BedZED (courtesy of the BioRegional Development Group).

double- or triple-glazed windows with low-emissivity glass. The walls are a mixture of brick and dense aggregate block cavity construction and timber stud weatherboarding with cavity blockwork, with a 300 mm-wide cavity filled with insulation. The large thermal mass of the dense blockwork inner leaf and precast concrete floors allows heat to be stored during warm periods and warmth to be radiated during cooler periods, significantly reducing the amount of external heating or cooling required.

Although the BedZED scheme has suffered a number of operational problems since its completion in 2002, these relate principally to the biomass-fuelled system for producing heat and electricity (CHP) and the reed beds for filtering sewage water for use in toilets and gardens (Slavin, 2006). The buildings themselves, on the other hand, appear to be functioning well and while the development is not yet carbon neutral, heating requirements for BedZED homes are only around 10% of those of a typical home (Ecozine, 2007).

As the movement of construction materials around the UK accounts for about 30% of all road freight, a policy of local sourcing of materials was adopted at BedZED. This resulted in some 120 tonnes of carbon dioxide emissions being saved, equivalent to 2% of the embodied carbon dioxide of the BedZED buildings (Green Building, 2007).

4.10.2 Winterton House, London

Winterton House is a 23-storey residential tower block in the Tower Hamlets area

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4.12 Winterton House (©Ramboll WhitbyBird).

of London. Built in 1968, it consisted of a lightweight steel frame with a central reinforced concrete service core. Lightweight precast concrete units were used for the floors with glass-reinforced plastic (GRP) panels for cladding. The original building quickly suffered from a variety of problems. These included ingress of water through the mastic joints, causing corrosion of the steel reinforcement in the floors, together with excessive sound transmission between rooms and the presence of asbestos as a means of fire protection. Three similar buildings erected around the same time also suffered with these problems and were demolished.

Instead of demolishing Winterton House, it was decided to undertake a major refurbishment of the property. In the mid1990s the building was therefore stripped back to the bare steel frame and reinforced concrete floors installed. It was then reclad with a freestanding outer skin of load-bearing brickwork (Fig. 4.12). Finally, the extra weight imposed on the frame by the new concrete floors was 'pulled out' of the steel columns and transferred across to the perimeter brickwork

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via a steel transfer framework at roof level. This involved the use of hydraulic jacks to prestress or 'prestrain' the brickwork, which then acted compositely with the steel frame of the building.

In addition to acting as a weatherproof cladding, the clay brickwork at Winterton House contributes to the load-bearing capacity of the building. This is radically different from the manner in which clay brickwork cladding is normally used on tall buildings, i.e. as a non-load-bearing rain screen, and can lead to thinner structural frames being required. Winterton House also demonstrated that masonry can be successfully employed to prolong the life of existing buildings, a key aim of sustainable construction generally. Other benefits of this cost-effective form of off-the-frame brickwork cladding include greater building robustness and, as the brickwork is generally thicker, the use of alternative bonding patterns and arch features to improve the visual appeal of buildings (Bingel, 2001).

4.10.3 Queen Square, Leeds

Queen Square is one of only two Georgian squares in Leeds still in their original state. Most of the square was built between 1803 and 1815 and was planned as three terraces round a central garden. The grade two listed properties were constructed of red brick with stone details, and consist of two- and three-storey buildings with basements and warehouse facilities (Fig. 4.13). Originally occupied by local, wealthy wool merchants and solicitors they have been used for a variety of purposes during their 200-year lives. These include schools, shops, private apartments and offices for various businesses and local societies. The properties are now part of Leeds Metropolitan University which has recently invested more than £1000 000 in their refurbishment to provide new office accommodation and teaching space. Queen Square is an excellent example of how masonry buildings can be successfully re-used, thereby avoiding the need for demolition and at the same time contributing to the attractiveness of the urban environment.

4.10.4 Community Centre at Swaffham, Norfolk

This £1.5 million. low-energy building consists of two large halls with adjoining kitchen and café together with offices and is used for training, meetings, social events and as a crèche. Thin-jointed Celcon Solar Plus Aircrete blocks form the entire envelope of the building and achieve the required U-value without the need for a cavity, insulation, ties or other components, i.e. simple construction. The blocks were easy to lay and there was little wastage. The cladding is a combination of cedar boarding and Sto render. The building also features high-performance windows and an air-handling system for fresh air and ventilation with a heat recovery system. An unusual feature is the sedum roof, a 'living' or 'green' roof, the vegetation providing insulation and protection from ultraviolet light (Fig. 4.14).

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4.13 Queen Square, Leeds.

4.14 Swaffham Community Centre, Norfolk (courtesy of H+H Celcon).

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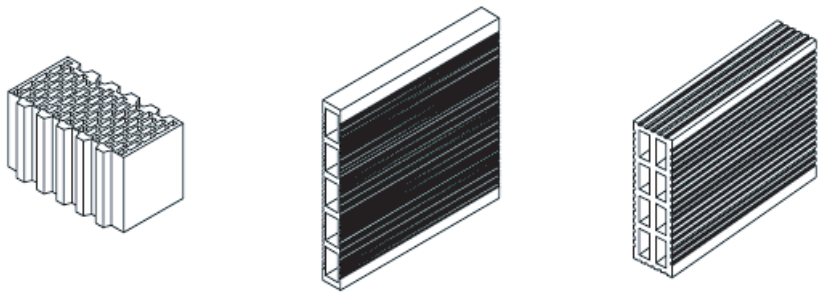

4.15 Highly perforated clay block units.

4.11 Future trends

As part of the drive towards more energy efficient buildings, the UK masonry industry has introduced aerated blocks and cavity walls with wider cavities and increased amounts of insulation. The development of new, more thermally efficient, products and forms of construction will continue as the regulations governing the operational energy of buildings are progressively tightened in future years. In addition, types of masonry products and forms of construction already in use in mainland Europe (Fig. 4.15) are likely to find their way on to the UK market. These include thick single-leaf walls built from highly perforated clay block units and subsequently sprayed with external insulating render. Greater use of unfired-clay bricks is also likely, as approximately 85% of a fired brick's embodied energy is due to the firing process itself.

Off-site manufacturing is also an area in which the masonry industry has, to date, made relatively little progress. This is due, in part, to the brittle nature of most forms of masonry construction and the cost-effectiveness of masonry pre-fabrication generally. The use of aerated blocks and thin-joint mortar systems for pre-fabricating lightweight walls that can then be transported to site appears to have significant potential in this respect.

4.12 References

Anderson J, Shiers D and Sinclair M (2002), *The Green Guide to Specification*, Oxford, Blackwell Publishing.

Beningfield N (2002), *Quality mortar mix is changing*. Available from: http://www.mortar.org.uk/.

Bingel P (2001), *Off-the-frame clay brickwork – Analysis and interpretation of results from the monitoring of Winterton House, London*, Final Report – Partners in Innovation Project Number 39/03/603, London, Department of Trade and Industry.

Bown A (2007), Whole life performance of clay brick masonry, PhD Thesis, Leeds Metropolitan University, Leeds, UK.

www.EngineeringEBooksPdf.com

Brick Development Association (2001a), *Use of traditional lime mortars in modern brickwork*. Available from: http://www.brick.org.uk/publications/.

Brick Development Association (2001b), *Observations on the use of reclaimed clay bricks*. Available from: http://www.reuse.it/salvo/bigrec.html.

Brick Development Association (2007), *A Sustainability Strategy for the Brick Industry*, Ascot, UK, Brick Development Association Ltd.

British Geological Survey (2007), *Mineral planning factsheet: brick clay*. Available from: http://www.mineralsuk.com/britmin/mpfbrickclay.pdf.

British Standards Institution (2003a), *BS EN 771-1:2003 Specification for masonry units. Clay masonry units*, London, British Standards Institution.

British Standards Institution (2003b), *BS EN 771-3:2003 Specification for masonry units. Aggregate concrete masonry units (dense and light-weight aggregates)*, London, British Standards Institution.

British Standards Institution (2005a), *BS EN 1996-1-1:2005. Eurocode 6. Design of masonry structures. General rules for reinforced and unreinforced masonry structures*, London, British Standards Institution.

British Standards Institution (2005b), *BS 5628-3:2005. Code of practice for the use of masonry. Materials and components, design and workmanship*, London, British Standards Institution.

British Standards Institution (2005c), *BS EN 1996-1-2:2005. Eurocode 6. Design of masonry structures. General rules. Structural fire design*, London, British Standards Institution.

British Standards Institution (2006), *BS 8500-1:2006 Concrete.* Complementary British Standard to BS EN 206-1. *Method of specifying and guidance for the specifier*, London, British Standards Institution.

British Standards Institution (2007), *BS EN 13501-1:2007. Fire classification of construction products and building elements. Classification using data from reaction to fire tests*, London, British Standards Institution.

Brundtland (1987), *Our common future: Report of the World Commission on Environment and Development*, UN General Assembly document A/42/427, Oxford University Press.

Building Products Magazine (2007), *Site specific*. Available from: http://www.buildingproducts.co.uk/building-feature/3.

Building Research Establishment (1998), *Aircrete: Thin Joint Mortar Systems,* Digest 432, Watford, Building Research Establishment.

Building Research Establishment (2007a), *Envest 2*. Available from: http://www.bre.co.uk/

Building Research Establishment (2007b), *BREEAM: BRE Environmental Assessment Method*. Available from: http://www.bre.co.uk/.

Chilterns Conservation Board (2005), *Chilterns buildings design guide – Chilterns brick, supplementary technical note*. Available from: http://www.chilternsaonb.org/downloads/Brick_Cons_Draft_0605.pdf.

Concrete Block Association (2006), *New European standards*. Available from: http://www.cba-blocks.org.uk/.

Concrete Centre (2006), *Masonry homes save* CO_2. Available from: http://www.concretecentre.com/.

Curtin W, Shaw G, Beck J, Bray W and Easterbrook D (2006), *The Structural Masonry Designers Manual* (Third Edition), Oxford, Blackwell Publishing.

Department of Communities and Local Government (2006a), *Housing statistics 2006*. Available from: http://www.communities.gov.uk/housing/.

Department of Communities and Local Government (2006b), *Design for Manufacture competition*. Available from: http://www.go-east.gov.uk/goeast/news/newsarchive/406975.

www.EngineeringEBooksPdf.com

Department of Communities and Local Government (2007), *Code for sustainable homes*. Available from: http://www.planningportal.gov.uk/uploads/code_for_sust_homes.pdf.

Department of Trade and Industry (2006), *Construction Statistics Annual Report 2006*, London, TSO.

Ecozine (2007), *BedZED*. Available from: http://www.ecozine.co.uk/Bedzed.htm.

Environment Agency (2007), *Sustainable materials*. Available from: http://www.environment-agency.gov.uk.

Errol Brick (2007), *'Eco Brick' unfired clay brick*. Available from: http://www.errolbrick.co.uk/.

Global Development Research Center (2007), *Sustainable development; definitions*. Available from: http://www.gdrc.org/sustdev/definitions.html.

Golaszewski J, Suchon S, Szwabowski J, O'Farrell M, Sabir B B and Wild S (1999), The influence of ground brick on the physical properties of mortar and concrete. In Dhir R K, Dyer T D, editors. *Modern Concrete Materials: Binders, Additions and Admixtures,* London Thomas Telford Ltd, pp. 119–130.

Green Building (2007), *BedZED construction materials report*. Available from: http://www.newbuilder.co.uk/books/Book_Bedzed1.asp.

Green Guide Update (2006), *Green Guide Update: BRE response to comments on Whole Life Performance Briefing Note (6)*. Available from: http://www.bre.co.uk/greenguide/.

Gupta J S (1992), Technology option for manufacture of calcined clay pozzolan (surkhi). In Hill N, Holmes S, Mather D, editors, *Lime and Other Alternative Cements*, London, Intermediate Technology Publications Ltd, pp. 191–198.

Hall (2007), *Mortgage advice*. Available from: http://www.alexanderhall.co.uk/.

Hansen T (1992), *Recycling of demolished concrete and masonry*, Rilem Report 6, London, E & FN Spon.

H+H Celcon (2007), *Blocks: manufacturing process*. Available from: http://www.hhcelcon.co.uk/.

Hammett M (2004), Bricks, blocks and pavers, *AJ Focus*, 09.2004, 30–40.

Howard N, Edwards S and Anderson J (1999), *BRE methodology for environmental profiles of construction materials, components and buildings*, Watford, BRE.

Ibstock (2003), *BS EN 771-1*: *European Standard Specification for clay masonry units compared to BS 3921 British Standard Specification for clay bricks,*. Available from: http://www.ibstock.com/.

Illston M and Domone P (2001), *Construction Materials: Their Nature and Behaviour*, London, New York, Spon Press.

Institution of Structural Engineers (1996), *Appraisal of Existing Structures* (Second Edition), London, The Institution of Structural Engineers.

International Organization for Standardization (2006), *ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework*, Geneva, International Organization for Standardization.

Jackson N and Dhir R (1997), *Civil Engineering Materials* (Fifth Edition), Basingstoke, Palgrave Macmillan.

Khatib J (2005), Properties of concrete incorporating fine recycled aggregate, *Cement and Concrete Research*, **35**, 763–769.

Limetechnology (2007), *Introduction to lime*. Available from: http://www.limetechnology.co.uk/pages/downloads_select.php.

Lynch G (1994), *Brickwork: History, Technology and Practice*, Volume 2, London, Donhead.

Mabon L (2002), Assessment, strengthening and preservation of masonry structures for

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continued use in today's infrastructure. In *International Association for Bridge and Structural Engineering Conference*, Melbourne, Australia. Available from: http://www.gifford.uk.com/publications/IABSE-Melbourne-2002.pdf.

Mortar Industry Association (2005), *Ready to use mortars*. Available from: http://www.mortar.org.uk/which_mortar02.htm.

Morton T (2006), *Feat of clay,* [Internet). Available from: http://www.iom3.org/materialsworld/feature-pdfs/jan06/feat_of_clay.pdf.

Office for National Statistics (2006), *UK National Statistics: Economy*. Available from: http://www.statistics.gov.uk/.

Royal Town Planning Institute (2004), *Response to specific questions from the Environmental Audit Committee, House of Commons*. Available from: http://www.communities.gov.uk/housing/.

Salvonews (2006), *BigREc Survey 1998*. Available from: http://www.reuse.it/salvo/bigrec.html.

Sayce S (2002), The quest for sustainable buildings: is longevity the key? In *Proceedings of the Eighth Annual International Sustainable Development Research Conference*, 8–9 April, University of Manchester, UK, pp. 399–408.

SimaPro7 (2007), *SimaPro7 introduction to LCA*. Available from: http://www.pre.nl/download/manuals/SimaPro7IntroductionToLCA.pdf.

Slavin T (2006), *Living in a dream*. Available from: http://www.guardian.co.uk/.

Steele K, Cole G, Parke G, Clarke B and Harding J (2002), *The application of life cycle assessment technique in the investigation of brick arch highway bridges.* Available from: http://www.brick.org.uk/.

Sumacon (2007), *The Sustainable Masonry Construction (SUMACON) network*. Available from: http://www.sumacon.org/.

Sutherland R (1988), Masonry as a decorative wrapping, *Masonry International*, **2**(3), 71–73.

Sutherland R (1993), Have we got it all wrong?, *Proceedings of The British Masonry Society*, **5**, 1–5.

Sutton P (2000), *Sustainability: what does it mean?* Available from: http://www.green-innovations.asn.au/sustblty.htm#more-or-less.

Thistlethwaite P (2004), *Assessing the sustainability of construction projects*, *BRE Centre for Sustainable Construction*. Available from: http://www.bfafh.de/inst4/45/ppt/2sustcon.pdf.

Wild, S, Khatib J, Sabir B B and Addis S D (1996), The potential of fired brick clay as a partial cement replacement material, In Dhir R K, Dyer T D, editors. *Concrete in the Service of Mankind: Concrete for Environment Protection and Enhancement*, London, E & FN Spon, pp. 685–696.

WRAP (2003), *FAQ's about recycled aggregates in concrete*. Available from: http://www.wrap.org.uk/.

WRAP (2006), *Use of recycled glass*,. Available from: http://www.wrap.org.uk/.

WRAP (2007), *Performance related approach to use of recycled aggregates*. Available from: http://www.wrap.org.uk/.

Your Home (2005), *Australia's guide to environmentally sustainable homes*, *Australian Government*. Available from: http://www.greenhouse.gov.au/yourhome/index.htm.

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5

Sustainability of cement, concrete and cement replacement materials in construction

M. GLAVIND
Danish Technological Institute, Denmark

Abstract: This chapter contains information about sustainability issues relating to concrete from a life cycle perspective, with a special focus on cement and cement replacement materials. The life cycle of concrete includes the production of raw materials for concrete, production of concrete and optimisation of the mix design, construction, use, and demolition and recycling of concrete. A guideline for the application of new materials is presented. Case studies show the effect of CO_2 uptake (carbonation) on the life cycle CO_2 emissions, different green solutions for a concrete bridge and how concrete reduces the energy need for heating and cooling.

Key words: supplementary cementitious materials, CO_2 emissions and uptake, life cycle impact, energy use, concrete mix design.

5.1 Introduction

During the last century concrete has developed into the most important building material in the world. This is partly due to the fact that concrete is produced from natural materials available in all parts of the globe and partly due to the fact that concrete is a versatile material giving architectural freedom.

The production of concrete amounts to 1.5–3 tonnes per capita per annum in the industrialised world. This makes the concrete industry, including all of its suppliers a major player in the building sector. Thus, improving the sustainability of the concrete industry will automatically lead to significant improvements in the building sector as a whole. The consumption pattern and growth reflect the effort made in industrial development. The two largest countries in the world are both still seeking rapid growth and it is expected that they will strongly will contribute to a significant growth in concrete consumption in the future.

Portland cement, the primary constituent of concrete, is produced and used in large quantities, about 237 million tonnes in the European Union (ERMCO, 2006) and 2.6 billion tonnes worldwide (US Geological survey, 2006). The production of 1 kg cement generates approximately 0.8–0.9 kg CO_2 emission. Ocean Shipping Consultants of Surrey, UK (Ocean Shipping Consultants, 2006) have estimated scenarios for the growth rate of cement consumption, see Fig. 5.1. Even for the low growth rate scenario, an expansion of approximately 30% is projected to the year

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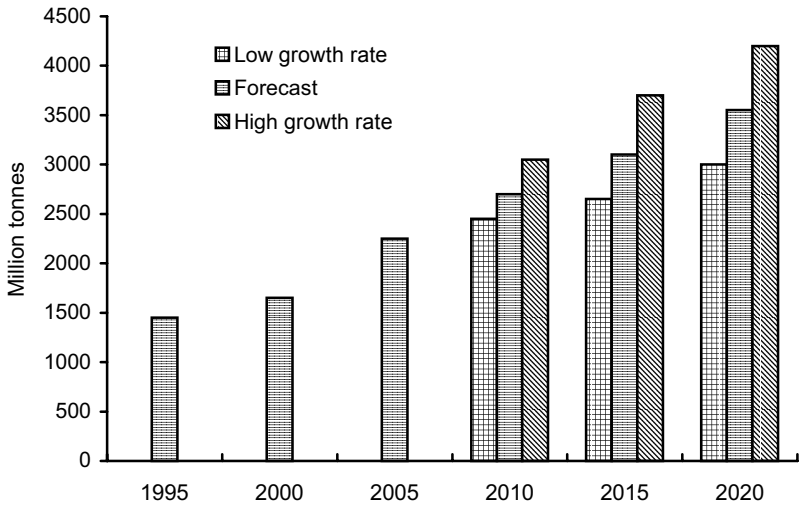

5.1 Cement consumption scenarios, (Ocean Shipping Consultants, 2006)

2020. For the high growth rate scenario, it is approximately 85%. Thus, the challenge is to meet the increasing demands for cement and concrete while reducing CO_2 emissions.

The construction industry as a whole has suffered from an image of being dirty, noisy and environmentally unfriendly, especially in 'heavy' concrete construction. This image is often based on lack of knowledge. The amount of information available regarding concrete and the environment is large, fragmented and often conflicting. Quite often it can be difficult to distinguish between knowledge and pure marketing.

Development of sustainable concrete structures – also termed 'green concrete' – has been going on for a number of years, especially in the countries where the government has a strong environmental profile like the Northern European countries. Many different tools have been developed in order to reduce the environmental profile of concrete structures. These tools and the technologies behind them vary considerably across countries and regions due to regional/national differences in legislation, market conditions and traditions in the construction industry. An important result of the work is the change of attitude in the industry from environmental matters being seen as ideological activities to taking responsibility and working systematically for the environment and the industry itself.

5.2 Life cycle aspects of concrete

In the Nordic network 'Concrete for the Environment' (Concrete for the Environment, 2003; Glavind *et al.*, 2006), a consensus was reached regarding the definition of sustainable concrete structures. The definition is based on the Brundtland

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Commission (United Nations, 1987) definition that sustainable development is 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. The definition of sustainable concrete structures reads:

> An environmentally sustainable concrete structure is a structure that is constructed so the total environmental impact during the entire life cycle, incl use of the structures, is reduced to a minimum. This means that the structure shall be designed and produced in a manner which is tailor-made for the use, i.e. to the specified lifetime, loads, environmental impact, maintenance strategy, heating need, etc. – or simply the right concrete for the right application. This shall be achieved by utilising the inherently environmentally beneficial properties of concrete, e.g. the high strength, good durability and the high thermal capacity. Furthermore, the concrete and its constituents shall be extracted and produced in an environmentally sound manner.

When assessing the environmental impact of concrete structures, it is essential to consider all life cycle phases, i.e. from cradle to grave. The life cycle of concrete products can be divided into the following life cycle phases:

- extraction and processing of raw materials;
- concrete production;
- construction;
- use;
- demolition and recycling.

It is generally accepted that most sustainability aspects of concrete may be considered under one of the following categories:

- natural resources;
- energy consumption/greenhouse effect;
- environmental effects;
- health and safety.

The resource consumption issue in relation to the application of concrete is not significant, because all the raw materials are easily accessible in surplus amounts, although in some regions natural sand and gravel are being depleted. One exception is the application of stainless steel reinforcement which requires scarce resources, i.e. chromium, nickel and molybdenum. The greenhouse effect from energy consumption is much in focus. A primary source of energy consumption is the production of cement clinker and steel reinforcement. In addition, energy resources are consumed by construction, demolition and recycling, and last but not least from the use, operation and maintenance of buildings and structures.

The environmental effects resulting from the application of concrete are, apart from the greenhouse effect, relatively poorly described. It is possible that these

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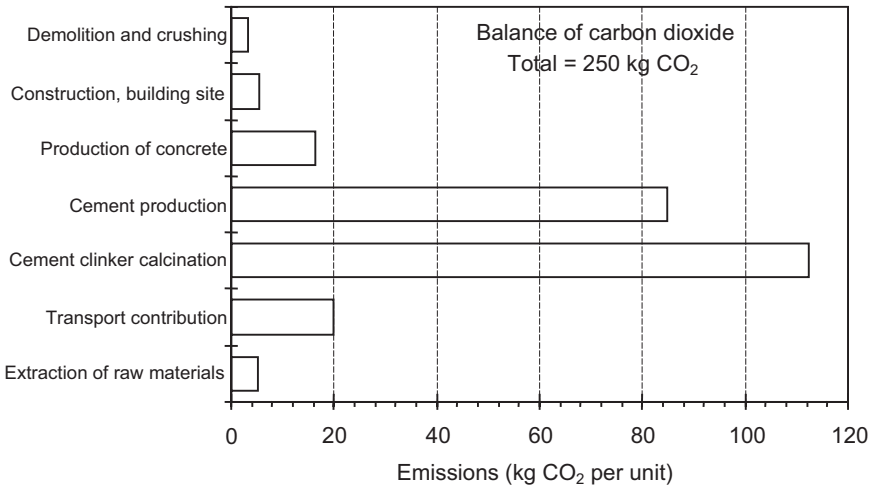

5.2 CO_2 emissions from various phases in the life cycle of a concrete product.

problems are limited, but the following potential problems have been identified:

- leaching of hydrocarbons from demolished concrete and concrete slurry;
- leaching of heavy metals from concrete and demolished concrete containing materials with high amounts of heavy metals;
- chemicals in admixtures and repair products.

The health and safety effects from the application of concrete are related to the consequences for the indoor climate and the working environment. Concrete has a bad indoor climate image and this is not justified. On the contrary, concrete is likely to be able to improve the indoor climate because of its good thermal properties. Working environment problems stem from noise, vibration, dust and accidents in the construction phase.

An example of a life cycle inventory of the CO_2 emissions of a concrete product is shown in Fig. 5.2. The functional unit is 1 m^3 concrete having 300 kg cementitious material including 80 kg fly ash. (FA) The transport contribution includes transport from the quarry to the concrete plant and from the concrete plant to the building site. Note that no contributions from the user phase are included and that the positive effect of CO_2 uptake is not taken into account.

5.3 Raw materials

Since concrete consists of a number of different constituents, the environmental impact of concrete is a complex mechanism partly governed by the individual impacts from each of these constituents and partly governed by the combined effect of the constituents when they are mixed together. The aggregate part of the

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concrete normally accounts for 70–75% of its volume and therefore the environmental issues of aggregate production strongly influence concrete production. Furthermore, cement production is associated with high energy consumption and CO_2 emissions. Thus, the sustainability of concrete as a material is strongly influenced by the cement industry and the aggregate industry. However, since concrete is most often reinforced by means of steel bars, this also needs to be included in a total sustainability analysis. The amount of steel present in a reinforced concrete structure varies according to its purpose and the design conditions, but a rebar content of 200 kg/m^3 concrete is not unusual for non-prestressed structures.

5.3.1 Cement

Production of cement

Cement is made by heating limestone and other raw materials to 1400–1450 °C in a rotary kiln. Fossil fuels such as coal and oil have usually been used to provide heat for the burning process. In the process, limestone ($CaCO_3$) first breaks down to calcium oxide (CaO) and carbon dioxide (CO_2). CaO then further reacts to form the Portland clinker. The clinker is ground with a small amount of gypsum into a powder, i.e. the cement. Some types of common cement also include other constituents in addition to clinker and gypsum such as limestone, granulated blast furnace slag, FA or other mineral by-products from industrial processes. Such cements are called blended cements, see the following section.

The most important environmental effects of cement production can be divided into:

(a) use of energy (fuel, electricity) and emissions associated with this (CO_2, SO_2 and dust);
(b) use of natural raw materials (mainly limestone).

In modern cement production the total CO_2 emission per metric tonne of clinker produced is normally 800–900 kg. Approximately 45% of this is from the calcinations process, i.e. the decarbonation of limestone.

The cement industry has over the last decades reduced the environmental impact from cement production very considerably. Cement manufacturing is a relatively energy intensive process. The very high temperatures used in the cement kiln have one great advantage: the potential for destroying hazardous waste materials such as used motor oil, spent solvents, paint residues, cleaning fluids, scrap tyres and municipal solid waste. These waste materials can be burned safely as the extremely high temperatures result in a complete combustion with very low pollution emissions; as opposed to municipal solid waste incinerators which operate at considerably lower temperatures. Indeed, for some chemicals, thermal destruction in a cement kiln is the safest method of disposal. Waste-derived fuels comprise a

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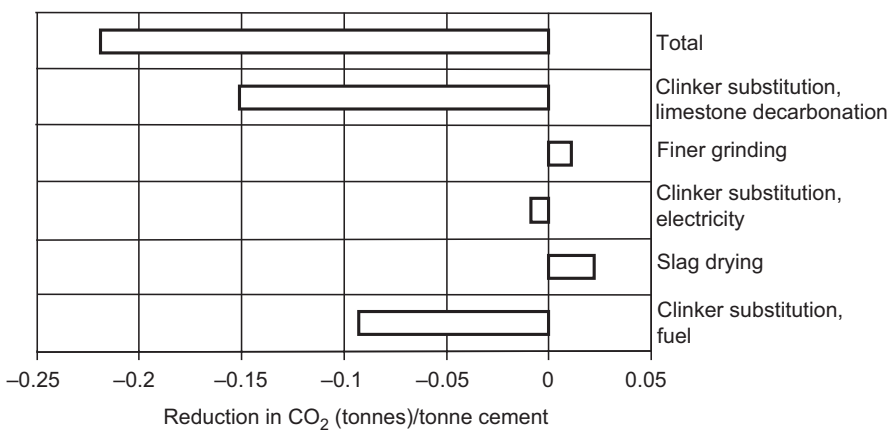
significant (and growing) part of the energy mix for cement plants. In this way, coal and oil are preserved and the cement industry help society by the destruction of waste materials.

Blended cement

Blended cements are gaining more and more markets. Blended cements are cements in which part of the clinker is substituted with other materials. Of particular significance throughout the world are granulated slag from the production of pig iron, FA and uncalcined limestone. In addition, regionally there are a growing number of mineral substances that are coming into use as cement constituents. The consumption of blended cements is currently increasing all over the world. However, there are differences regarding the cement types used in various countries, and the requirements of national industry standards also differ. The application of these standards varies from country to country, partly due to differences in standards.

Figure 5.3 shows an example of the changes in CO_2 emissions from the process of producing blended cement. This example the shows effect of the substitution of clinker by granulated slag for a CEM II/B-S 32, 5 with 35% granulated slag. It can be seen that, on the one hand, there are savings in CO_2 emissions from fuel consumption, from electricity consumption and from limestone decarbonation. On the other hand, there is an increase in CO_2 emission coming from additional thermal energy necessary for the drying of the granulated slag. Furthermore, the grinding has to be finer which again increases use of energy. However, in total, a significant reduction in CO_2 emissions is achieved.



5.3 CO_2 reductions from the production of blended cement in Germany. The example is for CEM IVB-S 32.5 cement with 35% granulated slag (Ecoserve Network, 2004a).

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In an extensive study performed by ECOserve (2004a), it is documented that the different types of blended cements have different performance characteristics regarding strength, workability and durability. Thus, it is possible to select a blended cement tailor-made for a specific application in concrete.

Modelling and testing of the leaching of concretes formed with blended cements have shown that leaching levels are the same as for Portland cement. Blended cements based on blast furnace slag show low Cr(VI) leachability resulting from the inherent reducing properties of blast furnace slag which will transform any Cr(VI) produced in the cement kiln to Cr(III), (ECOserve Network, 2004a).

New clinker types

A potential method of reducing CO_2 emissions from cement production is to develop new clinker types with alternative compositions, (Damtoft, 2007). One option, which has been extensively studied, is to produce clinker with high belite (C_2S) content. This emits only 51% CO_2 compared with 58% for alite (C_3S). However, it has not been possible to activate belite in order to achieve the same reactivity as for alite. Another option is to produce calcium sulpho-aluminate (CSA)-based clinker. Owing to cost constraints the most relevant mixtures have been of calcium silicate and CSA. These are termed 'the third cement series' in China. The drawback of CSA-based cements is that they require bauxite as the primary raw material which results in high costs. These alternatives could be the future cements, but norms and standards will have to be revised as the properties of the new clinkers will differ from conventional clinker.

5.3.2 Supplementary cementitious materials

Blending can also take place at the concrete factory, so that the concrete producer adds the supplementary cementitious materials himself. The preferred method depends strongly on local traditions, availability of materials, practical experience, material prices and the specifications given in standards.

A number of different materials are used to blend either the cement or the concrete. These materials are being used as a supplement to the clinker content/the binder matrix in the concrete, in most cases they allow the cement content to be lowered and in some cases specific concrete properties are improved. Some of the materials have a pozzolanic effect and thereby contribute to the hardening of the concrete, while others are inert.

Natural pozzolanas

Natural pozzolanas have been used since the dawn of Western civilisation, (Fidjestøl *et al.*, 2007). There are a number of sources for natural pozzolanas. The largest volumes are volcanic in origin such as the sources of Pozzuli and Thera

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(zeolite etc.), but other materials are organic such as diatomaceous earth or are found as deposits in hot springs – such as material produced in New Zealand called geosilica. The chemical activity and its rate are largely dependent on temperature and the fineness of the material. Therefore, these materials have often been considered to be slow to react, especially in colder climates.

By-product reactive materials

The most common supplementary materials in the category of by-product reactive materials are fly ash (FA), micro silica fume (SF) and ground granulated blast furnace slag (GGBS). These materials are basically industrial waste products that have been refined into beneficial well-proven supplementary materials. Other industrial waste products useful for concrete production include sewage sludge incineration ash from water treatment plants and rice husk ash from rice production.

FA and SF are pozzolanas contributing to the development of the concrete's properties (mechanical and durability properties). Their contribution is taken into account by using the *k*-value concept. However the *k*-values differ from one country to another, which is reflected in national standards.

FA from coal-fired power plants has been used in concrete for half a century and out of an annual European production of 40 million tonnes, half is used in the construction industry. The normal substitution rate is 10–20% (relative to cement weight) but experience has shown that up to 50% of the cement may be replaced with FA – the so-called high-volume FA concrete (Malhotra, 2007). FA is also the supplementary cementitious material that is available in the largest amounts. Malhotra (2007) estimates that it is safe to say that FA will be available in large amounts until at least 2050.

There are many investigations and many years of experience documenting the fact that replacing cement with FA improves the technical performance of fresh and/or hardened concrete. While FA will improve the workability of fresh concrete it also improves the durability by decreasing the concrete permeability, and by mitigating expansion due to alkali silica reaction and sulphate attack. When frost resistance is a requirement, the use of air entraining admixtures can cause problems owing to the residual coal content in the FA. The early strength of FA concrete is most often lower than that of corresponding pure Portland cement concrete, whereas the long-term strength is increased. The heat of hydration of FA concrete is low, making it well suited for mass concrete structures.

SF, a highly pozzolanic material, is a by-product from the production of silicon metal or ferro silicon alloys in smelters using electrical furnaces. It is normally not used as a cement replacement material, but as an addition, which contributes to CO_2 emissions reductions through enhancing the durability of concrete structures. SF has been used extensively for the last two decades. The current annual world production of SF is estimated at between 0.5 and 1.0 million tonnes, i.e. the

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availability of SF is very limited compared with other types of supplementary material. Therefore, SF is only expected to have a limited effect as a clinker-reducing supplementary material.

GGBS has been used as a partial replacement for Portland cement for at least a century. The annual production of blast furnace slag in Europe in 1999/2000 was about 56 million tonnes, of which 60% was granulated for use in blended cement or as a supplementary material in concrete. Germany, Belgium and the Netherlands have utilisation levels of GBFS of above 80%. The hydration of blast furnace slag in combination with Portland cement is complex, but it is well documented that concrete made with slag exhibits low heat of hydration, low permeability and improved durability in aggressive environments.

Sewage sludge incineration ash from water treatment plants has been investigated and its use in concrete applications has been found to be feasible, as described in a recent guideline (LIFE Project BioCrete, 2007). The ash can be reactive in concrete, but the degree of activity is dependent on the different burning techniques used and the source of the sewage sludge.

Rice husk ash has the potential to become an important supplementary cementitious material in the future. It is made by combustion of rice husks; if the combustion temperature is correct (below the temperature at which crystallisation occurs), the ash can have a very high SiO_2 content and show a good performance in concrete. It is not yet commercially available. The 660 million tonnes of rice grown each year give a theoretical maximum of 25 million tonnes rice husk ash (Fidjestøl *et al.*, 2007).

Nordic investigations have shown that recycled glass ground to approximately Blaine fineness, as for cement, can be used as cement replacement, (Sveinsdottir *et al.*, 1998; Hasholt *et al.*, 2004). The reactivity factor for glass filler/powder was lower than the reactivity factor for FA and the resultant strength was therefore also lower. All other concrete properties were at the same levels or better compared with the reference concrete. The price of the glass filler is relatively high, limiting its commercial use, but it can be an interesting supplementary material for white concrete because adding the glass filler does not affect the colour of the concrete.

Another organic material is bagasse, the waste from sugar cane production. The ash has a pozzolanic effect and in the future the technology to exploit this may be developed (Cordeiro, 2004).

Inert fillers

Other supplementary materials include limestone filler being used for cement and concrete production; it has been found to increase the workability and early strength, as well as reducing the compaction energy required, (ECOserve Network, 2004b). Limestone filler is receiving increased attention because of the increasing use of self-compacting concrete (SCC) where the need for fine particles to obtain adequate flow properties is essential.

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Manufactured products

Metakaolin is a highly reactive pozzolana formed by the calcinations of kaolinite (China clay). It has to be processed in a burning process like cement, although the temperature of production is between 700 and 900 °C as opposed to 1450 °C in the case of cement. Therefore, considerable CO_2 emissions are associated with the production of metakaolin. Taking this into consideration, and also bearing in mind that metakaolin is rather expensive and that only limited production is taking place, it seems unlikely that metakaolin will be a source of positive environmental impact in connection with concrete production. It might be economic in countries such as Brazil and Malaysia where the clay mineral is widely available.

5.3.3 Aggregate

Natural aggregate

Natural sand and gravel resources are being depleted in some regions and countries and the trend is towards using more crushed and manufactured aggregates as well as recycled material. Conflicts associated with land use for quarrying are common and the need for long-term planning is a pressing social, economic and political issue. The importance of mass balance and the need to reduce surplus materials is emphasised and the focus should be on no-waste production in the aggregate industry. The energy consumption for aggregate production is relatively small, compared with the energy consumption for the production of concrete but the transport of aggregates from quarry to customer has a large energy impact and is increasing. Therefore, an obvious green solution is to use local aggregates as far as possible.

Use of recycled concrete aggregates

The most comprehensive collection of research and knowledge on the use of recycled aggregates from hardened concrete has been collected under the auspices of RILEM (The International Union of Laboratories and Experts in Construction Materials, Systems and Structures) through several technical committees and a series of symposia, e.g. RILEM (2001). Several countries have implemented national standards and/or recommendations covering the production and application of recycled aggregate in concrete and road construction.

It seems that there is common agreement that the main technical problems facing further exploitation of recycled aggregate for concrete production are as follows.

1 Production aspects associated with the increased water absorption for recycled aggregate. This is particularly the case for the sand fraction.
2 The slightly lower performance of recycled aggregate concrete, depending on the degree of substitution and whether both coarse and fine aggregates are substituted.

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It seems that most of the recommendations that exist are based strongly on the RILEM specifications published in 1994 (RILEM, 1994). Here, recycled aggregate for concrete is basically categorised into three types:

- type I – primarily produced from masonry rubble;
- type II – primarily produced from concrete rubble;
- type III – mix with minimum 80% natural aggregates, maximum 10% of type I and the remaining part of type II.

When using recycled aggregates of type III, where only a part of the natural aggregates are substituted, it is assumed that the mechanical properties are unchanged from those of a conventional concrete based on natural aggregates. When a full substitution is performed strength, stiffness, creep and shrinkage properties are expected to change, which needs to be taken into account in the structural design.

5.3.4 Admixtures

The primary sustainability aspect of admixtures is the working environment. Concrete admixtures are most often based on lignosulphonates, melamine sulponates and polycarboxylates. Some of these substances contain formaldehyde, which is normally considered a harmful substance, but the concentrations are generally low (compared with limits for labelling purposes). These substances may cause problems when exposed to skin or inhaled. However, it is believed that admixtures are generally handled in a controlled manner so that the workers at the concrete plant and at the building site are not exposed to them.

In 1999, the German body of producers of chemical substances for the building sector published a state-of-the-art report on admixtures for concrete with a focus on environmental issues (Deutsche Bauchemie, 1999). The European project TESCOP also looked into the environmental impact of admixtures and concluded that the impact of admixtures on the working environment seems small compared with other topics (Glavind *et al.*, 2001).

5.3.5 Guidance for application of new materials in concrete

A number of materials are available for making sustainable concrete (as described previously in the section on Blended cement, Supplementary cementitious materials and Use of recycled concrete aggregates). However, it is important to document in advance of adding new materials to a concrete that these materials do not cause problems regarding the performance of the concrete. Table 5.1 gives an overview of all the possible properties that need to be investigated further before a new material is implemented. Of these, the properties related to durability and mechanical properties are crucial because if these are altered this has a large

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Table 5.1 Guidance for application for new materials into concrete production (Green Concrete, 2002 – www.greenconcrete.org)

PRELIMINARY EVALUATION OF SUITABILITY What constituent is to be substituted by the material?	BINDER	Cement	CHEMICAL AND MINERALOGICAL INVESTIGATION	Is the material hydraulic or inert?	PRE-TESTING OF ACTUAL CONCRETE MIX DESIGN INCLUDING CONTROL PARAMETERS, PRODUCTION AND PERFORMANCE PROPERTIES	PRODUCTION PROPERTIES	Slump	SUPPLEMENTARY TESTING (dependent on application and environmental exposure class)	MECHANICAL	Tensile strength
		Fly ash		Reactivity factor (k-factor)			Air content in fresh concrete			E-modulus
		Slag		Content of harmful substances that may impair the concrete quality and the environment			Separation			Stress–strain relationship
		Other		Content of new substances not normally found in concrete constituents			Strength development			Shrinkage/creep
							Heat development		Fire resistance	
	AGGREGATES	Fines (<4 mm)	COMPARISON WITH EN 12068	Grading curve		PERFORMANCE PROPERTIES	w/c ratio chloride and alkali content		DURABILITY	Chloride diffusion
				Absorption			Air content in hardened concrete			Carbonation
		Coarse		Alkali reactivity			Frost/thaw testing			Alkali reactivity
				Chloride and alkali content			Target strength (grade)			Sulphate resistance
							Separation tendency			
	Mixing water		Use guidelines in EN 1008							

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influence on the use of the materials. For instance, if the durability is worse the lifetime is decreased and the environmental footprint of the final concrete construction might not be as beneficial as originally intended. In addition to the flow chart, the relevant standards and specifications must of course be taken into consideration.

5.4 Manufacturing of concrete

Overall energy from manufacturing of concrete is not crucial. For concrete production the most relevant waste products to consider for reuse may stem from:

- recovered aggregate washed out from fresh concrete (rejected batches, excess production) and reused as concrete aggregates;
- washing water and water from saw cutting cleared from slurry and reused as mixing waster or washing water;
- recycled aggregate from concrete and demolition waste, i.e. hardened rubble being crushed; alternatively, recycled aggregate may be produced entirely from rejected concrete coming from ready-mix or precast plants.

5.4.1 Reusing water and aggregate

The technology for reusing water in concrete production is well known and is being widely used. Similarly, the technology for recovering aggregates from fresh concrete is straightforward, but it seems that the preferred way to dispose of rejected concrete is to let it harden and crush it for road-building purposes.

5.4.2 Environmental impact of form oils

Hydrocarbons have been detected in concrete slurry from the washing of mixers and cars, in waste concrete and in concrete waste from demolished constructions. The amounts are so high that authorities in some countries will not allow concrete slurry or waste concrete to be deposited directly on soil because of the risk of leaching of hydrocarbons to the groundwater.

The main source of the hydrocarbons is the form oils used to grease the mixers and the cars. Typically about 180 ml form oil/m^3 concrete is used. With a total annual concrete consumption of approximately 20 billion tonnes the total consumption of form oil is 1 billion m^3/year, which potentially can spread to the environment.

It is recommended that concrete manufacturers switch from mineral-based form oils to vegetable-based oils (Glavind and Nielsen, 2007). Practical experience with this substitution is in general good, however attention must be drawn to the fact that vegetable oil is organic and therefore it may rot under certain circumstances, thus producing bad smells and possible retardation of concrete surfaces. It is also

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recommended that, using education campaigns, employees are informed of the importance of being careful when handling hydraulic and lubrication oil at the production plant. It only takes a small amount of mineral oil to pollute the slurry. Finally, it is recommended that gas chromatography with mass spectroscopy (GC/MS) is used instead of gas chromatography with flame ionization detector (GS/FID) to detect hydrocarbons, because the former method can separate hydrocarbons from the free fatty acids and fatty acid esters and thereby avoid any overestimation of the hydrocarbon content.

5.4.3 Concrete plant energy

The production of concrete requires energy as for all other building materials. At the concrete plant, electricity and fuel are needed for mixers, conveyors, pumps, trucks and so on. The contribution from the concrete plant to the CO_2 footprint of concrete structures is minor compared with that of the cement production.

Even though it is important for the single concrete plant to minimise energy consumption, not only because of the environmental issues but also because of the costs, it is very difficult to describe the best method to reduce the energy consumption at a concrete plant. The methods used are very much dependent on the energy sector in each country. The use of electricity results in a range of greenhouse gas emissions depending on the various fuel types used, and these emissions vary by at least a factor of 10. It is estimated that the production of 1 m^3 ready-mix concrete requires about 100 MJ of energy and sometimes this may be doubled (fib, 2004).

5.4.4 Energy from transportation

Transportation also requires energy and thereby emits greenhouse gases. The amounts depend on the type of vehicle. A diesel truck, normally used for transportation of concrete and aggregate, emits about 0.1 kg/tonne/km while an ocean tanker emits less than one-tenth of this amount. The energy for transportation depends on the local conditions and especially the origin of the aggregates, since they constitute the major part of the concrete. On average, the transportation energy consumption is of the same order of magnitude as the concrete plant energy consumption.

5.4.5 Optimising concrete mix design

Many design models exist for optimising the mix design of concrete. The purpose of these models is primarily to be able to design concrete with specific properties and at the same time reduce its cost. In most countries the expensive concrete constituent is cement. Therefore, minimising the concrete cost in most cases also minimises its environmental impact. However, in some regions the most

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expensive part of the concrete may be the aggregate, the optimisation then becomes complicated and not as straightforward.

One way of optimising concrete composition is by optimising the aggregate in order to obtain dense packing of the aggregate particles, minimising the need for binder and thereby for cement, e.g. the Danish modification of the Linear Packing Density Model (Glavind *et al.*, 1993). Other models take into account all solid particles when calculating the optimal composition, e.g. the compressive packing model (de Larrard, 1999).

Another way of reducing the cement content in concrete is by careful use of admixtures. The development of normal and high-range water-reducing admixtures has reduced the water demand in concrete significantly and thereby also the quantity of cement. Admixtures have become normal constituents of concrete all across the world due to their obvious benefits for the manufacturers of concrete. Furthermore, new types are being constantly developed, ensuring that the price is kept at a reasonable level.

5.4.6 Self-compacting concrete (SCC) and the working environment

SCC is concrete that does not need any external energy to flow into its final position. SCC is expected to be the concrete of the future because of its advantages regarding quality, architectural freedom and, last but not least, working environment issues. The following data concerning improvements in the working environment have been documented (Nielsen, 2007).

For conventional concrete, noise and vibration are generated when the vibrators are being operated with noise levels sometimes exceeding 100 dB(A). Generally, ear protection is needed when operating poker vibrators. The same can be said about precast plants where vibration is often applied through formwork. Provided that the background noise level is low, the use of SCC can lower the noise exposure on and around the construction site to approximately one-tenth of the noise level produced when traditionally vibrated concrete is used. The reduction of noise levels will also improve the psychological working environment, improving internal communication at the site or the plant and providing less stressful surroundings, which again increases the health and safety for the workers.

Vibrations from handheld machines such as poker vibrators increase the risk of hand problems, especially problems such as poor blood circulation ('white fingers') and numbness. The use of SCC also prevents these problems. However, the main working environment improvement associated with using SCC is less lifting and improved ergonomics for the concrete workers. This is the case in particular for vertical casts (walls) where the vibration is generated by lowering and lifting the poker vibrator in the formwork. The working positions during these operations are stressful to the back.

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5.5 Construction

Environmental impacts during construction are usually not significant compared with the contributions from the other life cycle phases, see Fig. 5.2. However, there is one process that has not attracted much attention but which can result in non-negligible contributions to energy consumption (Nielsen, 1996). In some parts of the world with a humid climate and during construction of buildings, the drying of concrete can cost energy. Very often each cubic metre of concrete has a surplus water content of 30 litres which needs to be dried out before the finishing works are completed. During the winter period in particular, drying out of concrete involves large amounts of energy consumption, between 20 and 50 kW h/m^2 floor area or even higher depending on the conditions on the building site (Nielsen and Olsen, 2006). Furthermore, expenses for heating and dehumidifier equipment are added to the energy costs.

Concrete floors are left to dry out through the exposed upper surface by means of moisture diffusion which is by nature a slow process. Furthermore, the drying climate within the building is difficult to maintain due to the lack of windows, heating, etc. The best solution is the application of the so-called self-desiccating concrete. Nielsen and Olsen (2006) demonstrate how concrete mixes with water–cement ratios around 0.40 are capable of drying down to around 85% relative humidity (RH) without any exchange of moisture with the surroundings, i.e. under sealed conditions. This is due to the fact that the moisture is consumed in the hydration process and that the fine pore structure helps to lower the RH level generally. It should be noted that the self-desiccating effect depends on the alkali content of the cement used. Finally, it should also be noted that self-desiccation is taking place in all areas of the concrete and not just at a surface boundary exposed to a drying climate. For moisture-sensitive floorings, in particular, the use of self-desiccating concrete should be considered to speed up the drying.

5.6 Uses of concrete

Most of the environmental studies performed in the past 10–15 years have focused on materials and have neglected the operation and service phase, even though these phases can make the largest contribution to the total life cycle environmental impact. Furthermore, these are the phases where concrete can be used to solve environmental problems and minimise environmental impact. It is important to consider this life cycle phase in order to optimise a concrete structure, because a solution that appears to be green from a materials point of view can be a not-so-green solution when the later life cycle phases are taken into account. A very green material can result in a not-so-green construction if the durability is worse when compared with a traditional material.

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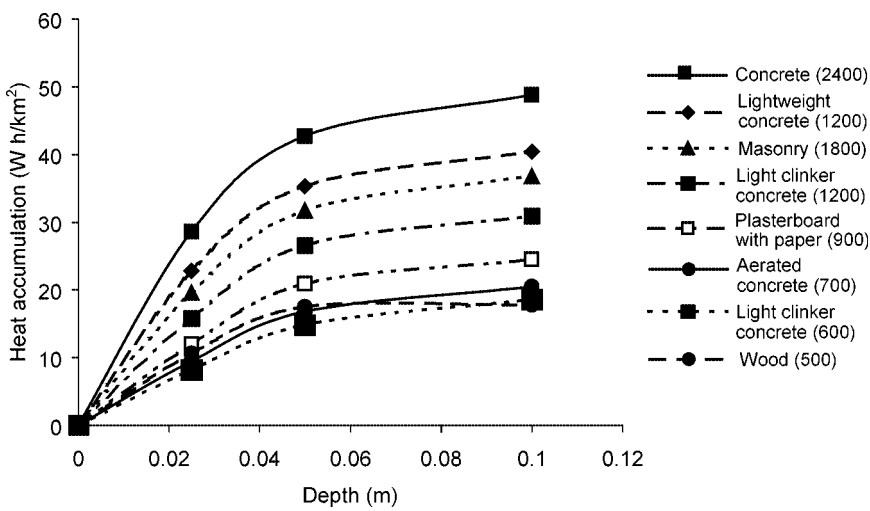
5.6.1 Buildings

Energy

For building, the user phase is typically the largest CO_2 contributor. The energy use for heating and cooling amounts up to about 40% of the total energy consumption. The energy performance of buildings is in many countries regulated by the authorities; however, increasing energy prices stimulate further improvement on a voluntary basis. Concrete and other heavyweight building materials have a beneficial effect on the energy performance and thermal comfort of a building due to their high thermal mass. This effect has been the subject of a number of recent investigations, see for example Biasoli and Oberg (2007), Olsen and Hansen (2007), and Portland Cement Association (2008).

The thermal storage effect depends on the effective heat capacity, i.e. the share of the total heat capacity that contributes to the heat exchange between the structure and the indoor air, during temperature cycles. Furthermore, the concrete surface must be exposed, otherwise the storage effect drops accordingly. Figure 5.4 shows the heat capacities of a number of building materials. It is obvious that concrete, especially normal weight concrete, has the largest heat accumulation capacity and that the effect is almost proportional to the density of the material. Heat penetrates the materials from the surface to a certain depth of the material. Because of the relatively high heat accumulation of concrete, the heat will penetrate relatively deep into concrete slabs and walls. Therefore, a larger part of the material can be utilised compared with materials with lower heat capacity.



5.4 Heat accumulation as a function of the depth of the materials. In the key, the figures in parentheses show the density of the materials (in kg/m³) (Olsen and Hansen, 2007).

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Calculations in various studies show that reductions of approximately 5–15% in the energy requirements for heating and cooling can be achieved when using concrete compared with lightweight building materials. The exact savings depend on the climate, the orientation (north, south, east or west) of the house, how much of the concrete surface is exposed, the ventilation system, etc. Furthermore, concrete can result in improved thermal comfort, because temperature variations are reduced. During the daytime, with sunshine and heat support from electrical devices and people, the temperature in the concrete will increase. Later the heat support drops and the heat transport changes so that the concrete gives back the stored heat to the room. This effect is useful both during winter and summer. The good thermal properties of concrete may also be used for active heat storage, where heating or cooling energy is being transported within pipes or canals in the concrete.

Indoor climate

Concrete is often accused of being bad for the indoor climate, i.e. for emitting volatile substances that deteriorate the air quality. However, there is no evidence for this statement. Several studies has provided evidence that concrete can not be accused of creating a bad indoor climate; see, for example, Concrete thinking (2008) or Bødker (2006), a study for the Danish Environmental Protection Agency. Specifically, it has been documented that concrete does not emit alcohols, aldehydes or amines in any significant amounts. The tests were performed in a climate chamber following EN 131419 and in a sensoric investigation with a test panel of 20 people. All the concrete types tested fulfilled the requirements for receiving the Danish Indoor Climate Label.

Concrete cast with mineral-based form oil does emit volatile hydrocarbons. However, it is not expected that this causes any problems in a building since the amounts are almost negligible after 28 days. When using FA, the emission of small amounts of ammonium can occur, although these emissions are insignificant after a few days. Concrete can even be an advantage for the indoor environment, because it can level out large temperature differences thus contributing to improved comfort for the inhabitants.

5.6.2 Civil structures

For civil structures, the key sustainability issues are durability together with mechanical strength and stiffness. It is also often important for a building owner to obtain a design with minimum maintenance requirements during its service life. Maintenance and repair of civil structures are often difficult to carry out and the users, e.g. traffic, of the structure are disturbed.

It is possible to reduce the environmental impact of buildings by optimising the construction (Glavind *et al*., 2005). A significant reduction of CO_2 emissions can

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be achieved by substituting traditional steel reinforcement with stainless steel reinforcement, which reduces maintenance activities. However, this approach should be used with care because the production of stainless steel uses scarce resources such as molybdenum, nickel and chromium.

Another structural design solution is to construct a bridge without asphalt and a moisture barrier. This saves materials and energy both during the construction and when repairing. However, the performance requirements for the concrete surface are even stricter than for normal bridge decks because the traffic will drive directly on the surface and the surface is directly exposed to weather conditions, de-icing salting, etc.

Other approaches are to design a structure in such a way that it is easy to substitute single parts of the construction. These single parts should be the parts that are most exposed; for a road bridge, for example, the most exposed parts are the columns and edge beams. The use of permanent formwork is also an alternative strategy, where a concrete with a lower quality and thereby reduced environmental impacts as a result.

As for buildings, the use of the civil structure can be the dominant factor when considering the environmental impact over the life cycle. For roads this concerns the traffic, and here it seems that it might be possible to have an impact on the energy consumption from traffic by using concrete, because it is harder to drive on and does not get deformations, and thereby saves on fuel use in cars and trucks.

5.6.3 Solving problems with cement and concrete

Concrete and cement can be used creatively to solve waste and pollution problems, to achieve energy efficient and comfortable buildings and to increase the service life, as described in previous sections. However, they can also be used to solve environmental problems by, for example, stabilising or encapsulating environmentally harmful substances. Examples of this are the use of concrete containers for storing radioactive waste in Russia, and the stabilisation of contaminated sediments in Norwegian harbours using cement (Gran, 2003; Linders, 2003).

5.7 Demolition and recycling

When a structure reaches the end of its service life it is demolished. The annual production of construction and demolition waste is huge; in Europe it is around 180 million tonnes and the figure is expected to increase significantly (ECOserve Network, 2006). Construction and demolition waste, especially from concrete buildings and structures, is highly recyclable when it is sorted and crushed down to usable fractions. However, the demolition and crushing processes require energy and lead to CO_2 emissions. Therefore, recycling of crushed concrete is most valuable where the transport distance between demolition site and the new application is small.

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Recycling of crushed concrete back into concrete production is possible, see previous section on Use of recycled concrete aggregates. However, until now the primary application of crushed concrete has been for construction purposes such as back-fill and road construction where it is a substitute for natural aggregates.

5.7.1 CO_2 uptake during carbonation

During the service life of a concrete structure the carbonation process is generally unwanted as it causes passivation of the alkalinity of the concrete cover and increases the risk of corrosion of the reinforcement. However, in many cases concrete serves in rather protected environments such as indoor applications. There is also a huge amount of unreinforced concrete where corrosion is not an issue. The amount of re-absorbed CO_2 during the service life is typically low. This is due to the fact that only the surface of the concrete is in contact with the atmosphere and not the bulk of the material. The rate of carbonation depends on the concrete quality, on the use of supplementary cementitious materials and on the environment, as described by Lagerblad (2005).

However, when a concrete structure is demolished and crushed the specific surface area of the concrete is multiplied significantly and the carbonation rate accelerates accordingly. It is an effect that has been overlooked in the past but has recently gained more and more attention and some of the studies performed indicate that it is an effect that can have a large effect on life cycle screenings where the CO_2 emission is overestimated if the CO_2 uptake is not subtracted; see, for example, the Nordic study by Pade and Guimaraes (2007) and the North American study by Gajda and Miller (2000). The two studies using somewhat different approaches both arrived at similar percentages of concrete volume to be carbonated during service life, i.e. 27–28% and 28–39%, respectively (see Fig. 5.5). In the Nordic study taking into account secondary life involving crushing of demolished concrete, the percentage of carbonated concrete in 100 years increased up to 86% in the country with the highest rate of crushing of demolished concrete, see Fig. 5.5. Between 33 and 57% of the CO_2 emitted from calcinations in cement production will have been taken up during 100 years.

5.8 Case studies

5.8.1 Effect of CO_2 uptake for a roof tile and a concrete edge beam

Figures 5.6 and 5.7 show the effect of CO_2 uptake on the life cycle of a 1 m (in length) highway edge beam and 1 m^2 roof tile, respectively (Pommer and Pade, 2005). The CO_2 balance of the edge beam is estimated based on 70 years of service life and 30 years of secondary life following demolition and crushing, whereas the

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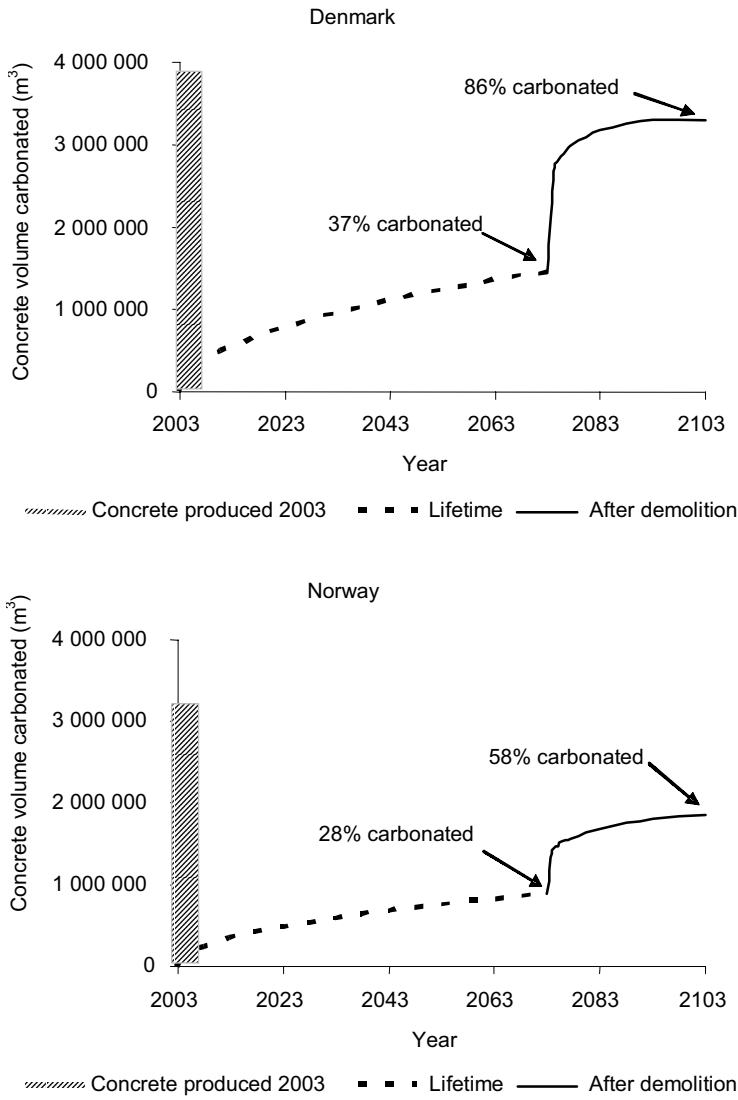

5.5 Carbonation of concrete produced in Denmark and Norway in the year 2003 (Pade and Guimaraes, 2007).

balance of the roof tile is based on 50 years of service life and 50 years of secondary life following demolition and crushing.

It can be seen that by taking CO_2 uptake from carbonation into account the CO_2 balance over 100 years is reduced by 18% and 28% for the edge beam and the roof tile, respectively. As both the edge beam and the roof tile are made from mix compositions corresponding to strengths higher than 35 MPa, the carbonation rates are low. Thus the majority of the carbonation takes place after demolition and

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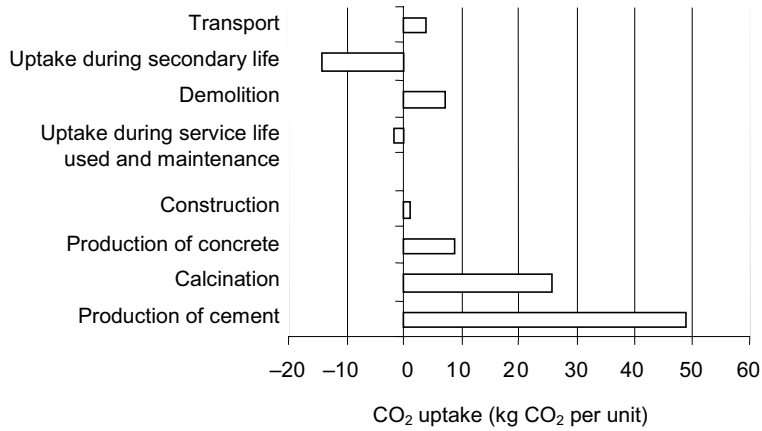
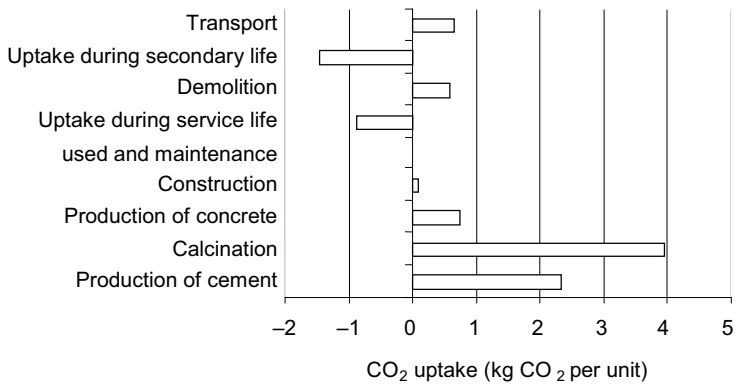


5.6 CO_2 balance of a highway edge beam. The mass of one unit is 502 kg, corresponding to 1 m of the edge beam (Pommer and Pade, 2005).



5.7 CO_2 balance of a roof tile. The mass of one unit is 42 kg ,corresponding to 1 m^2 of the roof tile (Pommer and Pade, 2005).

crushing, i.e. the particle size reduction from crushing is essential to obtaining a high CO_2 uptake for these two particular concrete products.

5.8.2 Concrete bridge with various green solutions

In the Danish Centre for Green Concrete, an extensive study was performed on different sustainable solutions (Damtoft *et al.*, 2001; Tølløse, 2002). One of these investigations involved a highway road bridge where different concrete compositions and structural solutions were tested. Figure 5.8 shows the CO_2 emissions of the bridge in its estimated lifetime of 74 years. The first three columns represent three different material solutions and traditional structural design, i.e. the first

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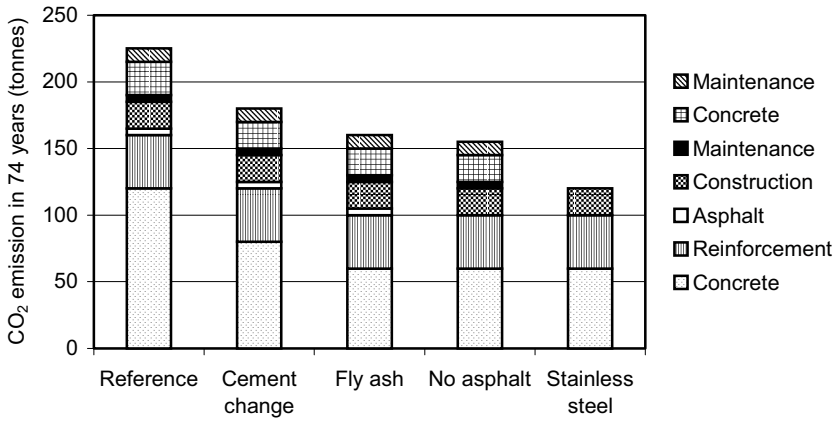

5.8 CO_2 emissions for different green solutions related to concrete mix design and structural solutions for a highway road bridge in Denmark (Tølløse, 2002).

column represents a reference bridge, the second column a bridge where the traditional bridge cement has been changed to a cement with reduced environmental impact and the third column where the cement change has been produced by substitution of part of the cement with fly ash. Columns four and five represent two different structural solutions where the concrete mix design is that with the least CO_2 emission, i.e. the mix in column three. The fourth column is based on a bridge with no asphalt and moisture barrier, i.e. where the cars and trucks are driving directly on the concrete bridge deck. The fifth column represents a bridge where the traditional black reinforcement has been substituted with stainless steel. It is estimated that this solution will eliminate the need for maintenance and repair. Table 5.2 gives an overview of the different green solutions.

It can be seen from Fig. 5.8 that it is possible to obtain significant reductions in CO_2 emissions by implementing the different green solutions and that both the concrete mix designs as well as changes in structural design are factors in these reductions. It should be noted that systematic testing of the concrete mixes in the laboratory has shown that the concrete mix designs have the same performance in relation to durability and mechanical properties. The only drawback of the change in concrete mix design is challenges in casting and optimising the chemical admixtures. The solutions have been tested in a real highway concrete bridge in Denmark and inspection after 5 years in use confirms the results of the laboratory testing.

5.8.3 Reduction of energy for heating and cooling

Investigations into the differences in heating and cooling requirements for an office building made of different material combinations were carried out by Olsen

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Table 5.2 Overview of green solutions for a highway road bridge in Denmark (Tølløse, 2002)

Green solution	Bridge cement (kg/m^3)	Cement with reduced environmental impact (kg/m^3)	Fly ash (kg/m^3)	Micro silica (kg/m^3)	Chemical admixtures (kg/m^3)	Aggregate (kg/m^3)	Equivalent wc	Structural design change
Reference	288	–	34	17	3.6	1786	0.45	–
Cement change	–	287	32	17	3.6	1733	0.47	–
Fly ash	–	189	137	18	9.3	1739	0.46	–
No asphalt	–	189	137	18	9.3	1739	0.46	No asphalt at bridge deck
Stainless steel	–	189	137	18	9.3	1739	0.46	No asphalt at bridge deck unless specified

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Table 5.3 Energy requirements (in kW h/m²)

Forced ventilation	Sun exposure	Heat capacity			
		Extra light (40 kW h/m²)	Medium light (80 kW h/m²)	Medium heavy 120 (kW h/m²)	Extra heavy (160 kW h/m²)
No	Medium	108.6	102.1	98.4	95.9
No	High	123.0	116.1	111.7	108.9
Yes	Medium	103.9	97.4	91.5	90.5
Yes	High	118.7	111.6	105.6	103.9

Table 5.4 Surplus heat (in kW h/m²)

Forced ventilation	Sun exposure	Heat capacity			
		Extra light (40 kW h/m²)	Medium light (80 kW h/m²)	Medium heavy 120 (kW h/m²)	Extra heavy (160 kW h/m²)
No	Medium	12.3	10.4	9.1	8.1
No	High	11.5	9.7	8.4	7.3
Yes	Medium	5.2	3.2	0.0	0.0
Yes	High	5.2	3.1	0.0	0.0

and Hansen (2007). The office building was a two-storey building with a total area of 400 m². Calculations were made for different scenarios of heat capacity, where the categories 'medium heavy' and 'extra heavy' correspond to a building where the main building materials are concrete. Other variations in the calculations included whether forced ventilation was used or not and whether the sun exposure was medium or high. The results for the energy requirements are shown in Table 5.3 and those for surplus heat are given in Table 5.4. The results show that in this specific case it is possible to achieve a significant reduction of the energy required for heating by using building materials with a high thermal mass. Reductions vary between 11 and 13% for the 'extra light' and the 'extra heavy' scenarios. In general, the energy requirement is lowest when forced ventilation is used and when the sun exposure is medium. Regarding the amount of surplus heat that has to be removed, this was highest in the extra light building with no forced ventilation and medium sun exposure, and lowest in the heavy and extra heavy buildings with forced ventilation. As an overall conclusion the results show that it is possible to exploit the good thermal properties of concrete to reduce the energy required for heating and cooling.

5.9 Future trends

Although much work has been done already to document and improve the environmental performance of concrete structures, the effort must continue because of the challenges that the concrete industry is facing. It is believed that the areas for

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future work regarding sustainable concrete structures will include the following.

1 A change from materials development to a holistic approach focusing on optimising the concrete structure during its entire life cycle. When assessing the environmental performance of a concrete structure the total structure in which the concrete is used should be considered. This includes the environmental impact associated with production of the various constituent materials, construction of the structure, use, maintenance, demolition and finally recycling of the demolished materials.
2 A change from a problem-solving approach to an approach utilising the environmentally beneficial properties of concrete, i.e. where concrete can be used to improve the environment. This is especially the case regarding energy, where attention in the future will be upon exploitation of the excellent thermal capacity of concrete. Concrete structures will help to reduce the energy needed for cooling and heating and at the same time ensure a good indoor climate.
3 The work related to the use of recycled materials and by-products will continue as it is an important and effective way of reducing the environmental impact of concrete and concrete structures, and because there is still unexploited potential in this area. The increased use of SCC and the consequent increased need for fines will drive this development.
4 Further documentation is required on CO_2 uptake and also guidance in the acceleration of this without altering the durability of the concrete and the recycling possibilities. This will be of benefit to overall CO_2 burden of the cement and concrete industries and also to life cycle assessments, for example when a choice has to be made between concrete and other building materials.
5 In the next generation of standards, it is expected that pure technological requirements will be supplied by environmental requirements. Furthermore, it is expected that there will be more focus on performance-based specifications rather than prescriptive design.

5.10 Sources of further information and advice

Much work is being carried out within the various industrial associations for cement and concrete, resulting in the formation of environmental work groups and the publication of environmental reports, for example:

- www.ermco.org;
- www.bibm.org;
- www.cembureau.eu;
- www.concretethinking.org;
- www.concrete.org;
- www.cement.org.;
- www.sustainableconcrete.org;
- www.sustainableconcrete.org/nz.

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In addition, international organisations such as fib and RILEM have formed a number of environmental task groups, see, for example, www.fib.epfl.ch and www.rilem.net.

5.11 References

Biasoli, F and Oberg, M, (2007), 'Concrete for energy efficient and comfortable building', in Proceedings of the International Conference on *Sustainability in the Cement and Concrete Industry*, Norway, pp. 593–600.

Bødker, J (2006), 'Emissions from concrete to the indoor environment' (in Danish), Report no. 18, Danish Environmental Protection Agency, Copenhagen, Denmark.

Concrete for the Environment (2003), A Nordic network, Newsletter 2003, www.concretefortheenvironment.net.

Concrete thinking (2008), 'Sustainable development with concrete', www.concrete thinking.org.

Cordeiro, G C (2004), 'Influence of mechanical grinding on the pozzolanic activity of residual sugarcane bagasse ash', in Proceedings of the International RILEM Conference on *The Use of Recycled Materials in Buildings and Structures*, Spain, pp. 731–740.

Damtoft, J S, Glavind, M and Munch-Petersen, C (2001), 'Danish Centre for Green Concrete', in Proceedings of the Third CANMET/ACI International Symposium on *Sustainable Development of Cement and Concrete*, Supplementary papers. pp. 401–419.

Damtoft, J S (2007), 'The sustainable cement production of the future', in Proceedings of the International Conference on *Sustainability in the Cement and Concrete industry*, Norway, pp. 75–85.

de Larrad, F (1999), *Concrete Mixture Proportioning – A Scientific Approach*, E&FN Spon, London.

Deutsche Bauchemie (1999), 'Concrete admixtures and the environment', State-of-the-art report, Deutsche Bauchemie, Frankfurt, Germany.

ECOserve Network (2004a), 'Cluster 2 production and application of blended cements', www.ecoserve.net.

ECOserve Network (2004b), 'Cluster 3, baseline report for the aggregate and concrete industries in Europe', www.eco-serve.net.

ECOserve Network (2006), 'Cluster 3, best available technology report for the aggregate and concrete industries in Europe', www.eco-serve.net.

ERMCO (European Ready Mixed Concrete Organization) (2006), 'Statistics 2006', www.ermco.org.

fib (2004), 'Environmental design', fib Bulletin no. 28, Federation International du Beton, Lausanne, Switzerland.

Fidjestøl, P, Dåstøl, M and Nielsen, T (2007), 'Sustainability of concrete construction', in Proceedings of the International conference on *Sustainability in the cement and concrete industry*, Norway, pp. 85–95.

Gajda, J and Miller, F M (2000), 'Concrete as a sink for atmospheric carbon dioxide, a literature review and estimation of CO_2 absorption by Portland cement concrete', R&D serial no. 2255, PCA, Chicago, USA.

Glavind, M, Olsen, G S and Munch-Petersen, C (1993), 'Packing calculations and concrete mix design', Nordic Concrete Research Publication no. 13, The Nordic Concrete Federation, Espoo, Finland, pp. 22–34.

Glavind, M, Damtoft, J S and Röttig, S (2001), 'Cleaner technology solutions in the life cycle of concrete products', in Proceedings of CANMET/ACI International Symposium for

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Sustainable Development of Cement and Concrete, San Francisco, USA, pp. 313–329.
Glavind, M, Mathiesen, D and Nielsen, C V (2005), 'Sustainable concrete structures – a win–win situation for industry and society', in *Achieving Sustainability in Construction*, Thomas Telford Publishing, London.
Glavind, M, Mehus, J, Gudmundson, G and Fidjestøl P (2006), 'Concrete – the sustainable construction material', *Concrete International*, **28**(5), 41–44.
Glavind, M and Nielsen, C V (2007), 'New knowledge on healthy and environmentally friendly concrete', featured at the 3rd International Symposium on *Sustainability in Cement and Concrete*, Istanbul.
Gran, H C (2003), 'Concrete solutions for containment of nuclear waste', presentation at Nordic seminar *Concrete – the sustainable material*, Oslo, Norway.
Hasholt, M T, Mathiesen, D, Hansen, H and Thøgersen, F (2004), 'Metoder til genanvendelse af farvede glasskår til produktion af tegl og beton og til vejbygning – fase 2' (in Danish), The Danish Environmental Protection Agency, Copenhagen, Denmark.
Lagerblad, B, (2005), 'Carbon dioxide uptake during concrete life cycle – State-of-the-art', CBI Report 2, Swedish Cement and Concrete Institute, Stockholm, Sweden.
LIFE Project BioCrete (2007), 'Bio ash in concrete – a guideline', www.biocrete.dk/english.
Linders, H (2003), 'Trondheim Harbor – containment of polluted sediments with cement', presentation at Nordic seminar *Concrete – the sustainable material*, Oslo, Norway.
Malhotra, V M (2007), 'Global warming and sustainability issues related to concrete technology', in Proceedings of the International Conference on *Sustainability in the Cement and Concrete Industry*, pp. 17–27.
Nielsen, L O (1996), 'Interaction between microclimate and concrete – a prerequisite for deterioration', *Construction and Building Materials*, **10**(5), 301–308.
Nielsen, C V and Olsen, L (2006), 'Drying of concrete' (in Danish), Report no. 37, Danish Environmental Protection Agency, Copenhagen, Denmark.
Nielsen, C V (2007), 'Does SCC really improve the working environment?', in Proceedings of the Fifth International RILEM Symposium on *Self-Compacting Concrete*, Volume 2, pp. 967–975.
Ocean Shipping Consultants Ltd (2006), 'Press release announcement, Global cement to 2020', Ocean Shipping Consultants Ltd, Surrey, UK.
Olsen, L and Hansen, M L S (2007), 'Heat storage in concrete' (in Danish), Danish Environmental Protection Agency, Copenhagen, Denmark.
Pade, C and Guimaraes, M (2007), 'The CO_2 uptake of concrete in a 100 year perspective', *Cement and Concrete Research*, **37**(9), 3–12.
Pommer, K and Pade, C (2005), 'Guidelines – uptake of carbon dioxide in the life cycle inventory of concrete', Danish Technological Institute, Denmark, www.teknologisk.dk.
Portland Cement Association (2008), Concrete homes save energy, www.cement.org.
RILEM (1994), 'RILEM recommendation, TC-121, Specifications for concrete with recycled aggregates', *Materials and Structures*, **27**(9), 557–559.
RILEM (2001), *Sustainable Raw Materials – Construction and Demolition Waste*, Report 22 (eds Ch F Hendriks and H S Pietersen), RILEM Publications, Bagneax, France.
Sveinsdottir, E L, Wallewik, O and Gunnarsson, G (1998), 'Recycled fines in concrete – Icelandic materials', The Icelandic Building Research Institute, Reykjavik, Iceland.
Tølløse, K (2002), 'Environmental screening of a concrete bridge' (in Danish), Centre for Green Concrete, Danish Technological Institute, Denmark.
United Nations (1987), 'Our common future, report of the World Commission on Environment and Development', General Assembly Resolution 42/187, United Nations, Geneva.
US Geological Survey (2006), 'Cement statistics 2006', www.minerals.usgs.gov.

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6

Sustainability of metals and alloys in construction

P. LAMBERT
Sheffield Hallam University, UK

Abstract: Metals and alloys have played an important role in the development of society from the iron age onwards. The materials employed from the industrial revolution onwards do not exist in nature. Because of their inherent value, recycling has long been a part of the life cycle for metallic objects. Most alloys in common use are based on iron which can quickly revert back to more stable but less useful compounds through the process of corrosion. Preventing this corrosion offers the most cost- and energy-efficient route to sustainability.

Key words: metals, alloys, ferrous alloys, stainless steel, scrap, corrosion, protection.

6.1 Introduction

Unlike most manufactured materials, metals have a long and successful history of recycling. Largely due to the significant inherent value of metals, scrap dealers have been an integral part of industrialised society since Georgian times. With the notable exception of gold and the occasional chunk of meteoric iron, metals are essentially as artificial to nature as plastic bags. Within the earth most metals only exist in stable combined states with other elements such as oxygen and sulphur. Iron, as an example, can be found as an oxide such as hematite or as a sulphide as in pyrite, the infamous 'fool's gold'.

Once we acknowledge the artificial nature of metals it is easier to appreciate the problems of oxidation and corrosion, when these essentially unstable materials convert back to the more stable compounds from which they were refined. Corrosion is a natural and normal process, reverting the metals to their lowest energy state. Ferrous or iron-based alloys such as steel can be considered to have a similar life cycle to their masters, we humans. Once 'born' their lifespan is dependent upon the appropriateness of the tasks they are given to perform and how well they are treated. Put to good use and properly cared for they can last to 100 years and beyond. Gold remains all but immortal and is treated accordingly.

The remainder of this chapter will address the matter of the birth, life, death and reincarnation (i.e. life cycle assessment) of metals and how this may act as a blueprint for the reuse and recycling of other material types.

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6.2 Ferrous alloys

Ferrous alloys, notably steel but initially also cast and wrought iron, represent the most important family of metallic materials. Iron-based materials account for by far the greatest proportion of manufactured metal items. Their popularity is more than just a simple matter of being relatively cheap or plentiful. Iron and steel offer a range of properties that fit well with the requirements of the manufactured world. They are relatively easy to form, are tough and forgiving in service, resist wear and damage and despite the occasionally bad press can be made sufficiently resistant to corrosion to give adequate service. They are also, and have always been, recyclable – with around 75% of feedstock for the production of new alloys coming from scrap.

The first iron was extracted by smelting iron oxide, much in the same way that copper alloys had been produced since the Bronze Age, the difference being the higher temperature required for iron. While copper melts at a little over 1000 °C, the melting point of iron is 1538 °C but fortunately drops to 1370 °C when alloyed with carbon at 1.7% or higher to produce cast iron, the mainstay of the eighteenth century's industrial revolution in manufactured goods.

6.2.1 Cast iron

With its historical roots in first-century China, cast iron became a key element of the industrial revolution. First with cannon and shot, then with pots and pans, cast iron allowed the mass production of durable goods for trade and conquest. Early cast irons were strong, hard and brittle. When fractured the rough surface caused by the flakes of graphite in the structure appears grey, hence grey cast iron. Lower silicon plus faster cooling produces an even stronger structure with more dispersed carbon that appears lighter when fractured, known as white cast iron. Further developments in composition and heat treatment lead to the production of tougher, less brittle cast irons with some ductility. More recent modifications through the addition of nickel have allowed the production of cast irons with exceptional strength and enhanced high-temperature properties (Elliot, 1988).

6.2.2 Wrought iron

While cast iron is strong, hard and resistant to wear, it is difficult to form other than by casting and can be brittle. Very early on it was recognised that a more malleable material would have its own benefits in many applications and wrought iron satisfied that need. Wrought iron, literally 'worked' iron, has a much lower carbon content, typically 0.15%, and has the ability to be hot worked to produce a wide range of functional and decorative objects in the hands of a skilled blacksmith.

Dating back to pre-Roman times, wrought iron was originally made by smelting iron ore with charcoal, a process by which the mixture is taken to just below the

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melting point of the iron resulting in a spongy mass or 'bloom' of iron and slag (a mixture of oxides, silicates and other impurities). Provided the iron does not melt, the carbon content remains low. There remains, however, the problem of the slag. Mechanically working the bloom removes the majority of the slag, leaving behind a relatively soft and malleable iron interspersed with fine slag inclusions producing the familiar fibrous structure of wrought iron.

The process for the manufacture of wrought iron was continually improved from the Middle Ages onwards until by the start of the twentieth century it could be produced quickly and cheaply in a near-continuous industrial process. While the attraction of wrought iron as a decorative material remains, its manufacture started dying out in the 1960s and has now all but disappeared, having been largely replaced by low-carbon steel (Kuhn, 1982).

6.2.3 Steel

The universally familiar steel is a simple alloy of iron and carbon. Other alloying elements such as manganese, silicon, copper and tungsten are commonly also present and can improve or modify the characteristics of the steel. A small amount of manganese is added to reduce the embrittling effects of iron sulphide during secondary steelmaking processes and to ensure low-temperature toughness. Low-carbon or 'mild' steels have carbon contents of 0.05–0.3% so the high-carbon pig iron produced by smelting iron ore and coke must be further refined. In this instance, 'low carbon' refers to a metallurgical necessity rather than a measure of its sustainability credentials.

The greatest benefit of low-carbon steel is its ability to be cut, shaped and joined with relative ease to produce a wide range of products. Where welding is required, the carbon content is kept below around 0.25%. The ductility of mild steel allows the forming of complex shapes and ensures that yielding occurs prior to failure, a valuable attribute when trying to avoid sudden and catastrophic failure of components and structures.

The biggest potential drawback to employing simple low-carbon steel is its need to be protected from the effects of moisture and oxygen leading to corrosion. While paints and greases can be used to great effect to prevent this occurring, there has long been an interest in more highly alloyed steels that can impart a degree of corrosion resistance without the need for protective coatings.

6.3 Stainless steel

Stainless steels offer significantly improved corrosion resistance, mainly through the addition of chromium. Stainless steels typically have 10% chromium content but can contain anywhere from 4 to 30%. The chromium allows the formation of a thin and protective film of chromium (III) oxide no more than 5 nm thick on the surface of the alloy. The film can repair itself provided there is oxygen. In addition

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to enhanced corrosion resistance properties stainless steels can show superior ductility and toughness when compared with conventional steels.

Because of their untarnished appearance, particularly the ferritic and austenitic grades, stainless steels are often employed for aesthetic uses where the additional cost may be easier to justify. The inclusion of significant levels of chromium and other relatively expensive alloying elements increases their value, both as stock material and as scrap for recycling, with the potential negative consequences of theft and pilfering.

In addition to chromium, a range of other alloying elements are commonly encountered in stainless steels, notably nickel but also including molybdenum, titanium and copper, as well as carbon and nitrogen as would be found in conventional steels. Three basic types of stainless steel are available, identified by their crystal structure:

(a) ferritic, such as the purposely confusing '18-0' grade used in utility cutlery;
(b) austenitic, which includes the well-known and respected '18-8' grade;
(c) martensitic, a heat-treatable engineering steel, often with little or no aesthetic appeal, but good for making cutting blades.

In addition to these three main types there are two variants, precipitation-hardened and duplex or super-duplex stainless steels (Beddoes & Parr, 1999).

Because of their improved corrosion properties, stainless steels have the potential to offer a more sustainable option where long, low-maintenance service life is of benefit. There is an additional cost but this is usually more than offset by the longer life and reduced need for additional protection measures such as coatings. Given their potentially greater importance as we move away from a period of built-in obsolescence and a throw-away culture it is worth considering this family of materials in greater depth.

6.3.1 Ferritic stainless steel

Ferritic stainless steels are magnetic, non-heat-treatable steels that contain 11–30% chromium but with little or no nickel. They are typically employed for non-structural applications where there is a requirement for good general corrosion resistance or good stress corrosion resistance (an unfortunate synergy of stress and corrosion leading to accelerated failure), such as in sea water applications, and can be useful for internal and decorative applications where aesthetics are the main consideration.

Ferritic stainless steels have good heat and corrosion resistance, in particular they are highly resistant to chloride stress corrosion cracking although their mechanical properties, such as low-temperature toughness, are generally poorer than austenitic grades. The corrosion performance is also poorer than the austenitic grades and they are more difficult to weld with a greater risk of weld sensitisation unless stabilised by alloy additions. With a maximum nickel content of 0.5% they

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Table 6.1 Classification and composition of common ferritic stainless steels

EN	BS	AISI	En	DIN	SS	Typical composition (%)				
						C	Cr	Ni	Mo	Other
1.4000	403S17	410S		X6Cr13	2301	0.08	12			
1.4002	405S17	405		X6CrAl13		0.08	12			0.2 Al
1.4003				X2Cr11		0.03	11	0.5		
1.4016	430S17	430	60	X6Cr17	2320	0.08	17			
1.4113	434S17	434		X6CrMo17-1		0.08	17		1	
1.4509						0.015	18			Nb, Ti
1.4510		430Ti		X6CrTi17		0.05	17			0.6 Ti
1.4511		430Nb		X6CrNb17		0.05	17			0.6 Nb
1.4512	409S19	409		X6CrTi12		0.03	11			0.5 Ti
1.4521		[444]		X2CrMoTi18-2		0.025	17			0.6 Ti

EN, Euro Norm; BS, British Standard; AISI, American Iron and Steel Institute; En, old EN designation; DIN, German Standard; SS, Swedish Standard.

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are significantly less expensive than austenitic grades and less prone to the price fluctuations associated with the volatile international nickel market. Table 6.1 gives the composition for a range of ferritic stainless steel grades, together with a range of international classifications. Where grades are quoted in the text the European Standard (EN) classification is given, followed by the American Iron and Steel Institute (AISI) equivalent in brackets.

The most commonly used grades of ferritic stainless steels are Types 1.4512 (409) and 1.4016 (430). Type 1.4512 is titanium stabilised to prevent sensitisation of welds and is, for example, commonly employed in stainless steel car exhaust systems. Type 1.4016 is more commonly employed for cheap cutlery, car trims and other everyday applications where weldability is unlikely to be an issue.

Where enhanced corrosion resistance is required Type 1.4113 (434) may be more appropriate and is suitable for applications requiring deep drawing such as the manufacture of thin-walled cylindrical items. The so-called low interstitial grades of ferritic stainless steel contain less than 0.03% carbon and nitrogen which enhances ductility, toughness and weldability. Welding conventional ferritic stainless steels can cause excessive grain growth, sensitisation and a decrease in ductility. Alternatively, the use of heat treatment after welding can minimise such problems, even when using the standard ferritic grades (Lula, 1982).

6.3.2 Austenitic stainless steel

Austenitic stainless steels have traditionally been the most widely used grade for general applications, although recent increases in the cost of nickel have resulted in it being relatively expensive and very variable in cost. The nickel, up to 10%, is added to ensure the formation of the austenitic structure. While relatively soft and weak in their annealed condition, austenitic stainless steels can be strengthened by cold working, precipitation hardening or through the addition of nitrogen. They have good ductility and toughness, even the high-strength grades, and their most notable feature is that they are non-magnetic. One consequence is that they can be used in the construction of buildings where large magnetic fields will be generated, for example, magnetic resonance imaging (MRI) medical scanner facilities. They retain these properties over a wide range of temperatures, often right down to cryogenic levels. A potentially negative property is that they can not be strengthened by heat treatment. Austenitic grades can display excellent corrosion resistance but are susceptible to stress corrosion cracking in certain specific environments.

Conventional chromium–nickel austenitic stainless steels include the well-known 18-8 (18% chrome, 8% nickel) grade. The chromium to nickel ratio can be optimised to improve formability and the carbon content reduced to enhance intergranular corrosion resistance. Molybdenum is often added to enhance the corrosion resistance, in particular the ability to resist pitting in environments containing chlorides. It is possible to partly replace the relatively expensive nickel with cheaper manganese or nitrogen additions to produce lower cost and lower

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performance chromium–manganese–low-nickel grades such as 1.4372 (the old 201 grade). Table 6.2 gives the composition for a range of austenitic stainless steel grades, together with a range of international classifications. Table 6.3 shows how the properties of a standard 18-8 austenitic stainless can be modified by changes in alloy composition.

Type 1.4301, more widely recognised as 304 or 18-8, has good corrosion resistance under atmospheric conditions and is commonly specified for architectural, food and beverage, chemical processing equipment and construction applications. The addition of 2–3% molybdenum found in Type 1.4401 (the old 316 grade) improves the pitting and crevice corrosion resistance and is used for similar applications to Type 1.4301 but where there are more aggressive conditions that could lead to pitting, such as marine environments.

Austenitic stainless steel is also used to produce reinforcement for use in concrete complying with the requirements of BS 6744:2001 and other international standards. Bars are available in Types 1.4301 (304) and 1.4401 (306), the latter being for particularly aggressive environments such as marine applications. Because of the relatively high and variable cost of austenitic grades, it is possible to obtain clad reinforcement with a stainless outer layer and a carbon steel core, although precautions must be taken to avoid bimetallic corrosion. Austenitic stainless steel is also used in many brickwork and facade support systems and is widely used for the manufacture of brick ties where they overcome many of the problems of premature corrosion encountered by earlier galvanised brick tie systems.

The familiar but now renamed 200 and 300 series austenitic grades are the most weldable types of stainless steels, especially in their low-carbon grades originally designated by an additional ‘L’. However, at the high temperatures involved in welding, sensitisation may occur where some of the chromium reacts with carbon in the steel to produce chromium carbide while depleting the chromium content of the surface. This can lead to severe localised corrosion but may be avoided if the stainless steel has a very low carbon content (<0.03%), such as Types 1.4307 (304L) and 1.4404 (316L), or if the steel is stabilised with titanium, Type 1.4541 (321), or niobium, Type 1.4550 (347).

Aside from the concerns of bimetallic corrosion, differences in the coefficients of thermal expansion between austenitic stainless and carbon steels mean that precautions must be taken to avoid distortion and cracking if these materials are joined by welding (Marshall, 1984).

6.3.3 Martensitic stainless steel

Through quenching and tempering, martensitic stainless steel can achieve greater hardness and hold a sharp edge, a significant advantage over the austenitic and ferritic grades. The downside is that the presence of the carbides that provide these characteristics reduces their corrosion resistance and ability to be easily formed.

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Table 6.2 Classification and composition of common austenitic stainless steels

EN	BS	AISI	En	DIN	SS	Typical composition (%)				
						C	Cr	Ni	Mo	Other
1.4301	304S31	304	58E	X5CrNi18-10	2333	0.07x	18	8		
1.4303	305S19	305		X5CrNi18-12		0.06x	18	11		
1.4305	303S31	303	58M	X10CrNiS18-9	2346	0.10x	18	8		0.35x S
1.4306		304L		X2CrNi19-11	2352	0.03x	18	10		
1.4307	304S11	304L			2352	0.03x	18	8		
1.4310	301S21	301		X12CrNi17-7	2331	0.05–0.15	17	6		
1.4311	304S61	304LN		X2CrNiN18-10	2371	0.03x	18	9		0.22x N
1.4372		201				0.15x	17	4.5		6.5 Mn
1.4401	316S31	316	58J	X5CrNiMo17-12-2	2347	0.07x	17	11	2	
1.4404	316S11	316L		X2CrNiMo17-13-2	2348	0.03x	17	11	2	
1.4406	316S61	316LN		X2CrNiMoN17-12-2		0.03x	17	11	2	0.22x N
1.4432	316S13	316L			2353	0.03x	17	11	2.5	
1.4435	316S13	316L		XCrNiMo18-14-3	2353	0.03x	17	13	2.5	
1.4436	316S33	316	58J	X5CrNiMo17-13-3	2343	0.05	17	11	2.5	
1.4438	317S12	317L			2367	0.03x	18	13	3	
1.4439				X2CrNiMoN17-13-5		0.03x	17	13	4	0.22x N
1.4541	321S31	321	58B	X6CrNiTi18-10	2337	0.08x	18	9		0.5 Ti
1.4550	347S31	347	58F	X6CrNiNb18-10	2338	0.08x	18	9		0.5 Nb
1.4567	394S17	304Cu				0.04x	18	9		4x Cu
1.4571	320S31	(316Ti)		X6CrNoMoTi17-12-2	2350	0.08x	17	11	2	0.5 Ti
1.4539	904S13			X1CrNiMoCuN25-20-5	2562	0.02x	19	24	4	2x Cu
1.4547					2378	0.02x	20	18	6	1x Cu
1.4529				X1CrNiMoCuN25-20-6		0.02x	19	24	6	1.5x Cu

'x' signifies that the figure is a maximum.

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Table 6.3 Modifying the properties of common austenitic grades

Requirement	Action	Example grades
Reduced risk of sensitisation	Lower C content	1.4307, 1.4401, 1.4438
	Add Ti	1.4541
	Add Nb	1.4550
Increased strength	Add N or Mo	1.4307
	Precipitation harden	2S143
Increased machinability	Add S	1.4305
	Add Se	Old BS 303 Se (no EN)
Increased oxidation resistance	Vary Cr and Ni content	1.4833, 1.4845
Reduced pitting attack	Add Mo	1.4401, 1.4438
Increased creep resistance	Add Nb	1.4550
Lower cost	Lower Ni, add Mn/N	1.4372

They have even poorer corrosion resistance than ferritic grades. Their ability to hold a sharp edge makes them ideal for knife blades and scalpels. The combination of good corrosion and wear resistance and high strength means they are suitable for valves, pumps and other similar machinery.

Martensitic stainless steels have between 11 and 18% chromium but can have up to 1% carbon which imparts the hardness and cutting ability. Occasionally they will also include nickel or molybdenum. The lower chromium grades are generally not suitable for atmospheric exposure as they will tarnish or corrode and are more likely to be used in machine applications where they have additional protection such as oil or grease. Table 6.4 gives the composition for a range of martensitic stainless steel grades, together with a range of international classifications.

Among the other characteristics of martensitic stainless steels are that they are magnetic and have good fatigue properties once heat treated. They generally do not have particularly good low-temperature properties and would not normally be used for cryogenic applications as they soon become brittle at low temperatures. Heat treatment, while improving strength and fatigue resistance, also reduces the toughness and they can also become brittle at temperatures above 430 °C. Welding needs to be carried out carefully due to their low ductility and the high carbon content of many grades makes them unsuitable for welded applications.

6.3.4 Precipitation hardening stainless steel

The addition of elements such as copper, aluminium, niobium and tantalum to chromium–nickel grades can lead to the formation of precipitates which in turn produce a high-strength stainless steel, in some cases stronger than the martensitic grades. These so-called ‘precipitation hardening’ (or PH) stainless steels have better ductility compared with martensitic grades of similar strength. They are also more suitable for welding and can display good corrosion resistance at elevated temperatures.

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Table 6.4 Classification and composition of common martensitic stainless steels

EN	BS	AISI	En	DIN	SS	Typical composition (%)				
						C	Cr	Ni	Mo	Other
1.4006	410S21	410	56A	X10Cr13		0.08–0.15	12			
1.4005	416S21	416	56AM	X12CrS13		0.08–0.15	12			0.35x S
1.4021	420S29	420	56B	X20Cr13	2303	0.16–0.25	12			
1.4028	420S45	420	56D	X30Cr13	2304	0.26–0.35	12			
1.4029	416S37	416	56CM			0.25–0.32	12			0.35x S
1.4034				X46Cr13		0.43–0.50	13			
1.4057	431S29	431	57	X20CrNi17-2		0.12–0.22	15	2		
1.4104	416S29	416	56BM	X12CRMoS		0.10–0.17	16		0.4	0.35x S
1.4112		440B		X90CrMoV18		0.85–0.95	17		1.0	0.10 V
1.4116				X45CrMoV15		0.45–0.55	14		0.6	0.10 V
1.4122				X35CrMo17		0.33–0.45	16		1.0	
1.4125		440C		X105CrMo17		0.95–1.20	17		0.6	
1.4418				X4CrNiMo16-5	2387	0.06x	15	4	1.0	0.02 N
1.4542		630		X5CrNiCuNb17-4		0.07x	17	4		4.00 Cu
1.4568		631				0.09x	17	7		1.00 Al
1.4594	460S52					0.70x	14	5	1.5	1.50 Cu

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Where the PH grades really show an advantage is that they can be supplied in the 'solution-treated' condition from which they can be machined prior to a relatively low temperature heat treatment or 'ageing' which imparts the increased strength with little or no distortion. They are employed where components need to have high-strength, high-temperature resistance and good corrosion resistance and are commonly used for gears, fastners and aircraft components, as well as the inevitable cutlery applications. If exposed to salty or sulphurous environments they can tarnish and are not typically selected for their aesthetic appearance (Lula, 1983; Zubek, 2006).

6.3.5 Duplex stainless steel

Duplex stainless steels have structures that combine aspects of ferritic and austenitic or martensitic grades. The resultant alloys are designed to display a favourable combination of the parent grades. For example, the austenitic/ferritic duplex steels have higher strength and better toughness than ferritic grades, are not susceptible to stress corrosion cracking, achieve better pitting resistance and can be welded relatively easily. On the downside, their resistance to crevice corrosion is poorer than the ferritic or austenitic grades with similar levels of chromium and molybdenum. The higher performing high-chromium grades are often designated as 'super-duplex'.

Duplex and super-duplex stainless steels are widely used in the highly demanding oil, gas, paper and petrochemical industries but have been less well known in many more traditional applications. However, increases and fluctuations in the price of nickel and the availability of so-called 'lean duplexes' has meant that it can be more cost effective to use a lower performing duplex grade than the more traditional and familiar austenitic stainless steel, even for applications such as reinforcing bars for concrete. Table 6.5 gives the composition for a range of duplex stainless steel grades, together with a range of international classifications.

6.4 Weathering steels

Weathering steels, sometimes referred to as high-strength low-alloy (HSLA) steels, are formulated to produce a dense, stable oxide layer that provides sufficient protection without the need for coating systems. This oxide layer results from the inclusion of alloying elements such as copper, chromium, nickel and phosphorous and is comparable with the patina seen on uncoated cast iron exposed to the atmosphere.

For the protective oxide layer to form, the steel needs to be exposed to cycles of wetting and drying. It is important that ponding of water and exposure to chloride ions are avoided as these can prevent the steel from being adequately protected and lead to unacceptable corrosion rates. A further limitation to the use of weathering steels is their appearance. The patina is visually similar to brown rust and can stain

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Table 6.5 Classification and composition of common duplex stainless steels

EN	BS	AISI	En	DIN	SS	Typical composition (%)				
						C	Cr	Ni	Mo	Other
1.4362				X2CrNiN23-4	2327	0.03x	22	4	0.4	0.4 Cu
1.4410					2328	0.03x	24	6	3	
1.4460		329		X4CrNiMoN27-5-2	2324	0.05x	25	5	1.5	
1.4462				X2CrNiMoN22-5-3	2377	0.03x	22	5	3	
1.4501	318S13					0.03x	24	6	3	0.5 W
1.4507						0.03x	24	6	3	1.0 Cu

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adjacent surfaces which may be problematic where aesthetics are a consideration and makes visual inspection somewhat more difficult. On the other hand, a number of iconic sculptures have been produced from this material, including the 'Angel of the North' in Gateshead, UK and the Picasso sculpture in Chicago, USA (McKenzie, 1978).

Being essentially a conventional steel, reuse and recycling are largely unaffected by the alloy additions.

6.5 Non-ferrous metals and alloys

While the vast majority of metal use is centred on ferrous-based alloys, there are significant amounts of other materials employed for specific applications where weight, strength or chemical resistance are important.

6.5.1 Aluminium

Aluminium is the most abundant metal in the earth's crust. Despite this, it was only comparatively recently that it could be produced and employed to any significant extent. It is a highly reactive element and is found in a wide range of naturally occurring compounds. The most common aluminium ore is bauxite but obtaining the metal from it is far from a straightforward matter.

The metal was first identified in the early nineteenth century and obtained the name 'aluminum' from Sir Humphry Davy. This was later modified to aluminium when elemental names were unified, although in the USA it was decided as recently as 1925 to revert to the original spelling. Commercial production of aluminium only became possible through the development of an electrolytic process which started with Davy but became commercially viable in the late 1880s through the Hall–Heroult process.

The method of production of aluminium has always been relatively energy intensive. The production of iron from ore uses approximately a quarter of the energy required to manufacture aluminium from raw products. When recycled from existing metal, both aluminium and ferrous materials require the same energy input by mass. As a consequence, aluminium with its lower bulk density can be seen as a more sustainable recycling option than steel.

Aluminium and its alloys generally display good corrosion resistance which further enhance their sustainability credentials. A large proportion of aluminium applications can take advantage of aluminium's ability to protect itself from most environments through the formation of a protective oxide layer. This is artificially thickened through the process known as anodising. Unlike weathering steel, the protective oxide layer is essentially invisible and can be modified with dyes and surface treatments to achieve a range of finishes.

Despite these apparent advantages of aluminium, steel remains dominant in most areas of construction and engineering due to its superior mechanical properties and

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better fire resistance, the melting point of aluminium being 660 °C compared with around 1370 °C for steel (Polmear, 1995).

6.5.2 Copper and copper alloys

The first discovery of copper may well have been over 10 000 years ago in the Middle East. The technology for its manufacture and fabrication were well advanced by the time of the Pharaohs, with 5000-year-old copper pipes still to be found in Egyptian tombs. Copper could be produced by a development of the smelting process first used for iron, but the metal itself was soon recognised for its superior malleability, durability and appearance.

The principal alloys of copper, brass (copper and zinc) and bronze (copper and tin) appear to have developed in parallel. The Egyptians were the first to recognise that bronze was better for casting than copper and was harder and more durable. Today the term 'bronze' is employed to describe a wide range of copper-based alloys such as aluminium bronze, silicon bronze and manganese bronze, each of which have special engineering characteristics.

Copper and its compounds are essentially toxic and can result in similar symptoms to arsenic poisoning. The levels of copper in drinking water are carefully monitored, although under normal circumstances copper is not particularly soluble. This toxicity makes copper valuable for anti-fouling applications (copper-bottoms on timber ships) and anti-bacterial applications such as copper door knobs in hospitals which can limit the spread of disease. Where copper sheeting is used as a roofing material consideration must be given to the possibly toxic qualities of the run-off water.

Conductivity, both electrical and thermal, is the other characteristic that makes copper so useful and valuable. It is second only to silver in terms of electrical conductivity and is a vital component in electrical power and signal transmission systems. Recycling of copper conductors is big business and the illicit stripping of copper wiring is of increasing concern, particularly as it often involves the removal of polymer sheathing by burning resulting in the release of potentially toxic fumes.

Atmospheric corrosion of copper alloys produces a characteristic blue/green discolouration. When used for aesthetic purposes it is usually necessary for copper and its alloys to be either protected with a transparent lacquer or have the surface modified with a chemical patination treatment that is designed to produce a stable and attractive finish. Without such treatments it can take many years for copper roofs and bronze statuary to take on the characteristic appearance of antiquity (Copper Development Association, 2004).

6.5.3 Lead

As with copper, the use of lead dates back thousands of years. Its early popularity was based on its relative ease of manufacture from widely available lead ores, low

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melting point, ease of fabrication and good corrosion resistance. Lead pipes were used for drinking water by the Romans and this is the source of the common terms plumbing and plumber. Lead oxides were widely used as pigments in drying oil paints, where they assisted in the through-hardening of the paint film. One further characteristic of lead that is difficult to replicate with other materials is its ability to act as a shield to radiation, particularly in hospital and nuclear applications.

Health concerns with respect to the effects of cumulative lead poisoning have resulted in the cessation of the plumbing and painting options, although many examples still exist in old buildings with the associated risks. For centuries lead sheet was the ultimate roofing system, although traditionally prey to unofficial and illegal recycling, especially from church roofs.

Lead continues to have a role in construction where its durability, formability and appearance are considered of value, such as with flashing. Some roofing is still carried out, particularly on historic structures. Lead-coated steel, or terne plate, is used for decorative roofing and cladding, although fears over lead exposure have resulted in much of it being replaced by zinc-coated alternatives.

When lead is exposed to the air it produces a characteristic layer of oxides and carbonates that gives the familiar lead patina finish. If left to occur naturally this can be uneven in appearance and result in staining of adjacent masonry, it is therefore preferable to treat new lead with patination oil, a mixture of linseed oil and other compounds, which encourages the formation of a stable, even and aesthetically pleasing surface finish (Blaskett & Boxall, 1990).

6.6 Corrosion

As previously discussed, steel has a similar life cycle to the people who use it. The length of time between 'conception' and 'death' is influenced by how well they are treated and how appropriately they are employed. For steel and other oxidisable metals, corrosion represents the biggest threat to a long and healthy life. For our purposes we will mostly concentrate on steel and the affects of aqueous corrosion where moisture and oxygen are involved (Lambert, 2005).

At the most basic level the corrosion process can be demonstrated by two dissimilar metals in an aqueous electrolyte that have been electrically connected to allow a flow of electrons from one to the other. One metal, the more reactive one, becomes the anode and essentially dissolves. The other, the cathode, remains unaffected but is essential for the corrosion process to continue. The reactions occurring at these anodic and cathodic sites are given below.

- *At the anode*
  $M \rightarrow M^{n+} + n^{e-}$
  (metal → metal ion + electrons)
- *At the cathode*
  In well-aerated neutral and alkaline environments

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$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

(Oxygen + water + electrons → hydroxyl ion)

In some cases, especially in acidic conditions or in the absence of oxygen, the following reactions can occur:

$2H_3O^+ + 2e^- \rightarrow H_2O + H_2$(gas)

(acidic conditions)

$2H_2O + 2e^- \rightarrow 2OH^- + H_2$(gas)

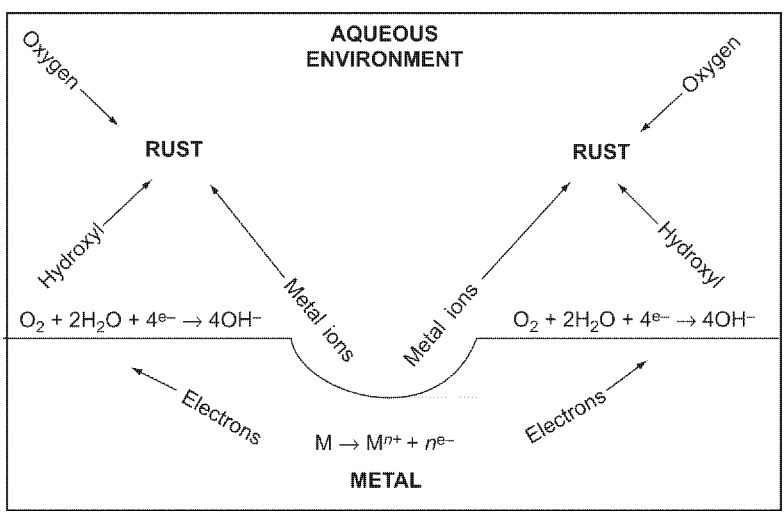
(neutral conditions)

The dissolved metal ions react with hydroxyl ions to form the corrosion products such as rust, as shown in Fig. 6.1. Production of hydrogen at the cathode can lead to hydrogen embrittlement and possible failure in some sensitive materials, for example, high-strength, low-alloy steels that are under stress.

Unfortunately, it is not necessary for there to be two different metals joined together as anodic and cathodic areas can be formed on a single surface in contact with the aggressive aqueous environment. Small differences in grain orientation, composition, hardness, moisture, oxygen or temperature are all that is required to differentiate cathodic and anodic areas. Corrosion can therefore occur at a large number of sites over the surface of the metal, each with their own local anodes and cathodes, as illustrated in Fig. 6.2.

6.6.1 General corrosion

General corrosion results in what at least appears to be a uniform attack of the metal surface. Closer examination will often identify an 'orange peel' effect, the dimples



6.1 A simple corrosion cell.

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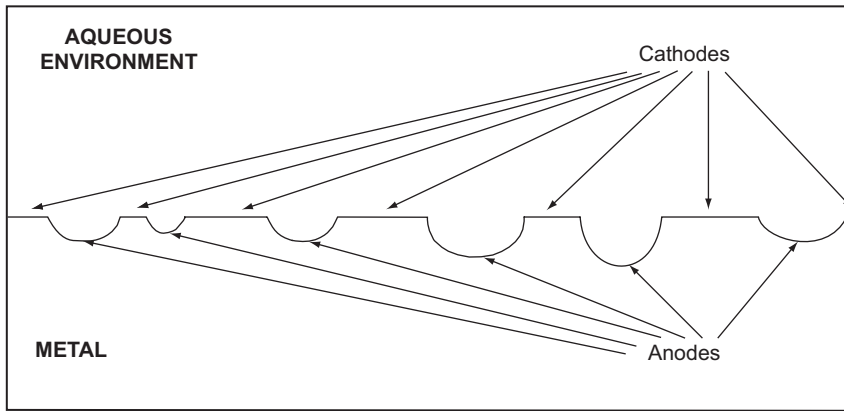

6.2 Anodes and cathodes.

being individual anodes surrounded by cathodic areas. It is worth noting that the corrosion product or rust is deposited over the whole of the affected area, not just where the anodes are located. Because the corrosion is evenly spread, the overall rate of penetration is generally quite low but can generate a large amount of corrosion product which may cause problems with aesthetics and contamination. It is possible to obtain typical corrosion rates for most commonly employed alloys in specific environments.

6.6.2 Pitting corrosion

Under particular circumstances corrosion can be localised in a small number of sites to produce pits. While the total amount of corrosion may be similar to that encountered with the general form, because it is more focused the corrosion rate is much higher and can lead to significant loss of section or perforation. Pitting corrosion can occur due to a number of causes but one of the most commonly recognised is due to chlorides, where the chloride ions locally disrupt the passive oxide film that normally protects metals. Pitting can also occur when there is a susceptible phase in a metal which is preferentially attacked.

Once initiated, a chloride-induced pit can be self-perpetuating, with chloride never actually being consumed but rather acting as a catalyst. Pitting is often associated with stagnant conditions which can cause problems when plant is idle or closed down for maintenance.

6.6.3 Crevice corrosion

Crevices are very effective initiators of corrosion. Wherever there is a fine gap, such as between two flanges, there is the risk of crevice corrosion being initiated. It is not necessary for both surfaces to be metals and crevices can even form

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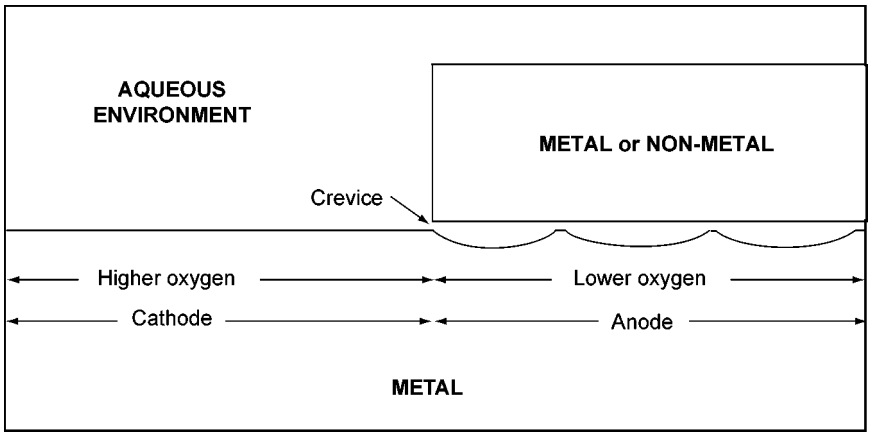

6.3 Crevice corrosion.

beneath surface deposits. The crevice retains water which quickly attains a lower oxygen content than outside the crevice. Even if the item in question is not submerged the crevice will retain water through capillary attraction. The difference in oxygen level between the crevice and exterior causes a corrosion cell to be formed, the part in the crevice being the anode, as illustrated in Fig. 6.3.

The relatively small anodic area is driven by the larger external cathode, resulting in high rates of corrosion. Unfortunately, the smaller the crevice, the more intensive the likely corrosion so the only way to deal with crevices effectively is to remove them completely, for example by replacing bolted connections with welded ones.

6.6.4 Galvanic corrosion

The formal recognition of galvanic or bimetallic corrosion dates back to 1763 when the iron nails securing the copper bottom of HMS *Alarm* were observed to have preferentially corroded. That said, all early attempts at producing electricity electrochemically with batteries employed this principle. It occurs when two dissimilar metals exposed to the same electrolyte are connected electrically, as previously discussed when describing a simple corrosion cell. Batteries and corrosion are essentially the same technology, although the polarity of the anodes and cathodes has been switched since when the function of batteries was first being described, for example by Benjamin Franklyn, it was believed that electricity flowed through the movement of positively charged particles rather than electrons.

Galvanic corrosion will only occur when the following conditions are satisfied.

1 The anodic and cathodic metals must be in the same electrolyte, which need not be particularly aggressive to either of them. The electrolyte can be a solution, condensation film or damp solid (including soil or concrete), the only requirements being that it contains moisture and dissolved ions.

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2 The anodic and cathodic reactions on the two metals must be able to proceed. In particular, the anodic metal must be susceptible to corrosion in the environment.
3 The two metals must be connected electrically, either directly or indirectly via a third metal, for example an earthing strap. Indeed, problems occur when components of different metals that have been purposely isolated to prevent galvanic corrosion are subsequently bonded to earth for electrical safety.
4 The two metals must have a sufficiently large potential difference to drive a significant galvanic current. This can be evaluated by comparing their position in an electrochemical series, although it must be noted that these are specific to the environment (Table 6.6 shows an electrochemical series for sea water, the values are in volts measured against a standard hydrogen electrode) and metals such as aluminium appear worse than might be expected as the effects of their protective oxide film resulting from anodising are not taken into account.

6.6.5 High-temperature corrosion

In addition to the more familiar 'wet' corrosion, metals can lose section through scaling in dry, high-temperature environments. At elevated temperatures, steel and other metals can react with oxygen or gaseous oxides of sulphur and carbon resulting in loss of metal, generation of corrosion products and possible changes in the mechanical characteristics of the alloy. High-temperature oxidation and other associated reactions have historically been problems for the power generation, aerospace and petrochemical industries. Alloys containing high chrome and especially high nickel contents can deliver superior performance at elevated temperatures but are inevitably expensive. In recent years more cost-effective solutions have been available through the use of engineering ceramics.

6.6.6 Corrosion protection and prevention

The most commonly employed method of protecting metals from corrosion is to apply a protective coating. By applying a thin adherent coating to the metal, moisture and aggressive species such as chloride ions are kept away from the surface and corrosion does not occur. In reality, most protective coating systems are more complex than simple barriers. They contain active species that enhance the bond to the metal surface and special fillers to increase the barrier properties. Coatings also provide a wide range of aesthetic options, particularly for ferrous materials that would otherwise come in any colour as long as it was a rusty brown.

Coating systems have changed dramatically in the last few years as many of the active ingredients were also harmful to the environment, the applicators or the public. Anti-corrosive components based on lead and chromium have been largely phased out and highly solvented systems are being replaced by water-based coatings which benefit the health of both the applicators and the environment.

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Table 6.6 Electrochemical series for sea water

Metal	Potential, *E* (volts)
Gold	+1.50
Silver	+0.80
Mercury	+0.79
Copper	+0.34
(Hydrogen)	0
Lead	–0.13
Tin	–0.14
Nickel	–0.25
Cadmium	–0.40
Iron	–0.44
Chromium	–0.74
Zinc	–0.76
Titanium	–0.63
Aluminium	–0.66
Magnesium	–2.37

There have been various attempts to use coatings to impart additional protection to reinforcing bars for concrete. The two most popular systems have been zinc galvanising and fusion-bonded epoxy. While each continues to be used in niche applications and more widely in specific parts of the world, they also can have considerable drawbacks. These are notably the reactivity of zinc in alkaline environments and the sensitivity of epoxy to construction damage and a tendency to soften with time.

Design plays an important role with respect to controlling corrosion. It is essential to avoid the trapping of dirt and water and ensure drain holes will not get blocked. As previously discussed, crevices should be avoided at all costs.

A number of common approaches to preventing galvanic corrosion may be employed, these include insulating the metals from each other, applying coatings to impede the anodic and cathodic reactions or applying cathodic protection as described later. Jointing compounds that exclude water and do not dry or crack can be used to protect joints. If the compounds have a corrosion inhibitor incorporated into them they may be effective in moderately aggressive conditions. If possible the compound should be overcoated.

When considering stainless steels, some grades are clearly more desirable to use than others for certain applications. In the construction industry the austenitic group of stainless steels are used most widely in applications such as dowels, fixtures, bolts, fasteners and reinforcements. Care must be taken in the choice of stainless steels to be used in specific situations as many problems such as galvanic corrosion, stress corrosion cracking, crevice corrosion, intergranular corrosion, pitting and galling may be encountered if the chosen grade is inappropriate (Revie, 2008).

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6.6.7 Cathodic protection

On the basis that corrosion relies on two processes occurring simultaneously, the anodic and cathodic reactions, and that only the anodic reactions result in a loss of metal, it is possible to prevent corrosion by making all the susceptible metal act as a cathode. The term cathodic protection was first coined by the ubiquitous Humphry Davy in 1824 when he described his concept for preventing the preferential corrosion of iron nails used to fix the copper sheeting to the bottoms of timber ships. As has already been described, the resulting galvanic corrosion caused the heads of the nails to fall off and the copper sheeting became detached.

Davy came up with the idea of fixing lumps of a third metal more likely to corrode than either the iron nails or copper sheet that would 'sacrifice' itself and prevent the nails from rotting away. Unfortunately, the original system was too effective and also prevented the corrosion of the copper which was required for anti-fouling properties. It was to be another hundred years before the real benefits of cathodic protection were identified and it is now unusual for a metal pipeline, ship, jetty or oilrig to not be protected by such a system.

The technique relies on the metal to be protected being in an electrolyte and cannot therefore be used to protect atmospherically exposed components and structures. The electrolyte may be sea water, fresh water, soil, sand, mud, concrete or masonry. The only requirement is that it contains moisture and can carry an ionic charge. While galvanic systems based on the preferential corrosion of a reactive metal (zinc, aluminium or magnesium) are still common, many systems now provide the protection by means of an impressed current.

The characteristic of an anode that is important in this process is the generation of electrons (see Section 6.6). This can be achieved with an inert anode and a direct current (DC) power supply. The most effective anode material for passing large quantities of current without dissolving is platinum. Thankfully, similar performance can be achieved with relatively inexpensive materials such as mixed metal oxide (MMO)-coated titanium and titania (titanium oxide). Figure 6.4 shows a simple schematic to illustrate the difference between impressed current and galvanic cathodic protection systems.

The construction industry has already made significant progress, with associated cost benefits, through the use of cathodic protection, mainly for the remediation of chloride-contaminated reinforced concrete structures (Chess, 1998). A recent comparison was carried out for a dual two-lane highway overbridge requiring repairs to two central supports. The cost for conventional repairs, including access and traffic management, was four times greater than for the cathodic protection option. Elsewhere, the cost of cathodic protection was found to be less than 5% of the cost of replacing the damaged supports to an elevated section of highway. As well as saving money, the cathodic protection option was found to greatly reduce the carbon footprint for the works and improve health and safety for workforce, motorists and local residents. Cathodic protection is still only rarely used on new

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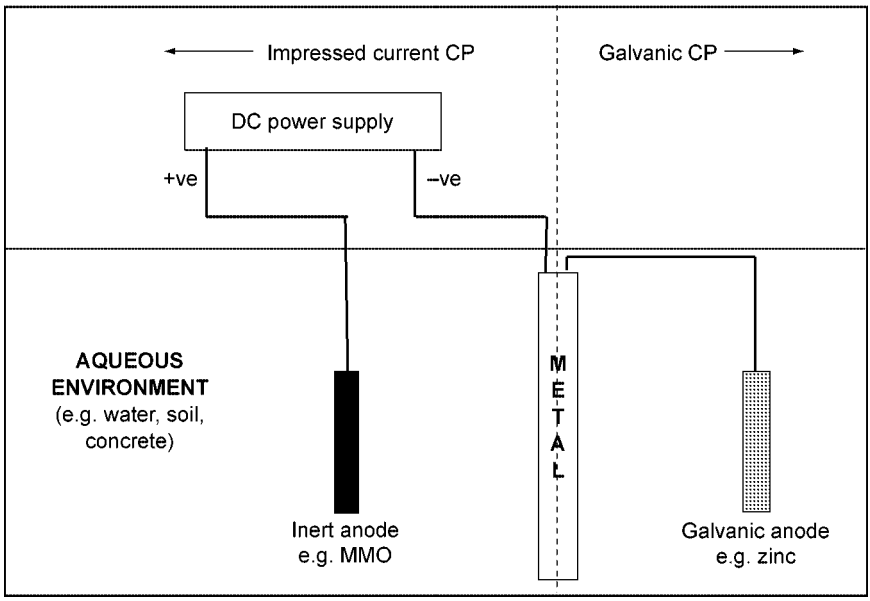

6.4 Impressed current and galvanic cathodic protection (CP).

reinforced concrete structures to prevent corrosion from occurring in the first place, although growth in this area has been reported in the aggressive environment of the Middle East (Arya & Vassie, 2005).

A more recent application for cathodic protection in the construction industry has been in the preservation of historic steel-framed buildings. Many of the grand municipal and commercial buildings constructed in the major cities of Europe and North America in the early part of the twentieth century employed a structural steel frame clad in masonry. This form of construction allowed for taller buildings with larger openings for windows and wide open floorspaces better suited for banking and commerce and cathodic protection solutions for such structures have been subject to considerable development (Lambert *et al.*, 2008).

6.7 Future trends

Metals continue to be in high demand and as more parts of the world aspire to Western levels of personal, corporate and municipal wealth the need for metals is anticipated to increase. Steel supply is particularly stretched given the huge tonnages required in the development of rapidly developing economies such as China and India.

Developments in the use of carbon nanotubes and similar technologies promise to revolutionise aspects of the electronics industry; however, the amounts of copper and other metals that such developments may replace are likely to be miniscule when compared with the overall demand, plus there remain health

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concerns regarding risk of inhalation or ingestion that have yet to be resolved.

Recycling of metals remains a major industry. Prevention of corrosion, particularly of ferrous materials, needs to be given higher status alongside recycling as a sustainable way of obtaining the maximum benefit from the energy invested in a metallic component. The benefits can already be seen in the motor industry where better design and more effective corrosion protection have made the corrosion of bodywork a relatively minor issue throughout the life of vehicles manufactured within the last 10–15 years. In the construction industry the value of recovered structural steelwork and reinforcing bars ensures that they enter the recycling system. Reuse rather than recycling of rolled steel beams and stanchions offers enormous potential savings but remains relatively rare in the absence of guidelines and government incentives.

As the benefits of longer component life become more widely recognised, the use of higher performance materials for sustainable rather than aesthetic reasons should become more common. Materials such as stainless steels and aluminium alloys could have much wider use in construction applications than is currently the case, and in turn provide longer service lives, lower maintenance and ultimately more sustainable solutions.

6.8 References

Arya C & Vassie P (2005), 'Assessing the sustainability of methods of repairing concrete bridges subjected to reinforcement corrosion', *International Journal of Materials and Product Technology*, **23**(3/4), 187–218.

Beddoes J & Parr J G (1999), *Introduction to stainless steels*, Ohio, ASM International.

Blaskett D R & Boxall D (1990), *Lead and its alloys*, New York, Ellis Horwood.

Chess P M (1998), *Cathodic protection of reinforced concrete*, London, E & F N Spon.

Copper Development Association (2004), 'Copper and copper alloys: compositions, applications and properties', CDA Publication 120, Hemel Hempstead, UK, CPA.

Elliot R (1988), *Cast iron technology*, London, Butterworth.

Kuhn F (1982), *Wrought iron*, London, Harrap.

Lambert P (2005), 'Corrosion mechanisms – an introduction to aqueous corrosion', Technical Note 5, Corrosion Prevention Association, Franham, Surrey.

Lambert P, Mangat P S, O'Flaherty F J & Wu, Y-Y (2008), 'Influence of resistivity on current and potential distribution of cathodic protection systems for steel framed masonry structures', Corrosion Engineering Science and Technology, **43**(1), 16–22.

Lula R A (1982), *Sourcebook on the ferritic stainless steel*, Ohio, ASM International.

Lula R A (1983), *Duplex stainless steels*, Ohio, ASM International.

Marshall P (1984), *Austenitic stainless steels*, Oxford, Elsevier Applied Science.

McKenzie M (1978), 'The corrosion performance of weathering steel in highways bridges', TRRL Laboratory Report 857, Wokingham, Berkshire, UK, Transport Research Laboratory.

Polmear I J (1995), *Light alloys: Metallurgy of the light metals*, Oxford, Butterworth-Heinemann.

Revie R W (2008), *Corrosion and corrosion control*, Chichester, Wiley.

Zubek L (2006), 'A technical review of precipitation hardening stainless steel grades', *Journal of the Spring Manufacturers Institute*, January, 14–16.

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7

Sustainability of glass in construction

C. ATKINS
Mott MacDonald, UK

Abstract: This chapter reviews the basic history and manufacture of glass. It then goes on to review the sustainability options, starting with reuse, moving to recycling, then to alternative uses of glass, highlighting the problems that arise due to the variety of types of glass currently in use.

Key words: sustainability, glass, construction.

7.1 Introduction

This chapter describes the history of glass. It goes on to include a description of the sources of the raw materials and the processes involved in the production of glass. Different types of glass are discussed, including a description of the small amounts of trace materials used to alter the properties of glass to enable its different uses. Following on from this a description of the recycling process is included and the energy benefits achieved by this process. The problems associated with glass recycling are then discussed, followed by an evaluation of the alternative uses for waste glass. Sources of further information are included at the end of the chapter.

7.2 History of glass

Glass has been around for quite some time. Examples are available that date from 2500 BC. By 1500 BC glass drinking vessels were commonplace. This is because the basic manufacturing process is relatively simple. A naturally occurring raw material is heated, and then formed into the desired shape. With the addition of minor elements, different properties are further enhanced.

7.3 Manufacture

As with most products, the composition of glass is carefully controlled, typically by purchasing relatively pure raw materials and mixing them carefully before addition to the melting furnace. The minor components are added at this stage, as is recycled glass, known as cullet. If the cullet comes from within the factory due to breakage or rejected glass it is known as domestic cullet. It has the main advantage of having a known composition. A typical plant will reject or lose

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Table 7.1 Embodied energy of glass

Glass type	Embodied energy (MJ/kg)
Float	15.9
Toughened	26.2
Laminated	16.3
Tinted	14.9

around 10% of its output which is recycled as domestic cullet. Cullet from external sources is known as foreign cullet. The exact composition will not be known, but because the basic ingredients are common to most manufacturers the use of cullet of the same colour should pose few problems.

The obvious problem is that foreign cullet is almost certain to contain other glassware, such as different colours, metals, ceramics or borosilicate glass that can either discolour a batch, pass unmelted through the furnace, or cause damage to the plant. This is compounded by end-user specifications requiring exact colour specifications that manufacturers consider excessive. It would be possible to operate a furnace at cullet levels of over 90%, but this depends on the levels of contamination and colour requirements.

The raw materials and cullet are then melted in the furnace, at temperatures up to 1600 °C. Once melted the raw materials must remain molten for a sufficient time to thoroughly mix and for bubbles to rise. Typically this can take around 16 hours. Following on from this the glass is then formed. This is achieved by blowing into moulds, floating for sheet glass, or forcing through small holes at high speed to form fibres.

At this stage the glass is highly stressed due to the differential cooling that has inevitably occurred as part of the manufacturing process. In order to remove the stresses the glass is annealed. This is achieved by reheating and cooling at a controlled rate. The duration of this process depends on the thickness of the glass. After this the glass is inspected and, if it passes, packaged and shipped out. The embodied energy for glass obviously has a major contribution from the original melt, but subsequent treatment also has a significant effect, as can be seen in Table 7.1 .

7.4 Composition

The basic ingredient of glass is sand and this constitutes approximately 60% of the raw ingredients. In this matter glass has a distinct advantage over other manufactured materials, in that its manufacture uses one of the most abundant materials on the surface of the planet. This minimises the energy involved in the first step of producing a material, i.e. extracting the raw ingredients. The other main ingredients are sodium carbonate (21%) and limestone (19%), the latter is predominantly calcium carbonate.

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Table 7.2 Effect of additives on glass

Additive	Effect on basic glass
Iron	Brown or green colour
Chromium	Green colour
Cobalt	Blue colour
Sodium sulphate	Improved refining
Lead	Enhanced refractive index
Alumina	Improved durability
Boron	Improved thermal properties

With the industrial revolution, sodium carbonate became available relatively cheaply. It was manufactured by the Solvay process that produces sodium carbonate from limestone and brine. As a result of this development the price of sodium carbonate dropped, and the use of glass increased dramatically. In the 1860s the Siemens brothers developed the modern-day regenerist furnace. At the beginning of the twentieth century, mass production of glass containers began, automated bottle and jar machines appeared in 1925, closely followed by automated lightbulb production. Continuous flat glass production using water-cooled rollers was introduced in 1925, with float glass being introduced in 1959 by Pilkingtons. A typical furnace today operates continuously for around 8 years, manufacturing 300 tonnes of glass every day at a thermal efficiency of around 4 GJ per tonne.

The commonest type of glass in use is soda lime glass, which accounts for more than 90% of all glass produced. It is made up of around 72% silica, 12% sodium oxide from soda ash and 11% calcium oxide. The remainder is made up of minor ingredients. Typical additives are shown in Table 7.2.

7.5 Types of glass and their usage

The commonest use of glass is in containers. This typically involves brown, green or clear glass. All container manufacturing uses the same basic composition which simplifies recycling. The only requirement becomes colour separation. Common types of glass can be categorised as follows:

- borosilicate glass is heat shock resistant and is commonly known by trade names such as Pyrex; it typically contains 80% silica, 4% sodium oxide, 2% alumina and 13% boric oxide;
- lead glass (or lead crystal) is made by substituting lead oxide for calcium oxide, it is easy to melt and has enhanced optical properties; it also has increased electrical resistance; higher lead contents can also be used to provide radioactive shielding;
- Fibreglass is made up of solid rods of glass in very fine filaments; in this form it can be used directly as insulation, but can also be formed with a polymer to produce glass-reinforced polymer (GRP) which has found widespread use as a

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rigid durable material in a broad range of applications; treated glass fibres are also used in glass-reinforced cement (GRC);
- cathode ray tubes are made up of a number of different types of glass, the screen is different to the funnel and the neck and contains high levels of barium, strontium and zirconium, but no lead; the remaining glass elements contain varying amounts of lead;
- other types of glasses are available such as optical glasses and sealing glasses but these are relatively small volumes.

7.6 Glass production

In 2005, glass container production in Western Europe and Turkey fell by 1.1% in 2004 to 18.778 million tonnes, according to statistics released by the European glass container manufacturers' federation FEVE (Federation Européenne du Verre d'Emballage). Germany was the largest producer responsible for 4.1 million tonnes. The current mass of glass manufactured in the UK annually is approximately 2.0 million tonnes. One million tonnes of glass is imported annually and 0.5 million tonnes of glass is exported; 875 000 tonnes is recovered. The UK's production has been falling slightly since 2003 but a new production plant has been opened which may alter this trend.

The global flat glass market in 2006 was approximately 44 million tonnes which equates to approximately 5.5 billion m^2, approximately five times bigger than the surface area of Hong Kong, twice the surface area of Luxembourg or 66% bigger than the state of Rhode Island in the USA. The estimated value was US$23 billion. Approximately 70% is consumed in windows for buildings, 10% for automotive applications and 20% in furniture and other interior applications. Europe, China and North America accounted for approximately 75% of the global demand, with 66% of the world production being the responsibility of four companies (NSG Group, Saint Gobain, Asahi and Guardian). Guardian do not have a global automotive glazing capability and presence, and so NSG, Saint Gobain and Asahi are responsible for approximately 75% of the world's automotive glazing. The global demand for float and sheet glass from 2006 is shown in Table 7.3 (Pilkington, 2007). The Pilkington report states that demand is growing at approximately 4% per annum.

7.7 Structural uses of glass

Some basic properties of glass are shown in Table 7.4. The figures in Table 7.4 relate to typical soda-lime silicate window glass. The main limiting factor is surface defects. The brittle nature of glass leads to rapid propagation of cracks and premature failure. Tempered glass uses controlled cooling to put the surface of glass into compression.

The primary structural use of glass is as cladding or windows for structural

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Table 7.3 Global demand for flat glass

Area	Demand (%)
Japan	3
South America	3.5
Former Soviet Union	5
South East Asia	7.5
North America	14
Europe	23.5
China	35
Rest of the World	8.5

Table 7.4 Structural properties of glass

Relative density	2.5
Ultimate tensile strength	30–90 MPa
Young's modulus	70×10^3 MPa
Poisson's ratio	0.23
Mohs hardness	6
Thermal coefficient of expansion	9×10^{-6}/K

frames. Typically the structural requirements are to resist wind loading, dead load and accidental impacts. The glazing is normally either supported in sealed units or anchored to the structure using metallic fixings. There are a range of standards governing this type of use, including BS EN 572 Glass in Buildings, BS 6262 Glazing for Buildings, ASTM C106 Standard Specification for Flat Glass (an example of a glass façade is shown in Fig. 7.1).

7.8 Reuse

Reuse is one of the most sustainable and long-established approaches to minimising waste. It requires a collection system. If the glass is to be reused for containers a cleaning system is also required. In addition, it typically requires the products to be made marginally stronger to allow for more frequent handling. In some cases, glass can also be coated to fill in surface imperfections and therefore make the material more robust.

The commonest incentive to reuse is financial. This is typically achieved by charging deposits on bottles that are refunded when the bottles are returned. This system benefits from being self-sorting, as the bottles that are returned typically come from an identifiable source, and can be returned to that same source. This means that the glass is likely to be made up of a known composition, which assists future recycling.

In the UK, the reuse of bottles has slowly been phased out, partly as distribution

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7.1 An example of a glass façade, Manchester Civil Justice Centre, UK (photo courtesy of Mott MacDonald).

centres have become more centralised although a range of factors is almost certain to have contributed. These include the phasing out of cash deposits on bottles, and the slow demise of the milk delivery round. The use of cash deposits on bottles in countries such as Germany continues and this is likely to be a contributory factor in the high recycling rates found in areas of Europe.

It is also possible to reuse architectural glass. The main drawback to this is the care required to extract the glass intact from its existing surroundings. For demolition work this may add an unacceptable delay to the programme. In addition, the glass can only be reused if the size of panes and the colour are appropriate. It is unlikely that the same site will accommodate identical windows and so removal and storage at a remote location will be required.

7.9 Recycling

As the reuse of glass containers has become less common, the specific use of

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disposal areas such as bottle banks has replaced this practice. The first bottle bank appeared in the UK in 1977, and glass recycling is now common in large parts of the globe. Where glass is not reused, the recycling process still involves glass collection and cleaning. In addition the material will be sorted. The combination of cleaning and sorting will remove unwanted elements. This is then followed by colour separation. It should be noted that while bottle banks commonly have separate areas for green, brown and clear glass, the risk of cross-contamination is such that the sorting process will still be applied. The glass is then crushed to the required size and issues to the manufacturing plant. As with all sustainability issued the arguments then begin to get a little more complex.

7.9.1 Geographic constraints

Glass is commonly produced at a small number of large plants. Around 90% of all the glass produced in the UK is produced by large-scale manufacturing centred in Yorkshire, St Helens in Merseyside and Scotland. A single plant in Harlow is the only large container manufacturer south of Yorkshire. Northern Ireland is served by a single container plant. Southern Ireland was served by a single container plant but this closed in 2002, so the Northern Ireland plant is the sole facility on the Irish mainland. There is no container or flat-glass manufacture in Wales, but it does host two fibreglass plants and one of the two UK plants manufacturing television screens.

In contrast to this there are over 20 000 bottle banks in the UK. As a result the cullet will require transport to the plant which can involve some considerable distance. While in the UK it is often said you are never more than 100 miles from the sea, you can be more than 100 miles from a glass manufacturing plant. Birmingham, the UK's second-largest city is over 80 miles from any plant.

7.9.2 Colour

The composition of container glass (in terms of colour) manufactured in the UK is 21% amber, 62% flint and 17% green glass (based on information provided by glass manufacturers). The maximum percentage of cullet that can be used in the manufacture of glass is 70% for amber, 60% for flint and 90% for green glass. The composition of container glass (in terms of colour) recovered annually in the UK is 18% amber, 30% flint and 52% green glass. This produces a significant imbalance in the amount that is available, compared with the amount that can be recycled in glass production. The problem is illustrated in Table 7.5.

The UK has a low recycling rate, with figures ranging between 35 and 55%. Based on the lowest figures of recovery, the UK recovers 149 000 tonnes of green glass that simply can not be used in manufacturing. If the quantities recovered were increased such that clear glass was using the maximum amount of cullet possible, and the proportions remained the same there would be approximately 1 million

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Table 7.5 Availability of glass for recycling

Type of glass	Percentage manufactured	Quantity manufactured in UK (tonnes)	Maximum quantity of cullet required (tonnes)	Percentage recovered	Quantity recovered (tonnes)	Difference (tonnes)
Green	17	340 000	306 000	52	455 000	149 000
Amber	21	420 000	294 000	18	157 500	–136 500
Flint	62	1240 000	744 000	30	262 500	–481 500

tonnes of green cullet stockpiled and over 175 000 tonnes of amber glass left unused per year. This net imbalance will be reflected in areas where the different coloured glass is imported from, e.g. Germany. Globally the trends depend on the correlation between glass production and glass use. Any country that imports a large number of containers that are a different colour to those it produces domestically will have this net imbalance.

7.9.3 Rates of recycling

Recycling rates vary from source to source. Figures quoted for China (Wu *et al.*, 2005) are 0%. The same source reports figures for Japan of 20% from 1996. Across Europe it is generally agreed that recycling rates in Western Europe and Turkey are improving steadily. According to FEVE (www.feve.org), the total amount collected rose from 9.376 million tonnes in 2003 to 9.559 million tonnes in 2004 and figures for 2006 were 10.455 million tonnes; however, recycling rates still vary enormously by country. While Sweden and Switzerland recycle approximately 95% of their glass containers, Greece and Turkey recycle less than 25%. The figures are not skewed by local production variations. Germany, Europe's biggest producer, recycles 86% of its glass containers; Table 7.6 shows the recycling rates available across Europe.

7.10 Alternative uses

As can be seen there are a number of problems associated with reuse and recycling of glass that have resulted in a need for alternative uses. This is especially true for coloured glass. It is interesting to note that while landfill is considered environmentally unsustainable and is economically punished, stockpiling is not. Provided there is room at a plant it usually works out more cost-effective to stockpile. This hampers alternative uses, as to take material from a stockpile and do something with it there will be an associated cost.

From the UK figures shown above it can be seen that an outlet is required for this increasing amount of green glass. As a result it is now reused in a variety of forms.

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Table 7.6 Glass recycling rates across Europe (www.feve.org)

Country	Metric tonnes ('000) collected*		Recycling rate
	2006	2007	2007
Austria	214	221	80%
Belgium	317	289	92%†
Bulgaria	54	48	32%‡
Czech Republic	142	133	50%
Denmark	119	121	84%
Estonia	11	12	47%
Finland	50	54	61%
France	1903	1950	61%
Germany	2550	n.a.	n.a.
Greece	20	26	13%‡
Hungary	25	34	20%
Ireland	98	124	73%
Italy	1256	1303	60%§
Netherlands	432	n.a.	n.a.
Norway	53	n.a.	n.a.
Poland	270	290	26%¶
Portugal	181	186	46%
Romania	16	15	9%‡
Slovakia	40	43	34%
Spain	840	936	56%
Sweden	159	171	94%
Switzerland	308	320	95%
Turkey	93	81	19%
United Kingdom	1303	1446	55%§
Total	10 455		

* From the general public and from bottlers.
† Based on an estimate of total consumption (314 000 tonnes): considering the market represented by its members and imported tonnage by consumers, FOST Plus (www.fostplus.be) records a rate of 109%; these figures relate to single-trip containers only.
‡ Estimates.
§ Collected cullet corresponds to actually recycled cullet.
¶ Provisional.

Glass is a hard, relatively inert material and therefore naturally lends itself to use as an aggregate. Glass can either be used as a bound or unbound aggregate and it has found its way into use in a variety of replacement coarse and fine aggregates.

It has been estimated that approximately 100 000 tonnes of glass are currently being used as road aggregate substitute. Separation and sorting does not need to be as stringent as the colour is not significant The excess green and brown glass can be reused in this form relatively straightforwardly. It should be noted, however, that if glass is collected for this purpose, it cannot be used in glass manufacturing, without being resorted. This can limit the available cullet. One plant in London is currently licensed to produce 50 000 tonnes per year of

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pulverised glass for use as a sand substitute. This needs to be compared with the amount of waste collected. In the UK municipal waste amounts to 30 million tonnes per year.

It is also worth noting that the environmental impact of stockpiling glass to be fed into the recycling scheme is considered negligible, but its reuse requires processing and transportation and so in some circumstances could be looked upon as causing a greater environmental impact. It is possible to apply penalty figures to reflect the viability of long-term storage but, as with many figures used in sustainability calculations, these must be treated with some caution.

7.10.1 Glass in concrete

As glass is considered an inert material that can be used as an aggregate, an obvious suggestion was to use it as an aggregate in concrete. This has been taking place since the early 1970s (Phillips *et al.*, 1972). Initial attempts were made to use glass as a replacement aggregate in concrete but were unsuccessful. In the highly alkaline environment that is produced as concrete hydrates the silica in most glass is in fact slightly soluble. This phenomenon was first encountered in concrete when using aggregates such as chert in concrete with high cement contents but had not been extensively encountered when glass aggregate was first employed. After a period of time the aggregate would swell and produce a characteristic type of three-legged cracking. This type of degradation was known as alkali aggregate reaction, or AAR. In general, glass is more reactive than the other types of aggregate used so early attempts to use glass as aggregate were always destined to fail. Glass as an aggregate in concrete remained an attractive potential use and so further research has been undertaken to investigate the possibilities.

An extensive research programme was undertaken by the Building Research Establishment (BRE) on the use of glass in concrete (Moulinier *et al.*, 2006). Flint glass was used as a coarse aggregate obtained from Northern Cullet. The level of alkalinity required to produce a reaction between the cement and aggregate was calculated to be 5.5 kg/m^3 and a range of concrete mixes were produced. The range included mixes with alkalinity levels of 2.68, 4.84, 5.5 and 7 kg/m^3 Na_2Oeq. These represented a low alkali mix, and mixes just below, on or above the calculated alkalinity threshold. In addition a range of cement replacement materials was used. These materials are typically low-cost industrial by-products that harden in an alkaline environment and are often used to produce a more durable concrete. In addition to the conventional cement replacements such as ground granulated blast furnace slag (GGBS), pulverised fuel ash (PFA) and metakaolin, powdered glass was also used. The samples were then subjected to standard tests for harmful expansion for 815 days (RILEM method AAR3 – Concrete prism test; RILEM is the International Union of Testing and Research Laboratories for Materials and Structures). The level of expansion considered to be harmful in this test is 0.05% if it occurs in less than 1 year. Cracking typically appears at expansions of more than 1%.

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The data obtained from the testing carried out to RILEM AAR-3 demonstrated that samples made using metakaolin as a cement replacement showed no harmful expansion, even at the highest alkalinity levels. The low-alkalinity mix made with PFA also showed no damaging expansion. All other samples showed damaging expansion. Additional outdoor exposure tests were undertaken which provided broadly comparable results.

While this series of tests only used one type of glass it does show the difficulties with using glass as an aggregate in concrete. It also shows that with further research the use of glass as an aggregate in concrete may be possible using cement replacement materials, possibly in conjunction with low-alkali cements. However, research has reported that glass releases alkali with time (Meland and Dahl, 2001) and so the use of low-alkali cements has not proved a straightforward solution.

In addition to this, the environmental impact of using glass as an aggregate has been shown to be higher than that obtained when using sand as an aggregate (simplistically this would be expected since glass is effectively heavily processed sand).

The reactivity of glass that limits its use as an aggregate does allow it to be used as a cement replacement at levels of up to 20%. As the amount of energy required to produce cement is quite large this has a more positive environmental impact than the use of glass as a replacement for sand.

7.10.2 Glass with bitumen

The use of glass as an alternative aggregate in bituminous materials was pioneered by the University of Missouri Rolla in the late 1960s where the term 'glasphalt' is understood to have been coined. A complete discussion of the term glasphalt is contained within the *Glasphalt Paving Handbook* (Day and Schaffer, 1994). Glasphalt was developed as a reaction to the previously mentioned problem of multicoloured recycled glass, as an alternative to disposal of the material in landfill. The basic approach was to replace various percentages of the aggregate included in the asphalt with glass. The amounts replaced ranged up to 50%, but more commonly a figure of 10% is used.

A large number of trial projects were undertaken in the United States, but typically these did not progress to full-scale trials for economic reasons. In 1996, the Clean Washington Center issued a document (CWC, 1996) entitled 'Best practices in glass recycling' that stated:

> It is not considered economical in most parts of the United States to collect glass, process it to a specification aggregate, blend the glass with natural aggregate, add the batch modifiers needed to meet specifications, and deal with the operational changes required for glasphalt. The best possibility for sustained production of glasphalt is in communities with municipal asphalt plants, because the community can make a direct correlation between the extra costs incurred in glasphalt installation and

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the savings from diverted solid waste tip fees. The best possibility for sustained use of glasphalt by private sector asphalt manufacturers and contractors is through the creation of ongoing financial incentives to use the glass.

Typically the use of glasphalt in the United States is limited to areas with a maximum speed limit of 40 mph or less. This includes some roads, but more commonly it is used in footways or car park areas. There are some concerns over the use of glass in asphalt, caused primarily by the surface texture of glass. Unlike limestone, glass is not porous and so will not bond to asphalt as well. As the asphalt debonds from the glass, moisture can penetrate the resultant voids. As this moisture is subject to freezing or hydraulic action the surface can further deteriorate. In order to minimise this problem the maximum size of the glass material has been restricted to that assigned to a US number 8 sieve (2.36 mm).

In the UK, glasphalt has been applied to a heavily trafficked section of one of the major routes after a series of smaller trials. The M6 in Cheshire which carries over 120 000 vehicles a day with a speed limit of 70 mph has been resurfaced using glasphalt. Long-term information on the performance of this material is not currently available.

7.10.3 Unbound glass

In addition to its use as a road base, glass has also been used in trials as an alternative filter medium in water treatment, as an alternative to sand in the sports turf industry and as an abrasive for blasting. It should be noted that it is reported that while sand is not used as an abrasive blast media due to the risk of silicosis caused by crystallised silica, glass as an abrasive contains very small quantities of crystallised silica and so is currently classed as nuisance dust (www.wrap.org.uk).

In its unbound form glass can be crushed and graded and used as an inert fill or aggregate material for almost anything that natural sands can be employed for. However, as stated above, in order to produce glass in a useable form it starts out mainly as sand, then is processed into glass. As glass it is manufactured into a useable form and packaged and sold. Then it is used and returned to a collection point, from where it is sorted, crushed, washed and graded to form a useable aggregate. As such it can be argued that this reuse of glass is environmentally less sustainable than using natural aggregates, and that the drive to use glass in construction as an alternative to landfill is politically motivated.

7.11 Conclusions

Recycling of glass is complicated by the fact that a single form of glass is not used. Reuse of glass is the most environmentally efficient option, but this is becoming less frequent in the UK due to economic restrictions. At manufacturing plants, recycling of waste glass produced at source is common practice. The material is

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known as local cullet and its use is considered safe since the material has a known composition. Recycling via bottle banks and other glass collection schemes is the next most efficient use of waste glass but due to the risk of cross-contamination the material needs to be sorted prior to use in glass production. The limited number of glass manufacturing sites means that material recycled in this manner often has to be shipped a significant distance. In addition, the majority of the glass recycled is green, whereas the majority of the glass produced is colourless. This results in a surplus of returned green glass. The remaining glass that is not required for glass production can be used as a bound or unbound aggregate. At present, can not be used as an aggregate in concrete, due to its reactivity with alkaline environments. It can, however, be used as a bound aggregate in asphalt.

Alternative uses involve the glass being used as an unbound aggregate. From a sustainability viewpoint this is less efficient than using natural aggregates since the material has started out as a natural aggregate, and has then been heavily processed to produce glass.

7.12 Sources of further information and advice

Useful websites include:

- www.wrap.org.uk;
- www.britglass.org.uk;
- www.feve.org.

7.13 References

Clean Washington Center (1996) Best practices in glass recycling, ref. BP-GL4-02-01, CWC, Washington DC.

Day, D. E., Schaffer, R. (1994) *Glasphalt Paving Handbook,* University of Missouri-Rolla), Missouri, USA.

Meland, I., Dahl, P. A. (2001) Recycling glass cullet as concrete aggregates – applicability and durability. In *Recycling and Reuse of Glass Cullet*, Eds Dhir, R.K, Limbachiya, M.C. and Dyer, T.D, Thomas Telford, London, pp. 167–178.

Moulinier, F., Lane, S., Dunster, A. (2006) The use of glass as aggregate in concrete, Final report, The Waste and Resources Action Programme (WRAP), Banbury, Oxon.

Phillips, J. C, Cahn, D. S, Keller, G. W. (1972) Refuse glass aggregate in Portland cement concrete. In Proceedings of the 3rd Mineral Waste Utilisation Symposium, Chicago, Illinois, March.

Pilkington (2007) Pilkington and the flat glass industry 2007, available at http://www.pilkington.com/pilkington-information/downloads/pilkington+and+the+flat+glass+industry+2007.htm.

Wu, S., Yang, W., Zue, Y. (2005) Preparation and properties of glass asphalt concrete. In Workshop on Recycled Materials in Road and Airfield Pavements, organised by the Norwegian Public Roads Administration, 25 June, Oslo, Norway.

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8

Sustainability of engineered wood products in construction

H. R. MILNER
Monash University, Australia

Abstract: Engineered wood products are made from a variety of wood substances which are held together by an adhesive; the aim being to use the wood fibre more efficiently by redistributing and reinforcing natural defects and by forming the products into structurally efficient shapes unachievable by sawing, thereby doing more with less wood fibre. While additional energy resources are required to process engineered wood products they remain largely renewable and thus sustainable compared with competing materials that involve considerable mining. This chapter describes the manufacture of these wood products, reviews life cycle analysis (LCA) studies of their application to domestic housing and describes their use in larger public buildings.

Key words: engineered, wood, products, life cycle, sustainability

8.1 Introduction

There are many general definitions of and comments about sustainability. A list of these compiled by Pearce and Walrath (2008) (http://maven.gtri.gatech.edu/sfi/resources/pdf/definitions.pdf) occupies 83 A4 pages and contains an average of, at least, two definitions per page. The World Commission on Environment and Development (WCED) in their report, *Our common future*, (WCED, 1987) (http://www.un-documents.net/wced-ocf.htm), puts it as follows.

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

The report is comprehensive and covers many issues beyond the scope of this book but it does make the point in Chapter 8 that energy consumption per unit of gross domestic product (GDP) in OECD (Organsation for Economic Co-operation and Development) countries has been dropping at the rate of 1–3% every year

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since the late 1960s. It takes this one step further and becomes more specific in highlighting the fact that 'older pulp and paper mills typically used 160 cubic metres of water per ton of pulp; those built during the 1970s, however, used only 70.' It also points out that 80–200 tons of water are used in steel production per ton of crude steel but this could be reduced to no more than 3 tons by the simple expedient of water recirculation.

With engineered timber products wood fibre is used with increased efficiency exemplified by adhesively bonded structural I-beams which weigh only a fraction of their solid wood counterparts. A 360 × 70 mm I-beam, with 40 mm thick flanges and 10 mm thick web, involves only one-third the wood fibre of a solid member of the same overall dimensions yet, in bending, will carry 60% of the load of its solid equivalent.

Engineered wood products comprise interconnected wood-based elements that are used as structural building elements. Within this chapter attention will be confined to wood products that involve adhesive bonding, these include: glued laminated timber (glulam), plywood, laminated veneer lumber (LVL), chipboard or particleboard, oriented strand board (OSB), parallel strand lumber (PSL) and structural I-beams. The reasons for using progressively more engineered wood products include:

- restrictions on harvesting in old-growth native forests which, in the past, were able to provide large structural sections, and a tendency towards using less mature and thus physically smaller, plantation grown trees;
- a desire by producers to reduce waste in the timber industry and to make greater use of the wood fibre available.

Other forms of engineered wood products involve nail-plating, but adhesive bonding is, by far, the most common, versatile and cost-effective interconnection technique.

8.2 Engineered wood products and sawn timber products

Sawn timber products are sold in 'stress grades' that limit knot size and the level of sloping grain. In particular, knots that occupy a large proportion of the cross-section cause local deviations of the grain direction and weakness due to the perpendicular-to-the-grain strength of timber being only one-tenth of its parallel-to-the-grain strength. While not all pieces in a production run have the same level of strength-reducing features it means that many pieces within the same timber grade could be designed using markedly higher stress levels if these were identified and marketed separately, although this is difficult in practice. Engineering design values are based on lower fifth percentile strengths and some softwoods, graded to a set of tightly defined rules, still exhibit coefficients of variation of around 0.4; this therefore implies that something like 90% of the pieces have

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strengths 1.5 times greater than their nominal design values which appears to imply considerable wastage of the wood fibre. With engineered wood products, the natural defects are redistributed which reduces coefficients of variation to 0.2 or less, allows the use of higher design stresses and makes more efficient use of the material. Engineered wood products have:

- the potential to exhibit high strength to weight ratios and use the raw material efficiently;
- a capacity with some engineered timber products (particleboard, medium density fibreboard and hardboard) to use the waste material from sawmilling operations and the manufacture of other engineered wood products;
- an ability to be reinforced by other materials (limited quantities of steel and exotic fibres including carbon, aramid and glass) to gain even higher efficiency;
- a capacity to use low-grade wood fibre by positioning it where low stress levels will exist in service;
- the characteristic that, while requiring more energy than sawn timber, they still use little energy in their production relative to manufactured materials such as steel, concrete and masonry;
- the capacity to act as carbon sinks during their service life;
- potential usage as fuel at the end of their life cycle, but releasing no more CO_2 than was absorbed during the growth of the original wood.

Recovery of wood fibre from the harvested log is a major problem for the timber industry. With the logs used to produce plywood, LVL and PSL it is possible to recover around 50% of the available log fibre volume. This figure is comparable with sawn timber recoveries. Sawn timber waste is largely a consequence of cutting rectangular timber from a log that is approximately round and tapered. Plywood, LVL and PSL involve log peeling but there exists a spindle core that cannot be peeled; see, for instance, Asia-Pacific Forestry Commission report on *Availability and use of mill residues* (http://www.fao.org/DOCREP/003/X6966E/X6966E02.htm) (Asia-Pacific Forestry Commission, 2001). Other engineered wood products such as particleboard are able to use sawmilling waste. Finally there is the issue of end-of-life disposal. A comprehensive review of end-of-life disposal issues by Taylor *et al*. (2005) can be viewed at http://www.fwpa.com.au/content/pdfs/PN05.1017.pdf. Taylor *et al.*'s report reviews legislation covering recycling, end-of-life disposal, contamination control, technologies for heat and energy production, wood preservative treatment and engineered wood products.

8.3 Products and raw elements

8.3.1 Finger jointed timber

Applications

Finger jointed timber (Fig. 8.1), is being increasingly used in domestic house

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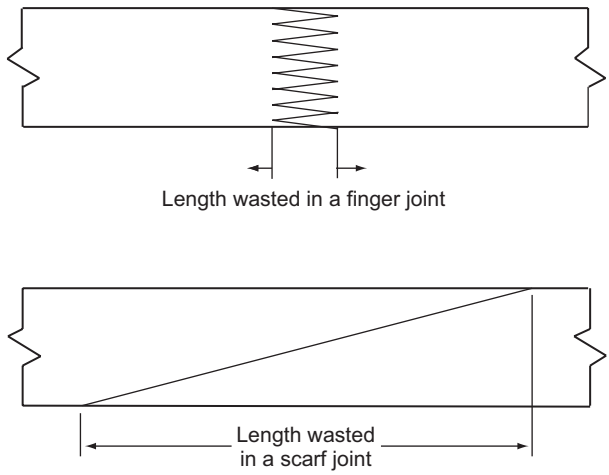

8.1 Finger and scarf joining timber illustrating the efficiency of finger jointing.

construction for wall studs and floor and roof framing members. There are some reservations over the reliability of finger jointed timber where it forms the sole load path and the loading is heavy tension or bending action but this is much less of an issue in domestic house construction where the level of structural redundancy is quite high. If suitable manufacturing safeguards are put in place, such as proof loading of finger joints, finger jointed timber can be a highly reliable form of timber construction. There have been concerns about using finger jointed timber in the bottom chords of roof trusses that are loaded in tension under dead and live load, especially in girder trusses which may be the sole load-carrying element for quite large roof areas.

Manufacture

Finger jointing is a waste reduction technology rather than an engineered wood product but does fall into a broader category of adhesively bonded timber that is used structurally. Timber elements are formed from 'mill shorts', i.e., short lengths of timber that arise from normal sawmilling operations. Because tree trunks taper, sawing methods invariably result in the production of short lengths that have no market value as sawn timber. These tapered sections can be further processed into chip and used to make other products as discussed below but the short, non-tapered sections can be end joined to form longer, usable lengths. Finger profiles are cut into the ends, adhesive is spread on one or both mating faces and the fingers pressed together. The concept of finger jointing evolved from scarf jointing, a much more wasteful jointing strategy, given that the taper angle is usually around 8° (see Fig. 8.1). Finger jointing also possesses processing advantages. With scarf

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joints, external clamping is required while the adhesive hardens but, with finger joints, the fit is sufficiently close that the timber, with care, can be handled prior to glue hardening. Production lines are usually arranged such that the joints are heat or radio-frequency cured and approach their final strengths within a short time frame.

8.3.2 Structural glulam

Applications

Structural glulam is an adhesively bonded timber product that is used extensively in larger scale timber structures (see Fig. 8.2). In its most general form it comprises a series of laminates (Fig. 8.3) having thicknesses in the range of 20–50 mm. There is no upper limit to the width and depth and members up to 1500 mm in depth and 250 mm in width can be manufactured and used to freely span substantial distances when used in an appropriate structural form. It can be pre-cambered to counteract the effect of dead load deflections and also curved with thin laminations down to a radius of the order of 10 m or less to produce a wide range of architectural shapes. Some structural forms involve bonded reinforcement of high-strength fibres (carbon, glass, aramid) or embedded steel; other forms involve curved shapes that are used in structural forms that permit external tension reinforcement such as with tied arches.

The fact that glulam spans considerable distances and is produced from relatively small diameter saw logs also means that the laminates have to be end (finger) jointed and, for wider glulam, also edge jointed (see Fig. 8.3). Structural glulam has engineering design properties exhibiting coefficients of variation of between 15 and 20% which is a consequence of redistributing and reinforcing defects, especially knots and sloping grain. The finger jointing quality is critical to the maintenance of consistent properties.

Manufacture

Details of the manufacturing method for structural glulam can be found on the Canadian Wood Council website (http://www.cwc.ca/NR/rdonlyres/5B9FFB1C-409C-4B65-BE03-338CC172F5EC/0/Glulam.pdf) but the major steps are outlined below.

- *Sawing and drying of the laminates.* Glulam manufacture commences with sawing logs to typical sawn timber (lumber in Canada and the USA) sizes and then kiln drying the material to a moisture content of around 10%. Typical laminating lengths, known as ‘shooks’ in Australia and New Zealand, are in the range of 2–4 m.

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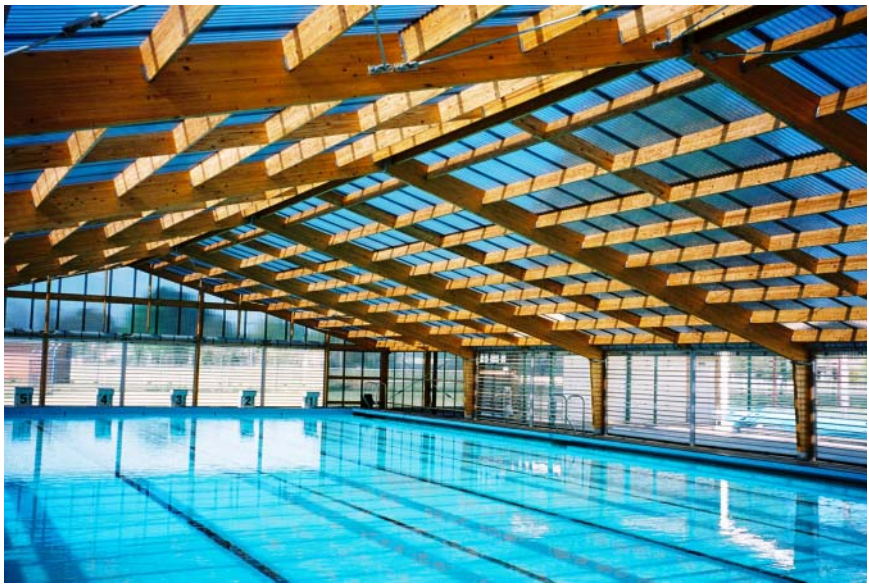
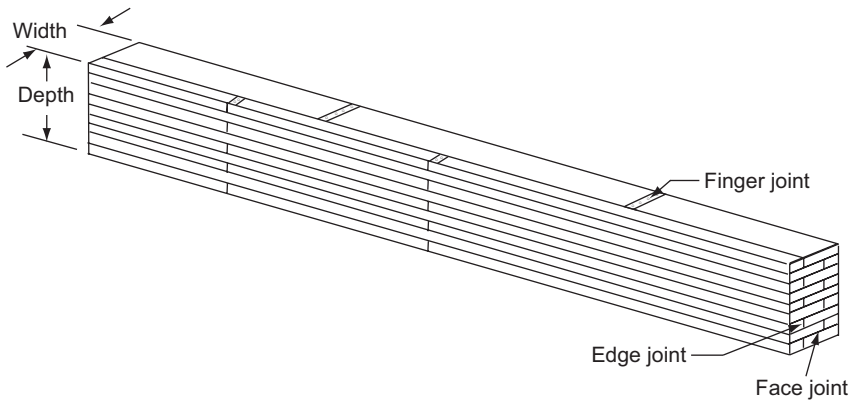


8.2 Swimming pool enclosure, Guyra, Australia. Courtesy of Hyne, Australia.



8.3 Large glulam member, with finger joints through the wide face. Finger joints can also be placed on the side face of the laminations.

- *Grading*. The laminates are graded, with the higher grade material being placed in the outer zones where higher stresses are present in bending applications. It is also possible to use higher modulus of elasticity (MOE) material which has a relatively high level of defects provided that these defects are removed by docking.
- *Finger jointing*. The shooks are finger jointed to form laminates of length equal

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to the length of beam that is to be manufactured, after which the end joint adhesive is allowed to cure.

- *Face dressing and initial assembly*. The laminates are commonly dressed then assembled dry in the sequence for which they are required in the final assembly.
- *Glue spread, lay-up and pressing*. The laminates are passed through a glue spreader that coats the face and edge joints; this is followed by assembly in a press. Once glue spread and assembly are complete, face pressures are applied of approximately 600 kPa for softwoods and 1 MPa for hardwoods. Any curvature required for a particular design is imparted to the beam within the press. It is also common for pre-camber to be built into the member to counteract the effect of dead loading but care is then required in construction to ensure that any beams are installed with the camber upwards.
- *Adhesive cure*. The adhesive is allowed to cure, usually by heating the pressed assembly.
- *Finishing*. The completed assembly is completed by dressing to size, sanding and filling of minor defects. It is usually wrapped in plastic for delivery to a construction site. Care is required to keep the product dry once it arrives on site.

8.3.3 Structural composite lumber

Applications and description

Structural composite lumber (SCL) is of US origin, as the use of the term 'lumber' suggests. The American Forest & Paper Association (AFPA) website (http://www.woodaware.info/PDFs/SCLandGlulam.pdf) (AFPA, 2008) categorises SCL according to its method of manufacture. The first manufacturing method relies on rotary peeling of logs (LVL (see Fig. 8.4) and PSL) and the second (laminated strand lumber (LSL) and oriented strand lumber (OSL) relies on a stranding process.

All SCL products are used as beams and can substitute for sawn timber in application, i.e., they can be used as joists, rafters and similar structural elements. They have engineering design properties with a very low statistical coefficient of variation of between 10 and 15% which implies that, on average, the wood fibre is being used more efficiently. According to the AFPA: 'Advancements in technology have given SCL manufacturers the ability to take apart a smaller log, sort the pieces, apply adhesive, and reassemble them back together into an engineered product. SCL products have grown in popularity because of the ability to manufacture long lengths and large cross-sectional dimensions with consistency.'

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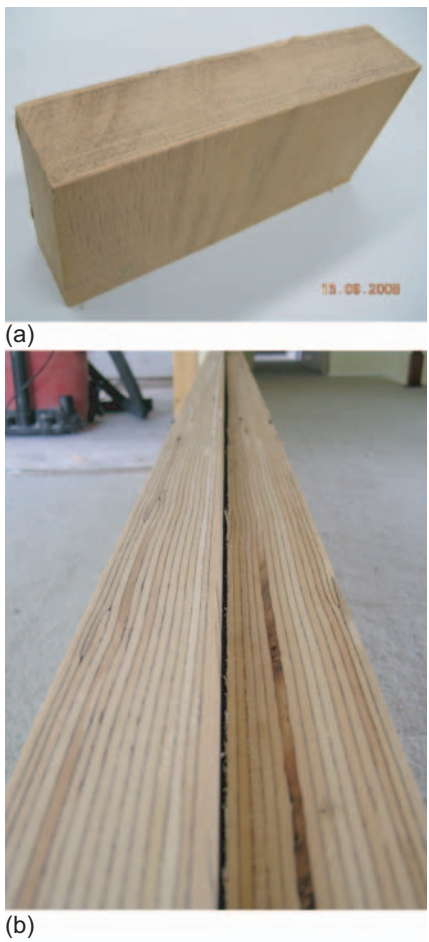
Manufacture

Again following the AFPA,

> Structural composite lumber products are produced through two primary log-processing methods – stranding and rotary peeling. The manufacturing process for all SCL typically includes sorting and aligning the strands or veneer, applying adhesive, and pressing the material together under heat and pressure. By redistributing natural defects, sorting for stiffness or density, and through quality control procedures, the resulting product is uniform. Stranding slices the entire log into 3-inch to 12-inch strands, similar to grating a block of cheese.

Further details are available on the AFPA website.



(a)

(b)

8.4 Laminated veneer lumber, a form of structural composite lumber.

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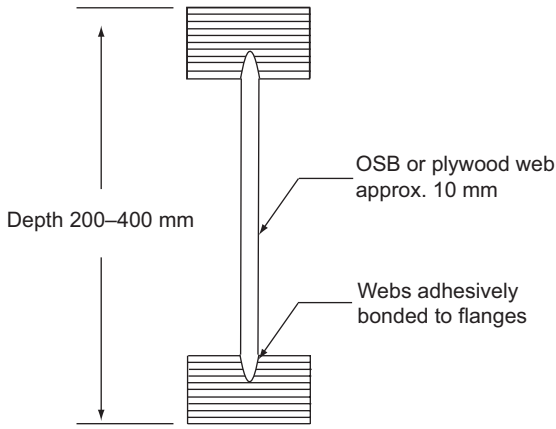

8.5 Typical timber I-beam cross-section.

8.3.4 Structural I-beams

Applications

According to Leichti *et al*. (1990) structural I-beams are old in concept, having been used in aircraft construction in the 1920s, but have only been used more widely in housing in recent times. They have found their way into timber construction as intermediate as opposed to main frame members, including floor and roof joists or purlins. Structural I-beams take the use of wood fibre to an extreme of efficiency and are very easy to handle due to their extremely high strength to weight ratio. Typically they use webs of OSB or plywood, see Section 8.3.5, and flanges of sawn timber or LVL (see Fig. 8.5).

Manufacture

The flanges are either sawn timber or SCL, the production of which has been described in Section 8.3.3. With sawn timber flanges it is usually necessary to finger joint the component pieces which can then be proof tested in tension prior to forming the final product. Subsequently, the flanges are grooved, the taper cut into the OSB or plywood web, the webs scarf jointed and, finally, the flanges and webs bonded. All adhesive curing is undertaken using radio-frequency methods.

8.3.5 Oriented strand board

Applications

OSB is a product of US origin described by Elmendorf (1949) and later patented (Elmendorf, 1965). According to Bailey (1996) a product called waferboard

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appeared on the market in the 1970s and the modern product now known as OSB developed from there. The information established by Bailey (http://fennerschool-associated.anu.edu.au/fpt/osb/2.html) contains considerable detail that can be read by the reader seeking access to more detail than contained in this chapter. OSB finds application in a variety of board applications as shear wall, sheathing and flooring. It is also used extensively as the web of I-beams.

Manufacture

OSB can be manufactured from low-grade wood plantation species which are chipped into flakes typically 0.5–0.7 mm thick, 19–38 mm wide and around 76 mm long; the long direction corresponds to the grain direction. Chip size is chosen to optimise resin use; usually phenol formaldehyde. The boards (typically 2440 × 1200 mm) are usually made up in three layers with the chips in the middle layer aligned approximately parallel to the 1200 mm edge and approximately parallel to the 2400 mm edge in the two surface layers. This gives the board reasonable strength and stiffness in the two directions. Typical lengthwise and transverse modulus of rupture (MOR) values are 30 and 20 MPa respectively and MOE values are 5 and 2 GPa respectively. OSB finds application wherever particleboard and plywood are used (e.g. flooring and sheathing) but is considered unsuitable for concrete formwork – where plywood is preferred; OSB is being used increasingly in more highly transformed timber products such as structural I-beam webs. The major steps involved in its manufacture are described briefly below.

- *Debarking and log docking*. After harvesting, transport and assembly at the mill site, the logs are debarked then docked into billets of a length that can be accommodated by the chipper or waferiser.
- *Chipping or waferising*. The billets are reduced to chips or wafers (sometimes called flakes or strands) in a machine that contains several hundred serrated knives which rotate at several hundred revolutions per minute. The fines are separated and then added back to the surface layers to provide a better quality finish.
- *Drying*. The wafers are next dried to approximately 5% moisture.
- *Resin application*. The wafers are then mixed with a powdered resin or are sprayed with a liquid resin at a rate in the range 2 to 6%.
- *Lay-up*. Lay-up occurs on a running belt that aligns the wafers by means of electrical field or by vibration. The surface layers are aligned in the belt direction and the core transversely. The unpressed lay-up is between 100 and 200 mm high.
- *Pressing*. The mat is cold pressed to allow air and water to escape and then hot pressed at around 205°C for approximately 10 minutes. The sheets are allowed to cool then finally finished to size.

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8.3.6 Plywood

Applications

Plywood is a sheet product used extensively in engineering construction in applications such as formwork for concrete, flooring, sound barriers in freeway construction, composite beams (webs in nailed box beams) as well as in non-structural applications such as furniture, wall panelling and the like. It is manufactured from larger diameter logs by a peeling process and performs its job economically by producing a high-strength product with very consistent properties, i.e., the engineering design properties have a low statistical variability of approximately 15%. The veneers are typically of the order of 1.5–3 mm thick and are arranged such that the wood grain runs at 90° in alternate plies which imparts strength and stiffness in both sheet directions. It is typically built up with an odd number of plies to thicknesses of between 3 and 30 mm.

Manufacture

The description below follows details given in the website of the Engineered Wood Products Association Australasia (Engineered Wood Products Association of Australasia, 2007).

- *Conditioning*. Following harvesting, transport and assembly at the mill site the logs are first conditioned in a heated water bath or by steam curing. It is important that good-quality logs be used and that these are not allowed to dry and split as this would severely disrupt the veneer peeling process that follows.
- *Peeling*. Logs are cut into billets and located in the spindles of the lathe. Because the logs are not perfectly round and taper to some extent, this is best achieved using a laser scan which establishes how to best position the billet to achieve maximum log recovery. The veneer is then peeled in its wet condition by rotating the billet against a lathe knife to form a continuous ribbon. Any splits in the log would disrupt the continuous ribbon which is a major reason that care must be taken with the logs in the stacking area by continuously spraying them with water.
- *Drying*. The ribbon can be clipped into shorter lengths before drying or can be dried as a continuous ribbon. Drying is continued until the veneer moisture content is between 6 and 12%.
- *Grading*. The veneers are next graded according to defect level. Typically, in appearance-grade plywood the higher quality defect-free veneers would be used for the outer plies.
- *Lay-up and bonding*. Adhesive is applied to the veneers, after which they are 'laid up' with the grain at right angles in each alternate veneer. Only one face of each veneer is glued. The sheets are typically rectangular in shape. The grain direction in the two face veneers is aligned in the long sheet direction.

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- *Pressing*. A cold press is applied to facilitate adhesive spread. After cold pressing, the plywood is hot pressed between platens heated to a temperature of around 140ºC and a pressure of around 1 MPa for a period of approximately 10 minutes.
- *Finishing*. After pressing the sheets are sprayed with water and allowed to cool; they are then trimmed to precise dimensions and the faces are sanded.

8.3.7 Chipboard or particleboard

Application

Chipboard (US, European and UK terminology) or particleboard (Australian and New Zealand terminology) involves the adhesive bonding of wood chip into a board product. Because of its low cost it is used extensively as a structural product in flooring in Australia and New Zealand. In recent years Australia has introduced requirements into the Building Code of Australia that require thermal insulation to be placed under the floor to limit heat transfer. This has required the placing of insulation under the flooring and introduced construction problems that threaten its viability. It has even been used as a shear wall. Elsewhere the product is used only in furniture construction and non-structural applications.

Chipboard has the virtue that it can be manufactured from relatively low cost wood chip. Typically it has an MOE in the range of 2–3 GPa and an MOR in the range of 9–20 MPa. Typically, its MOR parallel and perpendicular to the long edge of the sheets does not differ greatly although there is a slight tendency for it to be stronger in the long edge direction. Its density is typically around 250–400 kg/m^3.

Manufacture

A detailed description of the manufacturing process can be found on the Australian Wood Panels Association website (Australian Wood Panels Association, 2001). An abridged version is given below.

Wood particles or flakes constitute 80–90% of the weight of particleboard, usually made from pine species that come either from forest thinnings or sawmill residues. The binder (resin or adhesive) and the amount used, play a key role in the stability of the final board. Synthetic resins are generally used which, because their formulation can be varied, have the advantage of flexibility of curing time. In addition, they are thermosetting and cure rapidly and irreversibly by the application of heat. The amount of resin used is usually in the range of 4–12% of the dry wood weight. However this proportion may vary according to the type and size of wood fibres or particles. For example, in three-layer particleboard, the coarser core material may contain 4–10% resin, while the finer surface layers may have 10–12% resin.

Heat energy is required for drying, hot oil for the hot press and steam for

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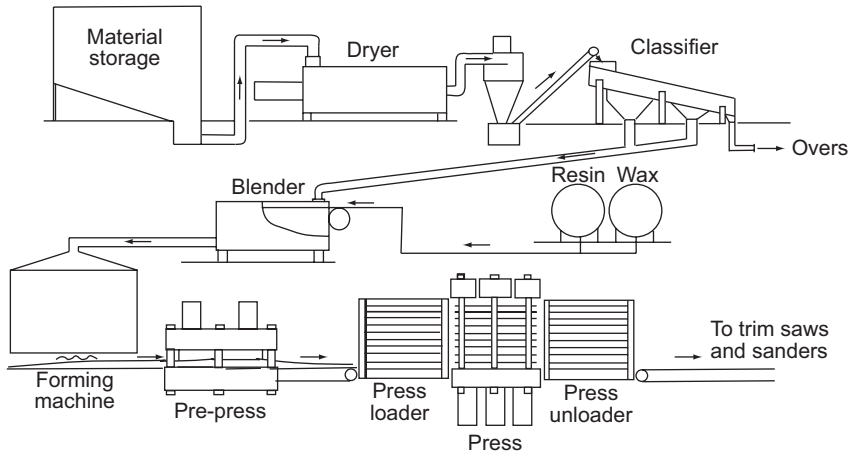

8.6 Particleboard manufacturing process.

pressing operations. Wood particles are passed through driers that reduce their moisture content to 3–5%. Most modern driers are direct-fired in that the particles are dried by direct contact with hot gas from the burners.

Resin, in the form of a liquid, is forced through nozzles and sprayed onto the particles, in a separate 'blender'; after this it is formed into a mat which is then subjected to heat and pressure to cure the resin and produce a board of the required thickness. Boards are sanded prior to sale or prior to prefinishing with various surface and edge treatments. The rough panels of particleboard and medium-density fibreboard (MDF) are trimmed after pressing and can be cut to size as required. The overall process is illustrated schematically in Fig. 8.6.

8.3.8 Fibreboard

Fibreboard types and applications

The primary types of structural fibreboard include MDF and hardboard, also known as high-density fibreboard or masonite. The latter name is strictly a trade name. Only the application and manufacture of MDF is described in this section.

MDF is a wood-based composite board that has a higher density than particleboard, in the range 600–800 kg/m^3, an MOR of 40 MPa and an MOE of 3 GPa. Because it is easier to machine and has good weathering characteristics it is tending to replace particleboard in applications such as furniture, cabinet making, joinery, craft work and flooring. It can be made from a variety of fibrous products including softwoods, hardwoods, bagasse, rubber wood, cotton stalks and other raw products.

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Manufacture

MDF comprises fibrous materials that have been broken down into the tracheids and vessels that make up the cellular structure of wood. The basic procedure is detailed below.

- *Debarking and log docking.* After harvesting, transport and assembly at the mill site, the logs are debarked then docked into billets of a length that can be accommodated by the chipper.
- *Chipping.* The billets are reduced to chips.
- *Pulping.* Pulping is the process that most distinguishes MDF from particleboard. In this process the chips are broken down into the tracheids and vessels that make up the basic cellular structure of wood. The end result of this process is a dispersed fibrous mass.
- *Blowline.* Following defibration the fibres enters the blowline where they are sprayed with wax and resin.
- *Lay-up.* Lay-up occurs on a running belt followed by a cold press that produces a mat of thickness between 250 and 600 mm.
- *Pressing.* The mat is hot pressed and during this time the adhesive cures. The sheets are allowed to cool then finished to size. Various finishes may be added.

8.4 Structural life and service environment

Human societies value so-called 'buildings of antiquity', especially those deemed to have historical significance such as the Egyptian pyramids and, the buildings of ancient Rome. However, not every building is held in such high regard and, indeed, the majority of buildings are commonly deemed to be perfectly satisfactory if they have a service life of 50 years. Typically because they become functionally obsolete as opposed to becoming structurally deficient. Structures such as tunnels, sewers, major bridges and dams tend to remain useful for much longer periods and are much more difficult and expensive to renovate or replace and, accordingly, a longer service life is desirable. It is now the practice in some cases of major bridge structures to specify service lives of 300 years in design/build contracts.

With adhesively bonded timber products, it would appear that a 50 year life is reasonably achievable in terms of the current state of adhesive bonding technology, the ease with which timber structures can be dismantled and the materials recycled, and the rotation periods for the harvesting of plantation timbers, also, typically, 50 years.

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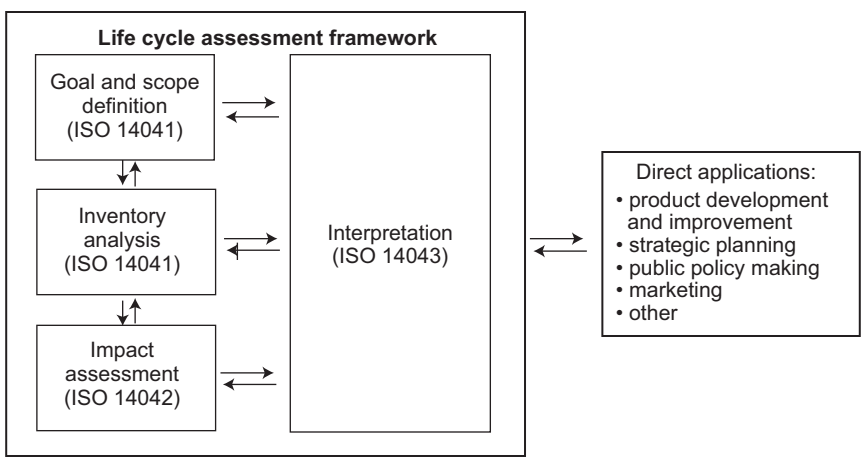
8.5 Sustainability, life cycle analysis and embodied energy

8.5.1 Introduction

At the beginning of this chapter sustainability was defined qualitatively. This definition does not lead to any measurable targets by which the performance of a company, building product or construction project can be evaluated. There are, however, sustainability indices in existence. Dow Jones is a subsidiary of News Corporation and a leading provider of global business news and information services; it publishes, among other things, sustainability indices (see http://www.sustainability-index.com/07_htmle/indexes/overview.html). The indices are specifically relevant to the industry sector and cover companies involved in mining, manufacturing, finance, retailing, etc. and also criteria related to economic, environmental and social factors. As such they are not widely applied in the building construction sector.

With building activity, government legislation in many jurisdictions requires that certain environmental criteria are met by the building industry. In New South Wales, Australia, new construction and building alterations are assessed using computer software (BASIX) that awards credit points on the basis of features that control operational sustainability parameters related to water usage, thermal comfort and operational energy. Once the construction details are entered (includes roof area, site area, geographic location, air-conditioning details and landscaping – including the planting of native vegetation etc.), the data are processed to determine the indices and the proponent is advised whether the construction meets targets set by government. If it fails to do so, a building permit



8.7 Life cycle assessment framework as laid down in ISO 14040:1997 (ISO, 1997).

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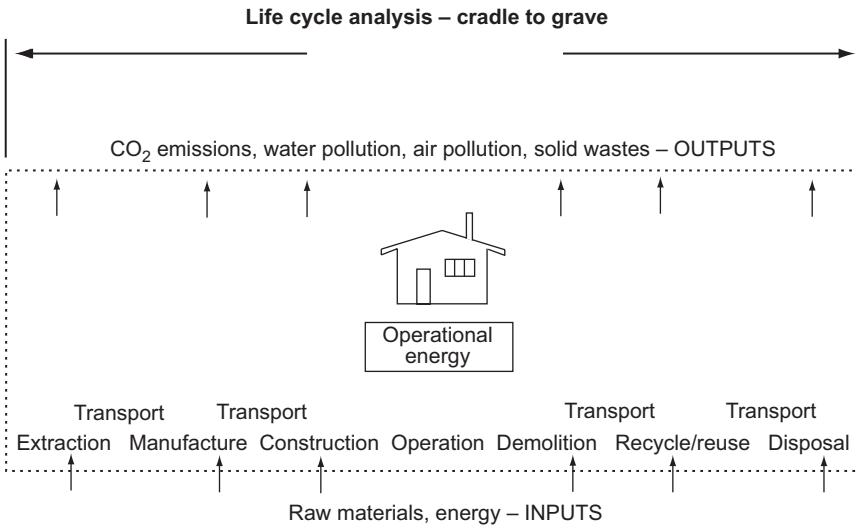

8.8 The cradle to grave approach.

will not be issued. Where the requirements are not being met, advice is given on the sort of changes necessary.

Analysis of sustainability of building construction materials and assembled buildings containing a mix of materials is usually conducted in accordance with a life cycle analysis (LCA). LCA examines the total impact of a material or product throughout its life according to methodology standardised in ISO 14040 (ISO, 1997) (see Fig. 8.7). This is not a straightforward matter as difficulties exist with its application to buildings as a whole in such matters as the definition of problem boundaries, e.g. the inclusion or exclusion of embodied energy associated with urban infrastructure. It is perhaps most commonly performed with the assistance of computer software, simPRO being the best known, which has the capacity to access the considerable database necessary to provide the information required.

8.6 Life cycle analysis

8.6.1 Introduction

The development of the ISO 14040–14043 series of standards has placed LCA on a disciplined footing. The general framework is illustrated in Fig. 8.7 and, when fully implemented, can be described as a 'cradle to grave' approach (Fig. 8.8). The term 'cradle to grave' is used to signify the impact of harvesting, manufacture, on-site construction, operation of the building, decommissioning and disposal of waste. In the case of timber products or products from a renewable source the analysis could be taken a stage further to that of 're-birth'. With other products made from non-renewable raw products there can be no re-birth; for example, the

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Table 8.1 Embodied energy values for selected construction materials including some engineered wood products; source, www.yourhome.gov.au/technical/pubs/fs52.pdf

Material	Process energy requirement embodied energy (MJ/kg)
Kiln-dried sawn softwood	3.4
Kiln-dried sawn hardwood	2.0
Air-dried sawn hardwood	0.5
Hardboard	24.2
Particleboard	8.0
MDF	11.3
Plywood	10.4
Glue-laminated timber	11.0
Laminated veneer lumber	11.0
Plastics – general	90
Polyvinyl chloride	80.0
Stabilised earth	0.7
Imported dimension granite	13.9
Local dimension granite	5.9
Gypsum plaster	2.9
Plasterboard	4.4
Fibre cement	4.8
Cement	5.6
In situ concrete	1.9
Precast steam-cured concrete	2.0
Precast tilt-up concrete	1.9
Clay bricks	2.5
Concrete blocks	1.5
Glass	12.7
Aluminium	170
Copper	100
Galvanised steel	38

coal extracted to make steel cannot be recovered from the steel. In this chapter, only the results of selected LCA studies are reported, not descriptions of the methodology.

8.6.2 Process energy requirement of selected building products

The most often quoted output from full LCAs is the cradle to grave energy use but most analyses are limited to so-called 'cradle-to-gate' analyses of so-called 'embodied energy'. According to Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), embodied energy can be defined as 'the energy consumed by all of the processes associated with the acquisition of natural resources to the production of a building, from the acquisition of natural resources to product delivery, including mining, manufacturing of materials and equipment,

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Table 8.2 Embodied energy (in MJ/m^2) of typical structural assemblies; source, Lawson (2006)

Assembly	Process energy requirement embodied energy (MJ/m^2)
Walls	
Timber frame, timber weatherboard, plasterboard lining	188
Timber frame, clay brick veneer external wall cladding, plasterboard lining	561
Timber frame, aluminium weatherboard, plasterboard lining	403
Steel frame, clay brick veneer, plasterboard lining	604
Double clay brick, plasterboard lined	906
Cement stabilised rammed earth	376
Floors	
Elevated timber floor	293
110 mm concrete slab on ground	645
200 mm precast concrete T-beam/infill	644
Roofs	
Timber frame, concrete tile, plasterboard ceiling	251
Timber frame, terracotta tile, plasterboard ceiling	271
Timber frame, steel sheet, plasterboard ceiling	330

transport and administrative functions'. Such analyses are impractical to perform since, in the case of wood products, they involve energy in planting, growing, transport to a manufacturing facility and, even before that, the energy involved in manufacturing the machinery involved and developing the road network along which the machinery must travel. It even involves the mining of metals to make the machinery which imposes insuperable difficult difficulties on where to limit the analysis. Process energy requirements (PER) are much simpler to quantify and are limited to measuring 'the energy directly related to the manufacture of the material'. PER can be measured in terms of mega-joules per kilogramme (MJ/kg) or similar units; see Table 8.1 which is an abridged version extracted from http://www.yourhome.gov.au/technical/pubs/fs52.pdf. These data are of limited value in that they take no account of the amounts of material required to complete a specific task.

8.6.3 Embodied energy of structural assemblies

What is more helpful is a measure of the embodied energy involved in completing typical assemblies since this also accounts for the structural efficiency of the material. The embodied energies for typical assemblies are given in Table 8.2. These data do not differentiate between sawn timber frames and those constructed from engineered timber products. In general, the higher the proportion of timber involved the lower the embodied energy.

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Table 8.3 Data as summarised by Eriksson (2004), collected from a variety of studies

Research study	Timber		Steel		Concrete	
	Cradle to gate energy use (MJ/m^2)	GWP (CO_2 equiv. kg/m^2)	Cradle to gate energy use (MJ/m^2)	GWP (CO_2 equiv. kg/m^2)	Cradle to gate energy use (MJ/m^2)	GWP (CO_2 equiv. kg/m^2)
Trahus Project, Sweden	–530	30			1770	400
Project Athena, Canada	1140	280	1760	340	2520	420
CORRIM, northern USA	969	207	1604	309		
CORRIM, southern USA	580	100	810	170		
Lund Institute of Technology, Sweden	680				1900	
Chalmers University, Sweden	840	40			1430	110

Note: Each study used different building structures, boundary conditions and units so that the data between projects are not comparable.
GWP, global warming potential; GWP is a factor that describes the GWP of all greenhouse gases (GHGs) relative to one unit of CO_2. GHGs include any of the following: CO_2 (carbon dioxide); CH_4 (methane); N_2O (nitrous oxide); PFCs (perfluorocarbons); HFCs (hydrofluorocarbons); and SF_6 (sulphur hexafluoride).

8.6.4 Completed buildings

Examples cited by Eriksson (2004)

Eriksson (2004), at the Eighth World Conference on Timber Engineering, summarised details of six studies undertaken by a range of different institutes in Sweden, Canada and the USA (see Table 8.3). Because the studies were performed on different building structures they should not be compared when reading down the table but can be compared when read horizontally, reflecting the choice of construction material. The output from the studies includes:

- cradle to grave energy use (MJ/m^2 of plan area);
- global warming potential (GWP, in terms of kg/m^2 of CO_2 equivalent gas produced).

The point is made that across all of these studies, in 'all cases, the wood structure results in lower energy use and global warming potential (GWP) than the alternatives, regardless of differing boundary conditions applied in the different studies'. Eriksson emphasised that care needs to be taken in selection of boundary conditions as this made comparisons difficult. The term 'boundary conditions' refers to where inputs to the LCA should be truncated. For example, goods need to be transported in the manufacture of timber products, which needs trucks, which need steel, which need coal, which needs steel, etc.

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Table 8.4 Positive and negative effects of forest utilisation

Positive effects	Negative effects
• General positive function of a diverse ecosystem	• Influence the natural processes of the ecosystem 'primary forests' (e.g. changing plant societies and age structure of trees)
• Use of solar energy and carbon dioxide and its conversion into wood as an important fuel and raw wood	• Use of fossil energy for the necessary operations
• Forests and wood function as carbon sinks	• Use of land and soil
• Wood is renewable and, by sustainable forest management practices, permanently available	
• Forests function as air cleaners	
• Forests protect soil, water and wildlife	
• Forests have a recreational function	
• Forests are part of the natural landscape	

Forest and Agricultural Organisation study

Scharai-Rad and Welling (2002), in a study undertaken for the Forest and Agricultural Organisation (FAO) of the United Nations, come to similar conclusions to those in the studies reported by Eriksson. The report first lists positive and negative effects that ensue from the use of renewable forest products; these effects are reproduced in Table 8.4. The study covered three different forms of house construction, and two different types of three-storey buildings. Much of the data used were based on earlier studies so that this report is a rich source of further data. A number of outputs are described in the FAO report including:

- energy for construction;
- acidification potential (AP), expressed in terms of SO_2 equivalent, indicates the likelihood of acid rain;
- eutrophication potential (EP), expressed in terms of phosphate equivalent, is increased by sewage and fertilisers use in agriculture; a high EP can lead to growth of algae in water, and render plants susceptible to disease;
- photochemical ozone creation potential (POCP), expressed in terms of ethene equivalent; a high POCP is associated with the production of summer smog.

The three houses studied included:

- a timber frame house made of wood, wood-based materials and mineral-based materials but with the share of wood-based materials being relatively high with a total covered floor area of 136 m^2;

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- a block house made of wood-based materials with an extremely low mineral-based material content and with a total covered floor area of 170 m^2;
- a brick house made from predominantly mineral-based materials with the use of wood-based materials being typical of the level of usage in Central Europe and with a total covered floor area of 136 m^2.

The energy inputs required to construct the dwellings (cradle to gate) are summarised in Table 8.5. The conclusion drawn by Scharai-Rad and Welling (2002) is that the 'energy inputs amount to 41 100 kW h for the brick house and 34 250 kW h for the timber-frame house as well as for the block-house which, therefore, demonstrates that energy consumption for the brick house is far above that for other houses. On the other hand, both the timber-frame house and the block-house contain much more renewable materials that can be utilised as CO_2-neutral fuel …'. It also needs to be realised that all house types include a concrete basement which, in the case of the two timber houses, triples the weight of construction materials and increases the brick house weight by around 80%.

Scharai-Rad and Welling's report also covers other outputs from the three houses including GWP, AP, EP and POCP. This analysis is carried out on two bases described as Case A and Case B. In Case B the waste wood at the conclusion of the project is used for thermal purposes which are then deducted from the Case A outputs. The results are presented in Table 8.6. Overall they report favourably about the virtues of wood-based products with respect to these parameters.

The issue of wood use at the end of the life of a structure in terms of LCA is controversial with different investigators treating the matter differently. Much depends on the investigator's view of sustainability. Certainly timber is capable of rebirth in the sense that it is largely composed of CO_2 and to CO_2 it can return whether by way of natural decay or burning. The CO_2 is then converted back to trees to complete the carbon cycle. If timber is placed in land-fill, the lack of oxygen means that it decays very slowly. The Cooperative Research Centre for Greenhouse Accounting indicates a loss of wood mass in land-fill of around 1.4–3.5% over a 50 year period; see http://www.greenhouse.crc.org.au/counting_carbon/wood.cfm. On the other hand, using coal or oil to manufacture cement

Table 8.5 Energy input for construction of three house types as reported by Scharai-Rad and Welling (2002)

House type	Covered floor area (m^2)	Energy input (kW h)	Energy input (kW h/m^2)*
Timber frame house	136	34250	252
Timber block house	170	34250	201
Brick house	136	41100	302

*Data not included in the original report.

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Table 8.6 GWP, AP, EP and POCP results for construction and adjustments made for use of waste timber as reported by Scharai-Rad and Welling (2002)

	GWP (kg CO_2 eq.)	AP (kg SO_2 eq.)	EP (kg phosphate eq.)	POCP (ethene eq.)
Case A				
Timber frame house	94 852	212	18	5.5
Timber block house	96 298	215	18	5.5
Brick house	114 980	256	22	6.6
Case B				
Timber frame house	79 248	176	15	4.5
Timber block house	52 957	118	10	3.1
Brick house	108 400	242	21	6.2

means that it is never possible to return the raw products to their original state, i.e., to truly sustain them as they were millions of years ago.

8.7 Structural adhesives

8.7.1 Introduction

The future of engineered wood products is heavily reliant on adhesives that meet minimum performance requirements. According to the International Organization for Standardization (ISO) TC 165 Committee, in their work in drafting ISO/CD 20152 (ISO, 2008a, 2008b), the adhesive must be:

(a) resistant to fungal attack;
(b) harmless to the timber substrate – neither too acidic nor too alkaline;
(c) chemically stable in timber infused with water, chemical preservatives and fire retardants;
(d) resistant to creep deformation and rupture under sustained load;
(e) resistant to debonding under varying moisture content;
(f) capable of creating strong bonds upon which its engineering design properties depend;
(g) durable.

There are a number of wood adhesives in use but relatively few are regarded as suitable for structural use. The most critical requirement is that of durability, i.e., under normal service conditions it must not debond over a typical life cycle period of 50 years. The most widely held view is that the adhesive bondlines must be as durable as the wood substrate for engineered wood products to be regarded as an acceptable form of construction.

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8.7.2 Specification of performance requirements

Well-manufactured phenolic resins are widely regarded as the most durable of wood adhesives. They are widely accepted to be as durable as the wood substrate and provide a benchmark against which other wood adhesives are compared. It should be added that, while they successfully bond softwoods, very high density (air dry density exceeding 1000 kg/m^3) and resinous hardwoods as well as resinous softwoods can present bonding problems.

European approach to adhesive assessment

In Europe, there are separate standards for phenolic and amino plastic (melamines and ureas) adhesives on the one hand and single-component polyurethanes on the other. Polyurethanes are relatively new to the timber bonding scene. For the phenolics and amino plastics, performance requirements are detailed in EN 301 (European Committee for Standardization, 2004a) and the test methods in the EN 302 series (European Committee for Standardization, 2004b, 2004c, 2004d, 2004e). Separate standards exist for single-component polyurethane adhesives; these standards include additional requirements, most notably for creep.

US approach to adhesive assessment

In the USA adhesives used in engineered timber products intended for full weather exposure must meet the requirements of ASTM D 2559 (ASTM, 2004). This includes tests of shear strengths and percentage wood failure at moisture contents in the range 8–12%, cyclic delamination and resistance to creep at temperatures of up to 71°C. As such the US standard is completely performance based. There is a lower limit on pH of 2.5 which is designed to limit acid attack of the wood fibre. Similar provisions are included in European, Canadian and ISO standards.

A perceived disadvantage of phenolic adhesives is their formaldehyde gas emissions. These emissions are regarded as carcinogenic although the concentrations from all wood products are well below any level that would cause concern (see the Formaldehyde Council website, http://www.formaldehyde.org/about_safety.html). Formaldehyde adhesives are two-component adhesives that require mixing and radio frequency or high-temperature curing in high-speed manufacturing operations; this contrasts with polyurethanes, which can be chemically modified to cure within minutes at room temperature.

Other approaches to adhesive assessment

In other jurisdictions, the philosophical approach to assessment differs. Rather than the standards referring to adhesives by chemical type, there are simply a series of standard test methods and performance requirements that are applied to all wood

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adhesives. The Canadian standard CSA O112.9 (CSA, 2004) and ISO/CD 20152.1 (ISO, 2008a, 2008b) are documents of this type. CSA O112.9 is the most highly developed; ISO 20152/CD is under development. These two standards are essentially identical with exception of performance testing at temperatures above 80 °C (NB, with ISO, the CD designation denotes a Committee Draft. ISO/CD 20152.1 is at the time of writing being balloted as a Draft International Standard at which point it will be designated ISO/DIS 20152.1.).

High-temperature performance of adhesives

A controversial issue that has arisen during the development of ISO/CD 20152.1 relates to high-temperature (fire) performance, a matter incompletely resolved. According to the writer's understanding, North American approaches require that adhesives used in I-beams must meet a minimum strength test requirement for temperatures as high as 230 °C. The European approach limits high-temperature creep testing of adhesives to 80 °C. The North American approach is a little difficult to follow in that unprotected I-beams have a very poor fire-rating unless protected due to their very thin webs, so that the method by which the flange and web are bonded is unlikely to make a great deal of difference to overall I-beam performance. According to correspondence with US representatives to the ISO Technical Committee TC 165, there is no intention at this time that the high-temperature test should apply to large-section products such as structural glulam which must be subjected to a full fire test where the beam is required to be fire-rated. The fact that wood is a poor conductor of heat and pyrolyses slowly (at around 0.6 mm/minute) means that the bondlines in large-section glulam never experience higher temperatures except close to the outer surfaces.

8.8 Case studies

8.8.1 Introduction

The choice of case studies is limited to two. Both structures employ timber framing but, of course, use a mix of materials. The Western Australian Maritime Museum was chosen to emphasise the point that operational costs are a major factor in the life cycle of any building, typically comprising at least 80% of the overall building cost. The Superior Dome, Michigan, USA is chosen because it has the largest overall span, by a small margin, of any timber building in the world. There are also many other excellent major and modern timber structures in Asia, Australasia, Europe, Japan and North America that can not be included. Domestic timber framed and clad structures with suitable insulation are also used extensively in many countries but are not discussed below. They have low thermal conductivity and low thermal mass which when combined with appropriate design can provide comfortable conditions for occupants.

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8.9 External view of the Western Australian Maritime Museum, Fremantle, Australia. Courtesy of the Australian Maritime Museum, Fremantle, Australia.

8.8.2 Glued laminated timber construction – the Australian Maritime Museum, Fremantle, Australia

The Western Australian Maritime Museum (Fig. 8.9) located in Fremantle, Australia, is both visually appealing and involves low operational energy. It is not large in span, but the glulam elements that form the building's three-pin arches provide a structure that involves low embodied energy (Fig.8.10).

In the case of this building, additional building costs were incurred that allowed a reduction in the operational energy use, specifically in relation to the heating and cooling system. The embodied energy costs (extraction, manufacture, construction and disposal) are typically equal to approximately 4 years of the operational costs. Assuming that the museum has a 50 year life, major savings in operational costs have a major impact on the overall energy demand of the building throughout its life.

According to data taken from the Australian Institute of Refrigeration Air Conditioning and Heating (AIRAH, 2003) website (http://www.airah.org.au/downloads/2003-08-F02.pdf), 'the building employs an aquifer heat rejection system that incorporates a ground-coupled heat sink, using a non-artesian cooling water bore system. …. The system operates on conducted sensible heat transfer only, and as such does not evaporate any water. It has reduced chiller plant electricity consumption by 35% compared to an air cooled system, and 22% compared to a conventional water cooled system.' Although the capital cost was higher, the operational costs were reduced. This highlights the important point that

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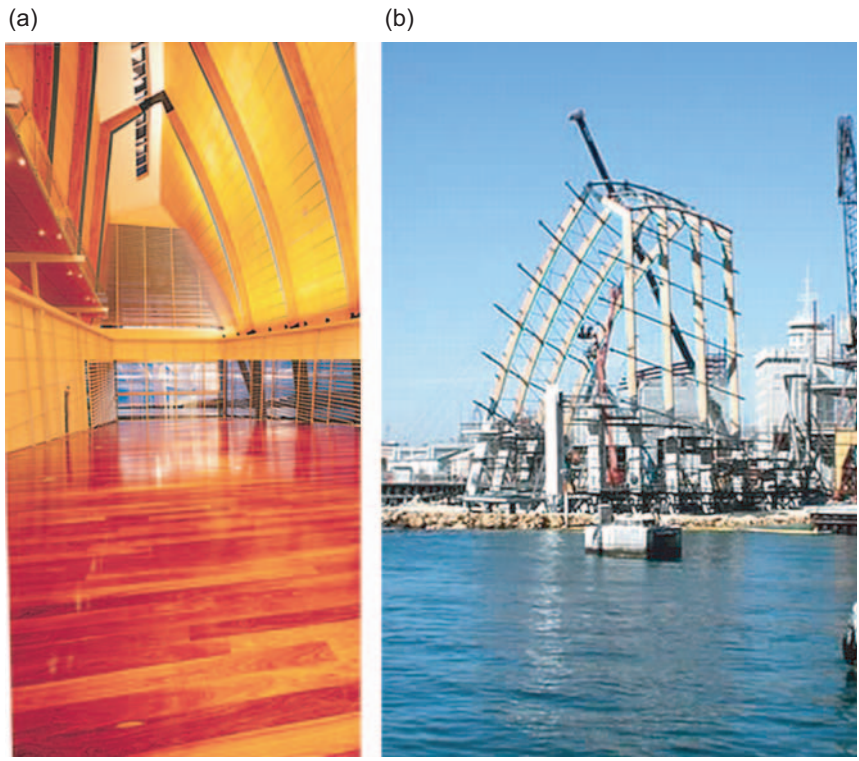

8.10 Western Australian Maritime Museum, Fremantle, Australia, showing the glulam three-pin arch exposed as an architectural feature (a) and during construction (b). Courtesy of the Australian Maritime Museum, Fremantle, Australia.

building and disposal costs are not the only factors that affect the sustainability of construction. Much has to do with building layout, the cladding and insulation used and the use made of passive environmental planning such as ventilation and passive environmental control.

8.8.3 Superior Dome, Northern Michigan University, USA

The Superior Dome is located on the campus of the Northern Michigan University, USA (Fig. 8.11); it has the largest span of any timber structure in the world. It highlights the point that large-scale buildings can be constructed from engineered wood products. The following description of the facility is quoted directly from the Northern Michigan University website (http://www.fao.org/docrep/004/y3609e/y3609e00.htm).

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(a) (b)

8.11 Exterior (a) and interior (b) view of the world's largest span timber structure at 163 m. Courtesy of Northern Michigan University, USA.

The Superior Dome has been home to the Wildcat football team since its construction in 1991 and is now also home to the Wildcat soccer and track teams. The Dome stands 14 stories high and encompasses 5.1 acres under its roof. Constructed of 781 Douglas Fir beams and 108.5 miles of fir decking, the Dome has a permanent seating capacity of 8,000, although the building can hold as many as 16,000 people.

The facility has a diameter of 536 feet and has the ability to withstand 60 pounds per square foot of snow and 80 mile-per-hour winds. The Dome's features include a retractable artificial turf carpet, the largest of its kind in the world. When extended, the turf has the ability to accommodate football, soccer (120 × 72 ft. field) and field hockey. Underneath the carpet is a synthetic playing surface that features three basketball/volleyball courts, two tennis courts and a 200-meter track. Three concession areas provide service to all events.

Twelve computerized winches extend the carpet over a cushion of air. It takes 30 minutes to retract the artificial turf carpet and approximately two hours for full set up to be completed.

The Superior Dome is also home of the United States Olympic Education Center offices, as well as special training areas for the USOEC's boxing, weightlifting and wrestling teams.

8.9 References

AFPA (American Forest & Paper Association) 2008, Structural composite lumber and glued laminated timber awareness guide, viewed 16 January 2008, http://www.woodaware.info/PDFs/SCLandGlulam.pdf.

Asia-Pacific Forestry Commission 2001, Availability and use of mill residues, viewed 16 January 2008, http://www.fao.org/DOCREP/003/X6966E/X6966E02.htm.

www.EngineeringEBooksPdf.com

ASTM 2004, ASTM D 2559 *Specification for adhesives for structural laminated wood products for use under exterior (wet use) exposure conditions*, ASTM International, West Conshohocken, PA, USA.

Australian Wood Panels Association 2001, Manufacture, viewed 16 January 2007, http://www.woodpanels.org.au/publications/datasheets/1.asp.

Bailey, G. 1996, Oriented strand board, viewed 16 January 2008, http://fennerschool-associated.anu.edu.au/fpt/osb/2.html.

CSA (Canadian Standards Association) 2004, CSA Standard O112.9, *Evaluation of adhesives for structural wood products (exterior exposure)*, CSA, Ontario, Canada.

Elmendorf, A. 1949, Wood fibres from veneer waste, *Proc. Forest Prod. Res. Soc.* **3**, 53–57.

Elmendorf, A. 1965, Oriented strand board, US Patent 3,164,511.

Engineered Wood Products Association of Australasia 2007, Structural plywood and LVL design manual, available at http://www.paa.asn.au/.

Eriksson, E, 2004, Comparative LCAs for wood and other construction materials, Proceedings of the Eighth World Conference on Timber Engineering, Lahti, Finland, pp. 183–188.

European Committee for Standardization 2004a, EN 301 2004, *Adhesives, phenolic and aminoplastic, for load-bearing timber structures – Classification and performance requirements*, CEN, Brussels.

European Committee for Standardization 2004b, EN 302-1 2004, *Adhesives for load-bearing timber structures – Test methods – Part 1: Determination of resistance to delamination*, CEN, Brussels.

European Committee for Standardization 2004c, EN 302-2 2004, *Adhesives for load-bearing timber structures – Test methods – Part 2: Determination of bond strength in longitudinal tensile shear strength*, CEN, Brussels.

European Committee for Standardization 2004d, EN 302-3 2004, *Adhesives for load-bearing timber structures – Test methods – Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength*, CEN, Brussels.

European Committee for Standardization 2004e, EN 302-4 2004, *Adhesives for load-bearing timber structures – Test methods – Part 4: Determination of the effects of wood shrinkage on the shear strength*, CEN, Brussels.

ISO (International Organization for Standardization) 1997, ISO 14040:1997 *Environmental management – Life cycle assessment – Principles and framework*, ISO, Geneva, Switzerland.

ISO (International Organization for Standardization) 2008a, ISO/CD 20152.1 *Timber structures – performance of adhesives – Part 1: Basic requirements*, ISO, Geneva, Switzerland.

ISO (International Organization for Standardization) 2008b, ISO/CD 20152.1 *Timber structures – performance of adhesives – Part 2: Additional requirements*, ISO, Geneva, Switzerland.

Lawson, B. 2000, *Building Materials, Energy and the Environment: towards Ecologically Sustainable Development*, Royal Australian Institute of Architects, Canberra, Australia.

Leichti, R. J., Falk, R. H. and Laufenberg, T. J. 1990, Prefabricated wood composite I-beams: a literature review, *Wood Fiber Sci.*, **2**(1), 62–79.

Pearce, A. and Walrath, L. (2008), Definitions of sustainability from the literature, viewed 16 January 2008, http://maven.gtri.gatech.edu/sfi/resources/pdf/definitions.pdf.

Scharai-Rad, M. and Welling, J. 2002, Environmental impacts and energy balances of wood products and major substitutes, available at http://www.fao.org/docrep/004/y3609e/y3609e00.htm.

www.EngineeringEBooksPdf.com

Taylor, J., Mann, R., Reilly, M., Warnken, M., Pincic, D. and Death, D. 2005, Recycling and end-of-life disposal of timber products, viewed 16 January, 2008, http://www.fwpa.com.au/content/pdfs/PN05.1017.pdf.

WCED (World Commission on Environment and Development) 1987, Our common future; Report of the World Commission on Environment and Development, viewed 16 January 2008, http://www.un-documents.net/wced-ocf.htm.

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9

The use of waste tyre rubber in civil engineering works

N. OIKONOMOU and S. MAVRIDOU
Aristotle University of Thessaloniki, Greece

Abstract: Scrap tyres are being generated and accumulated in large volumes causing an increasing threat to the environment. In order to eliminate the negative effect of these depositions and in terms of sustainable development there is great interest in the recycling of these non-hazardous solid wastes. The potential of using rubber from worn tyres in many civil engineering works has been studied for more than 30 years. Applications where tyres can be used and where the addition of tyre rubber has proven to be effective in protecting the environment and conserving natural resources include the production of cement mixtures, road construction and geotechnical works. Recycling of tyres in the applications mentioned above represents a suitable means of disposal for both environmental and economic reasons.

Key words: sustainable development, scrap tyres, cement products, bituminous mixtures, soil mixtures.

9.1 Introduction

Solid waste management is one of the major environmental concerns worldwide. For the last 30 years many studies have been conducted in order to assess the feasibility of using industrial by-products and waste materials in civil engineering applications. The motives for such studies have been and still are:

- the high cost, the continuous reduction in supplies and the negative environmental impact from the use of natural aggregates;
- legislation, which bans the disposal of wastes in landfills;
- recycling in general, as is demanded by the requirement for sustainable development.

A steady stream of large volumes of waste tyres is generated annually owing to the continual increase in the numbers of all kinds of vehicles. For the European Community (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Holland, Portugal, Spain, Sweden, UK), it is estimated that up to 250 million waste tyres are generated annually, while equal amounts are estimated for Eastern Europe, North America, Latin America, Japan and the Middle East. In addition to this, enormous quantities of tyres have already been stockpiled or land-filled (3 billion waste tyres inside the EC and almost 1 billion in North America (http://www.etra.eu.com)).

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These tyres are often deposited in an uncontrolled manner, because of the noticeable rapid depletion in sites available for waste disposal, causing major environmental problems. Water accumulation inside the tyres provides ideal temperature and moisture conditions for the spread of mosquitoes, mice, rats and vermin. At the same time, the quantity of oxygen that exists in the interior of the tyres is enough to cause fire in appropriate conditions, because of their inflammable components, with resulting negative impacts on the atmosphere and on human health. Within the last 10 years, the State of California has seen two of its largest tyre stockpiles – located in Tracy and Westley – catch fire; in Westley, at the west side of Stainislaus County, approximately 7 million scrap tyres were involved in the fire, which was caused by a lightning storm (http://www.netfeed.com/~jhill/tirefire.htm). These fires have raised concerns about the need to eliminate the existing stockpiles and to develop additional end uses for tyres.

Over the next few decades, these stockpiles of scrapped tyres should reduce in size as a result of application of Council Directive 1999/31/EC on the Landfill of Waste and other relevant legislation worldwide. Under Council Directive 1999/31/EC, whole tyres (except those with outside diameters greater than 1400 mm and also bicycle tyres) have already been banned from landfill, while since mid-2006, when the landfill ban came into full effect, all tyres (including shredded tyres), must be recovered. The general aim of this Directive is, by way of stringent operational and technical requirements for the waste and landfills, to provide measures, procedures and guidance to prevent or reduce as far as possible the pollution of surface water, groundwater, soil and air, as well as any resulting risk to human health, from landfilling of waste (http://www.etra.eu.com). As a result of this Directive, many EC Member States already have national associations – composed of key economic operators, tyre manufacturers, importers, retailers, collectors and recyclers – who aim to promote the collection and recovery of used tyres, to participate in research and development activities and to act quite naturally as the counterparts to local authorities. Some of these associations are listed in Table 9.1.

Tyres, which are included in the European Waste Catalogue (2002) as non-dangerous wastes, consist of synthetic and natural rubber, sulphur and sulphur compounds, silica, phenolic resin, oil (aromatic, napthenic, paraffinic), fabric (polyester, nylon), petroleum waxes, pigments (zinc oxide, titanium dioxide), carbon black, fatty acids, inert materials and steel wires (Siddique and Naik, 2004).

Rubber from worn vehicles tyres (passenger cars, buses, trucks, bicycles), after being shredded into smaller pieces, can often be reused in civil engineering applications. Two main methods are used to grind tyres to the required size: the first method is related to ambient size reduction using mechanical processes at or above room temperature and the second method is related to cryogenic size reduction by the use of liquid nitrogen or commercial agents to reduce the tyre to the desired size. The first process produces rubber chips with a rough surface, while cryogenic grinding is generally used for the production of rubber in the form

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Table 9.1 Associations dealing with tyre recycling (http://www.Blic.de)

Country	Organisation	Website
Belgium	Recytyre	http://www.recytyre.be
France	Aliapur	http://www.aliapur.com
Germany	Gavs	h.hirsch@wdk.de
Greece	Ecoelastika	http://www.ecoelastika.gr
Hungary	Magusz	magusz@mail.datanet.hu
Italy	Eco.Pne.Us	http://www.ecopneus.it
The Netherlands	Recybem	v.oosternrijk@hccnet.nl
Norway	Dekkretur	http://www.dekkretur.no
Spain	Nedes	consorcio@arrakis.es
Poland	Cuo	http://www.utylizacjaopon.pl
Portugal	Valorpneu	http://www.valorpneu.pt
Romania	Eco Anvelope	florin.brabete@ecoromania.ro
Sweden	Sdab	http://www.svdab.se
UK	Used Tyre Working Group	http://www.tyredisposal.co.uk

Table 9.2 Summary of materials and their sizes (taken from CEN Workshop Agreement (CWA) 14243-2002 (CWA, 2002))

Material	Size
Cuts	>300 mm
Shred	50–300 mm
Chips	10–50 mm
Granulate	1–10 mm
Powder	<1 mm
Fine powder	<500 μm
Buffings	0–40 mm
Reclaim	Depends on input
Devulcanisate	Depends on powder
Pyrolitic char	<10 mm
Carbon products	<500 μm

of powder (Eleazer *et al*., 1992). By reducing the particle size of worn tyres, separation of steel wires and textile fibres can be achieved as well as a further treatment of the worn tyres so that commercial particle sizes are created. Scrap tyres are shredded for use in various applications, with the actual size, ranging from >300 mm to <500 μm, depending upon the intended use, as shown in Table 9.2.

In the following sections, the effect of the addition of tyre rubber in different civil engineering works, based on research over the last 15 years, is examined. Section 9.2 deals with the use of waste tyres in cement-based materials (e.g. mortar, concrete) whereas Sections 9.3 and 9.4 are concerned with the use of waste tyres in bituminous mixtures and in geotechnical applications respectively. Other applications of waste tyres are highlighted in Section 9.5, while in Section 9.6 data on life cycle assessment of tyres are presented.

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9.2 Tyre rubber in concrete and mortars

9.2.1 Introduction

Research on cement-based products modified with tyre rubber – such as concrete and mortar – has been carried out for many years in order to examine the potential utilisation of waste tyres in concrete production. Waste tyres have been used to partially replace the aggregates in mortars and concrete. Tyre rubber can be used to produce workable concrete for specific applications, provided that adequate selection processes are undertaken – including the amount, gradation and shape of tyre particles. This section deals with the properties of either mortar or concrete modified with waste tyre rubber.

9.2.2 Specific weight

The specific weight of concrete modified with waste rubber reduces as the level of substitution of aggregates with tyre particles increases. This reduction can be attributed to the specific weight of tyre rubber being lower than that of traditional aggregates (0.9–1.16 g/cm^3 for tyre rubber compared with 2.65–2.67 g/cm^3 for aggregates) (Oikonomou *et al*., 2006; Khaloo *et al*., 2008). However, Khatib and Bayomy (1999) showed that the decrease in specific weight is almost negligible for rubber contents lower than 10–20% of the total aggregate volume.

9.2.3 Workability

The workability, defined as the ease with which concrete can be mixed, transported and been put into moulds, is affected by the interactions of tyre rubber particles and mineral aggregates. Rubberised concrete has been found to be less workable than conventional concrete as the rubber content increases (Khatib and Bayomy, 1999; Albano *et al*., 2005; Oikonomou *et al*., 2006). It was also observed that mixtures made with fine crumb rubber were more workable than those made with coarse tyre chips or a combination of tyre chips and crumb rubber (Khatib and Bayomy, 1999).

Conversely, studies by the current authors on cement mortars showed that the workability of mortars with coarse rubber particles (maximum size of 4 mm) is better that that of mortars including fine rubber particles (0–1.18 mm). On the other hand, Raghavan *et al*. (1998) reported that mortars modified with tyre shreds achieved workability comparable with or better than conventional mortars.

9.2.4 Water Absorption

The durability of a material is often related to its capacity to resist water absorption. The primary transport mechanism by which water enters cement composites is

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capillarity by suction. The smaller the capillarity, the higher the durability of the composite.

According to Segre and Joekes (2000), cement paste modified with tyre rubber particles is characterised by a decrease in both the amount of capillary water absorption and its speed with an increase in rubber content. This could be due to the ability of rubber to repel water.

Oikonomou *et al*. (2006) have studied the addition of tyre rubber to cement mortars as a replacement for the aggregates (sand) and found that open porosity and capillarity by suction decrease with the use of tyre rubber. This decrease can be attributed to the smaller volume of pores in the mortars and to the fact that these pores can not be easily reached by the water. Moreover, Benazzouk *et al*. (2007) investigated the water absorption of cement composites containing shredded rubber wastes; tyre rubber has been used as a partial replacement for cement in order to develop lightweight construction materials. Test results for the hydraulic transport properties showed that incorporation of tyre rubber into such composites tends to reduce the water absorption of the composites.

9.2.5 Microstructure

Different kinds of microscopes are useful tools for observing and analysing the microstructural characteristics of cement-based products. Analysis of the microstructure of rubberised cement products has been conducted using stereoscopes

9.1 Rubber particles as observed with a stereoscope (magnification ×40).

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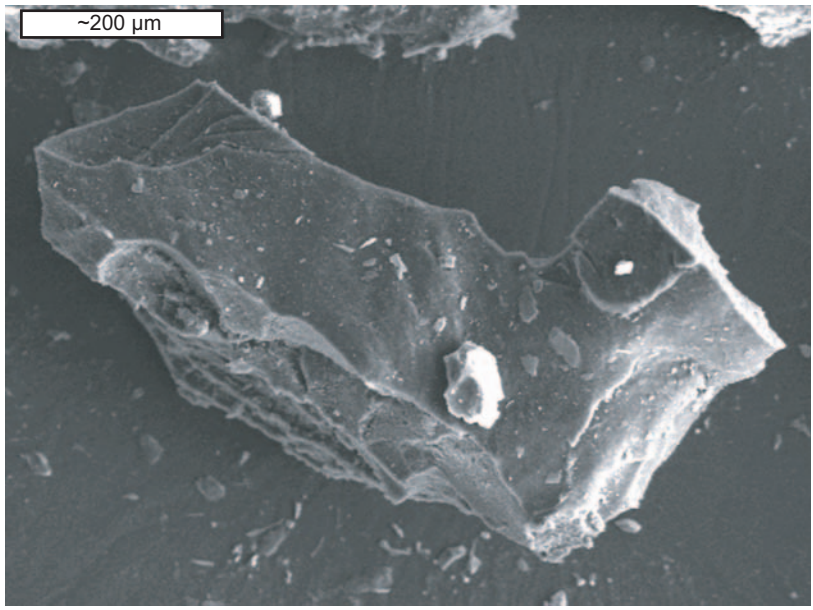
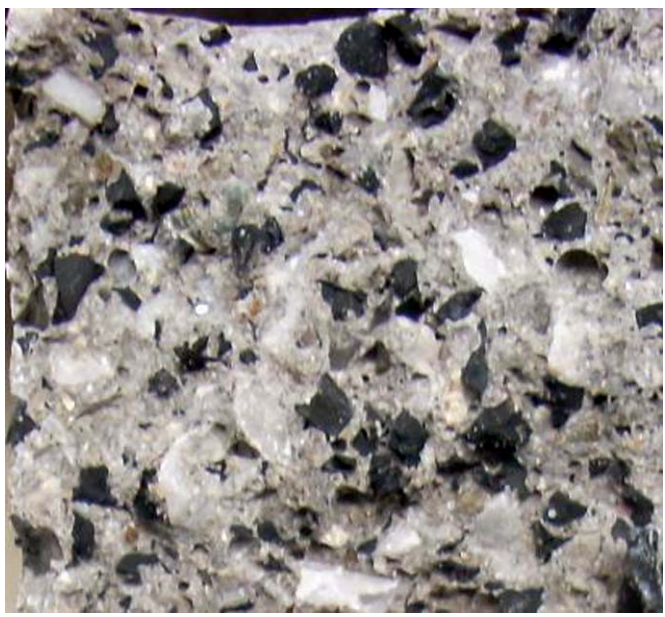


9.2 Rubber particles as observed with a SEM.



9.3 Rubber distribution in rubberised concrete mixture.

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and scanning electron microscope (SEM). For stereoscopic observations, small pieces of cement mortars or concrete have been used without any treatment in order to examine the bonding between the rubber particles and the cement matrix. For scanning electron microscopy, very small samples were coated with gold after having been subjected to full vacuum inside the electron microscope. Initially, the surface and shape of tyre rubber particles was examined, as seen for example in Figs 9.1 and 9.2 (Oikonomou *et al*., 2006). Tyre rubber particles are seen to be homogeneously distributed in the cement paste with no segregation (Fig. 9.3).

For conventional mixtures there is perfect adherence between aggregates and cement paste. However the adhesion is not as perfect when rubber particles are added to such mixtures (Segre and Joekes 2000; Turatsinze *et al*., 2005; Oikonomou *et al*., 2006), although improvement of this adhesion between rubber particles and matrix can be achieved by the use of various means. As far as styrene–butadiene rubber (SBR) latex and anionic bitumen emulsion are concerned, microscopic examination showed that these sorts of additives are well bonded to the rubber particle surface, hence strengthening the bonding between cement paste, aggregates, additives and rubber particles. Moreover, rubber particles also act as crack arresters (Turatsinze *et al*., 2005; Oikonomou *et al*., 2006).

9.2.6 Mechanical characteristics

Rubber aggregate substitution is found to decrease the strength of cement-based products (Siddique and Naik, 2004; Turatsinze *et al*., 2005; Oikonomou *et al*., 2006). This reduction varies depending upon the percentage, the size and the surface texture of the rubber particles as well as the type of cement (Siddique and Naik, 2004). Li *et al*. (2004) concluded that concrete containing waste tyre rubber in the form of fibres has higher strength compared with that made with larger rubber particles (chips). Using crumb rubber (particles ranging in size from 4.75 mm to less than 0.075 mm) to replace fine aggregates resulted in a reduction in concrete strength and this decrease is even greater when crumb rubber was used to replace the coarse aggregates (Eldin and Senouci, 1993). An increase in the crumb rubber percentage resulted in further decrease in strength properties. This decrease is attributed to the weak bonding between the rubber particles and the cement matrix.

Further research to improve this bonding has therefore been conducted. Rubber particles were pre-treated/washed using various methods including water, saturated aqueous solution of NaOH and coupling agents (Naik and Singh, 1991; Rostami *et al*., 1993); in addition, the following admixtures were added to the concrete mixtures: an Underwater Concrete System (UCS) (Turatsinze *et al*., 2005); super plasticiser; a 60% anionic asphalt emulsion (Oikonomou *et al*., 2006); and SBR latex (Lee *et al*., 1998; Oikonomou *et al*., 2006).

It has been noted (Siddique and Naik, 2004) that concrete containing water-

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washed rubber particles or rubber particles treated with carbon tetrachloride showed a smaller reduction in compressive strength compared with concrete containing untreated rubber particles. Meanwhile, the addition of latex in cement-based products results in an even smaller reduction in compressive strength because the latex enhances the adherence of the rubber particles and the cement mixture (Lee *et al*., 1998, Oikonomou *et al*., 2006).

As far as flexural and split tensile strengths are concerned, it was observed that these properties decreased at a slower rate compared with compressive strength (Topçu *et al*., 1995; Pierce and Williams, 2004; Oikonomou *et al*., 2006). As expected, since the strength of cement composites modified with tyre rubber decreases and given the fact that mechanical strength is closely related to the dynamic modulus of elasticity, the dynamic modulus of elasticity decreases with the increase in rubber percentage. This reduction results in the production of a less brittle material (Albano *et al*., 2005; Oikonomou *et al*., 2006; Khaloo *et al*., 2008).

9.2.7 Durability

There has not been a great deal of research on the durability of concrete modified with waste rubber. Cement mortars containing waste rubber showed a decrease in chloride ion penetration as the percentage of tyre rubber increases. There is a further decrease in chloride ion penetration when adding commercial products comprising an anionic bitumen emulsion and SBR latex (N. Oikonomou and S. Mavridou, unpublished observations, 2007). On the other hand, according to Gesoglu and Güneyisi (2007), for a given water:cement ratio and with a moist curing period of 3 and 7 days, the use of rubber increased the chloride ion penetration through concrete and the degree of ion permeability depended on the rubber percentage used. After 28 days of curing there was a greater reduction in the magnitude of the chloride ion penetration into the mortar.

9.3 Tyre rubber in asphalt mixtures

9.3.1 Introduction

Rubberised asphalt mixtures consist of asphalt, aggregates and tyre rubber granules. Rubber aggregates can be used as bitumen modifiers or as substitutes for natural aggregates. There are two ways of producing rubberised asphalt mixtures. In the first method, the ‘wet process’, rubber particles are mixed with bitumen at elevated temperature prior to mixing with the hot aggregates; in the second method, the ‘dry process’, rubber particles replace a small portion of the mineral aggregate in the asphalt mix before the addition of the bitumen. Many studies have been conducted investigating asphalt mixtures made using both the wet and the dry processes.

Tyre rubber has been used in asphalt mixtures providing rubberised asphalt with

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better skid resistance, reduced fatigue cracking, improved resistance to rutting, improved tensile strength and toughness, longer pavement life and reduced maintenance costs compared with conventional mixtures (Khosla and Trogdon, 1990; Fedroff *et al*., 1996; Khatib and Bayomy, 1999; Airey *et al*., 2004). Rubberised asphalt mixtures show better performance at high temperatures, they can be used in a variety of climate conditions and they are more flexible at low and sub-under zero temperatures, while the thickness of an asphalt layer can be reduced from 50 to 38 mm (http://www.ruberizedasphalt.org). Moreover, rubberised asphalt concrete is cost effective, saving as much as $22 000 per lane mile over conventional asphalt projects (http://ladpw.org/epd/tirerecycling/RAC-REAS.cfm). This market for worn vehicle tyres can consume large quantities of scrap tyres in a positive manner.

9.3.2 Wet process

Procedure

The wet method, of which there are two types – terminal blend and wet process high viscosity – can be used to produce rubberised asphalt with superior properties compared with conventional asphalt. In this method, finely ground tyre rubber is mixed with bitumen at 15–20% by mass, prior to mixing with the aggregates. This modification of the bitumen results in physical and compositional changes in an interaction process where rubber particles swell in the bitumen by absorbing a percentage of the lighter fraction of the bitumen to form a viscous gel, with an increase in the viscosity of the rubberised binder (Heitzman, 1992). Moreover, this method involves less risk as the interaction between crumb rubber and bitumen can be controlled during the digestion process. Mixtures produced with this method consume larger quantities of tyres and are available to a larger market. In California, the wet process is the most common method used to produce rubberised asphalt concrete. The only additional equipment required for the wet process is a special blending unit to mix the bitumen with the rubber particles.

Properties

In the wet process, the properties of the rubberised asphalt depend on various parameters such as the characteristics of the asphalt binder and of the rubber particles – including size, percentage of rubber added, mixing temperature and mixing time. Preliminary production trials of these modified asphalt mixtures showed that when the asphalt is laid, weak bonding has been noticed between the components of the mixture: this has resulted in loose rubber particles and distributed aggregates on the surface of the pavement. According to laboratory tests, rubber particles retain a larger proportion of the bitumen compared with the aggregates, suggesting an interaction between bitumen and rubber (Airey *et al*.,

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2001). Studies on dense, graded rubberised asphalt mixtures produced using the wet method, and containing 3–5% crumb rubber by total aggregate weight, showed that such mixtures are more vulnerable to moisture damage compared with conventional mixtures while their stiffness reduced by 30–75% depending on the crumb rubber content (Rahman *et al*., 2004). However, when fine rubber particles (< 1mm size) are added to asphalt mixtures – as they are in many US states such as Florida, Colorado and Kansas – they produce mixtures with improved characteristics in terms of stiffness and resistance to permanent deformation and rut, while particles of such gradation are more effective than coarser ones as far as rutting resistance is concerned. Despite these results, resistance to rut should be further examined for various sizes and proportions of rubber in such mixtures.

Tortum *et al*. (2005) studied the effects of tyre rubber and aggregate gradation, mixing and compaction temperature, tyre rubber and binder ratio, and mixing time on bituminous mixtures. They concluded that for specific conditions, rubberised asphalt mixtures performed better than the conventional mixture.

Punith *et al*. (2002) examined the tensile strength characteristics of Dense Bituminous Macadam (DBM) mixes with crumb rubber. Results showed improved characteristics in terms of Marshall stability and indirect tensile strength at various temperatures under soaked and unsoaked conditions. Both of these properties increased as the tyre rubber percentage increased. For unsoaked conditions in particular, the indirect tensile strength was higher compared with that of the soaked samples, while it decreased as temperature increased. Additionally, at high temperatures tensile strength was almost the same for both the plain and the rubberised DBM mixture; thus rubberised mixtures are expected to have a longer life than the conventional DBM.

Tyre rubber inclusions can modify a conventional hot-mix asphalt in terms of flexural fatigue life, since mixtures that include rubber treated using different processes (cryogenic or ambient) show greater fatigue life than conventional mixtures regardless of the void content, which may vary from one mixture to another for the same category of bitumen (Pais *et al*., 2001).

A pilot project was conducted in Taiwan; two test sections were studied, the first section had a gap-graded design while the second had an open-graded design. The incorporation of ground tyre rubber showed that these mixtures can have equal or even better field density and smoothness than conventional mixtures. Field measurements and visual observations indicated that these mixtures performed well (Chiu, 2008).

Another test project was conducted in Florida and was evaluated after 10 years. Results showed that the addition of crumb rubber using the wet process improved the crack resistance of surface mixtures; another test project conducted using the dry process (described in the following section) resulted in more cracked areas (Choubane *et al*., 1999).

The use of rubberised asphalt is becoming more popular given the fact that it produces pavements with reduced noise pollution. This was first noted in Brussels,

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Belgium, in 1981, in an asphalt rubber hot mix called 'Drainasphalt'. Other countries, where rubberised asphalt mixtures have been used and where equal or lower traffic noise reduction levels have been reported include Canada (1991), England (1998), France (1984), Germany (1980), Austria (1988) and the Netherlands (1988). As a result, many states of the USA (Arizona, Florida, California, Texas, etc.) and other countries around the world continue to use such mixtures (http://www.rubberpavements.org).

9.3.3 Dry process

Procedure

Rubberized asphalt mixtures produced by the dry process were first used in Sweden in the late 1960s in order to improve asphalt pavement skid resistance and durability. This method was patented with the name 'Rubit', while in the USA it was patented with the name 'PlusRide'. In this system, mixtures are prepared by the addition of 1–3% (by weight of total mix) rubber particles as a replacement for aggregates in gap-graded aggregate and then mixed with hot asphalt cement. These mixtures require 1.5–2% more asphalt than a conventional mix.

Another system, which uses the dry process, is the generic system. This system was developed in the late 1980s to early 1990s and uses fine and coarse rubber particles at up to 3% (by weight) in a dense-graded aggregate mixture. Experimental pavement sections have been placed in Florida, New York, Oregon and Ontario (Epps, 1994). Usually the amount of crumb rubber, as well as the size of the rubber is smaller than that used in the PlusRide system. The generic system is a two-component system in which the fine rubber particles act with the asphalt while the coarse particles perform as an elastic aggregate in the mixture.

The dry process, in contrast to the wet process, does not require special equipment but it has been a far less popular method. This unpopularity is because of the increased costs of having to use special graded aggregate to incorporate the reclaimed tyre rubber, in addition to construction difficulties, poor reproducibility and premature failure of asphalt road surfacing (Hunt, 2002). However, this method has the potential to consume larger quantities of rubber from worn vehicle tyres, which is environmentally beneficial.

Properties

Rubber in rubberised asphalt mixtures increases the elasticity of the mixture; it can enhance the bonding between binder and aggregates, resulting in an increase in fatigue life and in the resistance to rutting, and it can lead to a reduction of the thermal and reflecting cracking of these mixtures (Fernandes *et al*., 2002). In this process, the interaction between rubber particles and bitumen can not be easily

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controlled since it starts as soon as aggregates are mixed with bitumen. When these mixtures are constructed correctly, such pavements are better for icy road conditions (http://www.rubberisedasphalt.org) (Khalid and Artamendi, 2002).

Recent studies concluded that during mixing and transportation, rubber reacts with bitumen, changing the properties, shape and rigidity of the rubber; as a result the performance of the asphalt mixture changes (Airey *et al*., 2003). Studies on the effect of moisture on the mechanical properties of rubberised asphalt mixtures showed that stiffness is reduced by the incorporation of rubber particles (2–8 mm), and that stiffness decreases with increasing rubber content. This reduction was attributed to the voids created by rubber particles in the mixture; as a result more water penetrated into the matrix during saturation giving a weaker structure. For rubberised asphalt mixtures, resistance to permanent deformation was found to decrease compared with the control mixtures, in terms of strain rate, because of the moisture conditioning; however, the presence of rubber in the mixtures resulted in an increase in fatigue performance before moisture conditioning. Therefore, rubberised asphalt mixtures result in better mechanical characteristics than the control mixtures during the early stages. However, when exposed to moisture for long periods this enhanced performance is reduced (Rahman *et al*., 2004).

When rubber (particle size <2 mm) is added to asphalt mixtures, the compaction and strength characteristics are improved as the rubber fills the existing voids within the granular skeleton (Kettab and Bali, 2004). Studies on crumb rubber asphalt mixtures showed that the addition of rubber at 10–15% (by weight of the bitumen) caused a reduction in penetration into bitumen and softening point, while viscosity increased with crumb rubber content and decreased as temperature was elevated (Khalid and Artamendi, 2002).

According to Fernandes *et al*. (2002), rubberised dense asphalt mixtures showed lower Marshall stability values than the control mixture, while the flowability increased with the rubber content. These mixtures did not meet the requirements of the Brazilian Standards. Rubberised asphalt mixtures showed lower values for resilient modulus and tensile strength compared with conventional mixtures, while gradation of the rubber was found to have a small influence on the tensile strength. Moreover, the reduction in resilient modulus was higher as the size and content of the rubber increased. In addition, mixtures with fine rubber particles (0.15–1.18 mm size) at up to 2% (by weight of the total mix) showed very good performance in terms of rutting resistance.

A study conducted in Greece, in rubber-modified asphalt mixtures using the dry process, did not meet the requirements of Hellenic Standards when mixtures contained rubber at more than 1% (by weight of the aggregates) (Oikonomou *et al*., 2007).

Microstructure

Conventional and rubberised mixtures, produced with the dry process, have been

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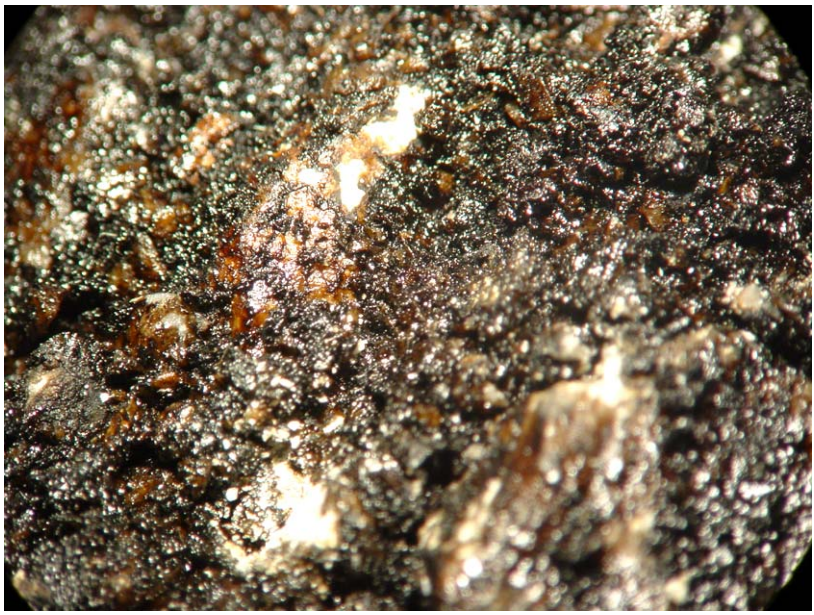
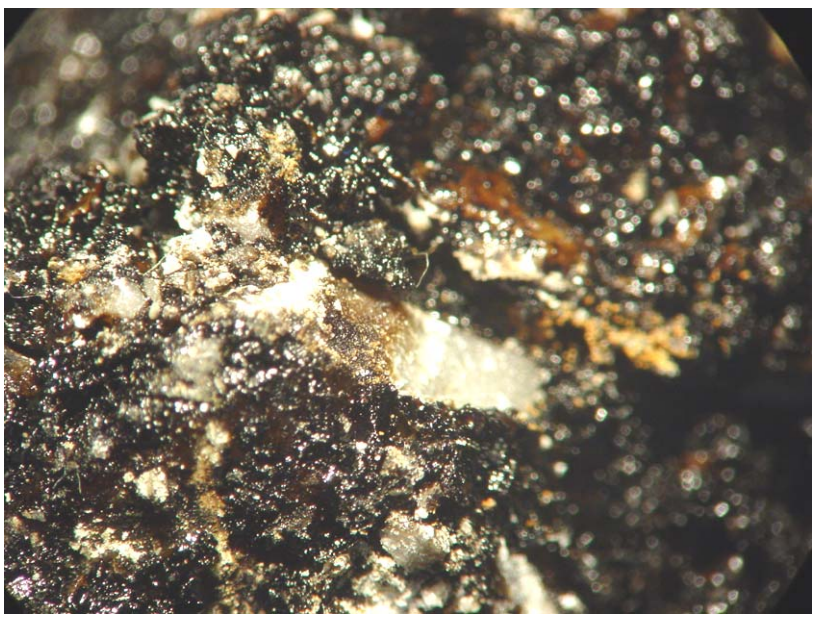


9.4 Conventional asphalt mixture (magnification ×40).



9.5 Rubberised asphalt mixture (magnification ×40).

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examined by the use of a stereoscope (Leica Wild M10) as shown in Figs 9.4 and 9.5. The rubber particles are well mixed with the aggregates resulting in satisfactory bonding (Oikonomou *et al*., 2007).

9.4 Tyre rubber in geotechnical works

9.4.1 Introduction

Highway embankments made of heavy materials are often built over soft ground and this can sometimes lead to settlement and instability of the embankment. Geomaterials are lighter and help to alleviate this problem. Moreover, the backfill behind a retaining wall can be constructed with geomaterials; this can lead to reduced earth pressure on the structure and allows a thinner retaining wall to be used.

Tyres can be used in geotechnical works alone or mixed with soil. In the form of shreds, tyres provide a lightweight construction material often with improved engineering properties, such as strength, compared with those of the soils alone. Shredded tyres exhibit very good frictional properties alone or mixed with soils by enhancing the strength of soils internally, providing them with stability and inducing negligible differential settlement. Tyre chips are known to leach some organic and inorganic contaminants, such as manganese and iron, but this is not at a level whereby they could be classified as hazardous wastes; however, they can be used in areas of high contamination levels since they act as a sorbent medium (Edil, 2004). Moreover, according to results of leaching studies, metals are leached most readily at low pH and organics at high pH, so it is preferable to use tyre shreds in environments with a near neutral pH (ASTM D6270-98) (ASTM, 2004).

In an investigation of an embankment constructed in Lakeville in the USA, the levels of all metals in the groundwater were below the standard limits prescribed for secondary drinking water. In addition to this, tyre chips have high sorption capacity for volatile organic chemicals, which means that tyres can be used to eliminate chemicals from contaminated water (Park *et al*., 1996). The only problem that may arise when tyres used as fill material in embankments are not well covered by soil is that self-heating of the tyres is likely to occur; this can be solved by the proper design and construction of each project. This problem can also be avoided by reducing the quantity of fine tyre pieces, limiting the thickness of the tyre layers to 3 m and restricting access of the fill to air and water. Tyre shred–sand mixtures were found to be effective in inhibiting exothermic reactions since the tyre shreds are entirely covered with the sand (Yoon *et al*., 2006). The design guidelines given in ASTM D6270-98 Standard Practice for Use of Scrap Tires in Civil Engineering Applications (ASTM, 2004) have been developed in order to minimise this reaction by minimising factors that could possibly create favourable conditions for exothermic reactions.

In Minnesota, Oregon, Colorado, Indiana and many more US states, scrap tyres

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Table 9.3 Properties of rubber (taken from CWA 14243-2002 (CWA, 2002))

1.	Compacted density	2.3–4.8 kN/m^3 compared to soil at 15.6–19.5 kN/m^3
2.	Compacted dry unit weight	1/3 that of soil
3.	Compressibility	3 times more compressible than soil
4.	Density	1/3 to 1/2 less dense than granular fill
5.	Durability	Non-biodegradable
6.	Earth pressure	Low compared to soil or sand, up to 50% less
7.	Friction characteristics	Higher compared to soil
8.	Horizontal stress	On weak base: lower than with conventional backfill
9.	Modulus in elastic range	1/10 of sand
10.	Permeability	Greater than 10 cm/s
11.	Poisson's ratio	0.2–0.3 corresponding to K_o values of 0.3–0.4
12.	Specific gravity	±1.14–1.27 kg/m^3 compared to soil at 2.20–2.80 kg/m^3
13.	Thermal insulation	8 times more effective than gravel
14.	Unit weight	Half the typical unit weight of gravel
15.	Vertical stress	On weak base: smaller than granular backfill

are already being used as a fill in roadway embankments (Minnesota Pollution Control Agency 1990; Bossher *et al.*, 1992), while in Maine, efforts have been made in order to use tyre chips as backfill material for retaining walls and as a road subgrade fill or insulation layer (Humphrey and Sandford, 1993).

In addition, tyres prevent rock slides and help to limit erosion in inaccessible arid areas. When filled with soil and composting materials, often containing rubber granulates, and planted with hardy seedlings, tyres provide green space in otherwise barren areas. Moreover, tyres can be used in drainage systems for biogas: to prepare the base, stabilise the sloping walls, protect piping, and provide a protective wall around central evacuation pipes and preferential channels for improved hydraulic flow (http://www.etra.au.com).

In order to analyse the feasibility of tyre rubber as a potential fill material, its engineering properties need investigating. Some of these properties, which make rubber, right and proper for geotechnical use according to CEN Workshop Agreement (CWA) 14243-2002 (CWA, 2002) are listed in Table 9.3.

9.4.2 Physical characteristics of soils modified with tyre rubber

Unit weight

Unit weight varies from 5 kN/m^3 for tyre chips alone to 13 kN/m^3 for tyre chips mixed in equal proportions (by volume) with soil (50%). Results on soil–tyre chip mixtures indicate that the unit weight decreases as the tyre chip proportion increases, at a rate of approximately 1.5 kN/m^3 per 10% tyre chips (by volume)

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(Edil and Bosscher, 1994). According to Humphrey (1995), unit weights of compacted tyre chips are greater than those of non-compacted chips, while they are about one-third of the unit weights of conventional soil fills. The unit weight of chips alone is also not much affected by the compaction method, since only a modest compactive effort is required to achieve their maximum unit weight. This unit weight is not very sensitive to the size of the chips, despite the fact that unit weight increases as chip size increases when a mechanical compactor is used for the compaction (Ahmed and Lovell, 1993).

Compaction characteristics

Standard or modified Proctor (compaction) tests are run to determine the optimum moisture content at which the dry unit weights or densities of soils are greatest. These tests are essential, since the stability and settlement of an earth-fill structure such as a highway embankment and bridge abutment depend on how well the fill material is compacted. Therefore, characteristics of the soil alone and of soils mixed with rubber have been determined. It was concluded that the dry densities of clayey soil mixed with rubber (in any size) decrease as the amount of rubber increases. This fact makes tyre rubber a feasible material for use as lightweight fill material (Cetin *et al*., 2006).

For a sandy mud soil, laboratory results were similar to those mentioned above. Dry densities were found to decrease as the percentage of rubber increased regardless of the rubber size (N. Oikonomou and S. Mavridou, unpublished observations, 2008)

Atterberg limits

Testing of Atterberg limits is performed only on the soil fraction passing through a No. 40 sieve, according to ASTM D4318-00 (ASTM, 2003). Therefore, mixtures of cohesive clayey soil and fine rubber particles (<0.425 mm size) have been studied and results showed that as the percentage of tyre rubber increased, the clay content decreased and consequently Atterberg limits also decreased. In particular, the liquid limit stayed unchanged until levels of waste tyre reached 30%, and then it started to decrease; the plastic limit stayed about the same up to 10% waste tyre inclusion levels, started to decrease at levels of 20% and then stayed the same (Cetin *et al*., 2006). The plasticity index was found to stay the same for rubber chips up to 10% inclusion levels, while according to N. Oikonomou and S. Mavridou (unpublished observations, 2008) this was found to slightly decrease as the percentage of rubber increased to 10%.

Permeability

Permeability, which is the capacity of a soil to conduct liquid or gas, affects

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leachate flow and landfill gas migration (ASTM D653-90) (ASTM, 1994). Permeability is found to decrease under normal load due to compression of tyre waste particles and due to the resulting reduction in void volume. Permeability values for clayey soil are low and are found to increase as normal pressure decreases and as the percentage of tyre chips increases. Permeability values of tyre rubber chips (fine or coarse) are typical of those of sands, which means that rubber chips–granulates, alone or mixed with sand, can be used as lightweight fill material (Cetin *et al*., 2006). When mixed with clean uniform sand or with a fine glacial till, tyre chips of 3 mm maximum size induce an increase in hydraulic conductivity (Ahmed and Lovell, 1993; Edil and Bosscher, 1994). Moreover, the permeability of tyre rubber is greater than that of most granular aggregate. This high permeability makes it attractive for use in drainage layers in landfill liners and caps (Humphrey, 1995).

Thermal conductivity

Although the thermal conductivity of tyre shreds is significantly lower than that of common soil (ASTM D6270-98) (ASTM, 2004), thermal conductivity was found to increase as the particle size of the tyre rubber, the water content and the compaction level increased. This was found to be greater for tyre chips tested under frozen conditions compared with those tested in thaw conditions (Humphrey, 1995).

Hydraulic conductivity

The most important engineering property for the use of tyre rubber as a drainage material in landfill cover is hydraulic conductivity, which has to be high enough to allow the easy drainage of water. Reddy and Marella (2001) evaluated the variation in the hydraulic conductivity of tyre shreds with their size. Results showed a wide range of values for hydraulic conductivity which has been attributed to differences in (a) the size and composition of the tyre shreds, (b) compaction level and (c) normal stress. Moreover, tyre shreds of larger size possessed a high enough hydraulic conductivity to serve as effective drainage material in landfill covers.

9.4.3 Mechanical characteristics of soils modified with tyre rubber

Shear strength

The tyre chips used in construction are mainly 50–100 mm long, although longer and bigger shreds can also be used. These chips have friction angles between 20–30° and cohesion of 3–11.5 kPa based on relevant laboratory tests (Humphrey and Sandford, 1993). Tyre shred–sand mixtures (with shreds up to 102 mm in size) – with different percentages of tyre shreds, shred aspect ratios and sand matrix relative densities – have been tested in triaxial compression. According to results,

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strength was increased with relatively high friction angles, and this has also been noted in field observations of sand–tyre chip mixtures. However, the strength decreases as the tyre chip percentage increases beyond 30%. This is attributed to the performance of the mixture, which behaves more as a mass with sand inclusions rather than a reinforced soil (Foose *et al*., 1996).

Tatlisoz *et al*. (1997) tested mixtures made of sand, sandy silt and clay and the results of the tests showed that tyre chips and soil–tyre chip mixtures behaved like soils, but required more deformation to mobilise their ultimate shear strength. Incorporation of tyre chips in sand and in sandy-silt mixtures resulted in increased shear strength while mixtures made of clay and tyre chips had the same, or lower, shear strength as soil (i.e. clay) alone. Mixtures of sandy silt–tyre chips and sand–tyre chips give a linear shear strength envelope and have a cohesion intercept – which for the sand–tyre mixtures can be attributed to penetration of sands into the rubber particles due to elastic deformation under conditions of no or low normal stress; while the shear strength envelopes of the sand–tyre chip mixtures can be non-linear, with no cohesion intercept. However, the addition of rubber, in the form of shreds or fibres, to the mixtures can give non-linear Mohr–Coulomb envelopes. According to Ghazavi (2004), at a given normal stress applied on sandy–tyre chip mixtures, the shear strength of the soil modified with waste rubber was found to improve compared with that of the sand alone, and the higher the waste tyre content the higher the shear strength, provided that the level of compaction was similar. A relatively clear peak in the shear resistance of almost all samples has been observed, regardless of compaction level and rubber contents, except in the case of rubber grains alone where shear stress increased slightly with increasing horizontal deformation.

Results of the direct shear tests on the sandy silt–tyre chip mixtures showed an improvement in strength as the percentage of rubber increased (from 10% to 20%) for the sandy silt–tyre chip mixtures compared with values for the sandy silt alone; this was attributed to the higher friction angle and greater cohesion. The increase in strength for sand–tyre chip mixtures is related to the increased initial friction angle while for the sandy silt–tyre chip mixtures this increase is due to increases in cohesion and not in friction angle (Foose *et al*., 1996).

For mixtures made of clay and tyre chips there was no increase in strength. In fact, a decrease in shear strength was noted at low normal stresses. This reduction was attributed to the weak bonding between tyre rubber and clay. However, according to Cetin *et al*. (2006), the shear strength increases by 30% (when fine (<0.425 mm) tyre chips are used) and by 20% (when coarse (2–4.75 mm) tyre chip mixtures are used), cohesion increases as the amount of rubber increases up to 40%, while the angle of internal friction decreases. In addition, the mixtures of sand and tyre rubber particles are materials that exert less lateral earth pressures on retaining structures compared with those exerted by sand alone. Lee *et al*. (1999) observed that in contrast to the settlement, the horizontal pressure of a rubber–sand mixture on a retaining wall was lower than that of a gravel backfill.

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Consolidation

Consolidation is an important property if the soil is to be subjected to high compressive stresses. Using tyre chips and tyre chip–soil mixtures, the consolidation decreases as stress level increases (Humphrey, 1995). Sand–tyre and sandy silt–tyre mixtures have been examined for compression and showed similar stress–strain curves regardless of the type of soil or the amount of tyre chips. However clay–tyre chip mixtures exhibited higher strains. Compression on sand–tyre mixtures was found to increase significantly for tyre rubber contents greater than 30% (by weight of sand) (Edil *et al*., 1990). Additionally, clay–tyre chip mixtures compress relatively more compared with sandy silt–tyre chip and sand–tyre chip mixtures, while specimens of pure tyre chip compress the most. Therefore, it can be concluded that backfills of soil mixed with tyre may be less compressible than those consisting of pure tyre chips (Edil, 2004).

Bearing capacity ratio

Laboratory tests have been conducted on soils and, in particular sand, reinforced with tyre rubber in order to investigate the effect of rubber particles on the bearing capacity of the soil. Results on sand–tyre shred mixtures showed an increase in the bearing capacity ratio and a decrease in post-peak resistance reductions, depending on the rubber content and the aspect ratio. Furthermore, it can be concluded that a minimum length of shred must be provided for better results. However, after an optimum level of rubber content and size, the bearing capacity seemed to decrease (Hataf and Rahimi, 2006). According to N. Oikonomou and S. Mavridou (unpublished observations, 2008), preliminary studies on sandy-mud mixtures with rubber granules (2 mm size) showed lower values for California bearing ratio (CBR) compared with those for the sandy mud alone. However, further studies on this property need to be made, by changing the size and the amount of rubber particles as well as the type of soil.

9.5 Other applications

A certain proportion of waste tyres are reused as treads or are reclaimed for other forms of reuse/recycling. Waste tyres can be used in cement kilns as an alternative fuel, or in the production of electricity, despite the fact that the incineration of tyres, which is an undesirable option, can not be achieved without pollution and contribution to climate change.

In addition to these general non-civil engineering applications, several studies have been carried out in order to examine the feasibility of the addition of these wastes in cement and asphalt concrete as well as in geotechnical works, where tyres take the place of conventional construction materials such as fills or aggregates. The design engineer is responsible for determining the appropriateness of

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using scrap tyres in a particular application and for selecting applicable tests and specifications to facilitate construction and environmental protection.

Recent trends in Europe and worldwide have seen tyres used in many applications: as coatings, as a means for preventing soils from sliding, for sea embankments, as a means for inhibiting erosion near sea, as artificial reefs in marine environments, for temporary and heavy-load roads, as off-shore breakwaters, in retaining walls, as sound barriers, in drainage culvert beds, for riverbank and coastal stabilisation, as bridge abutment fill, in tram-rail beds, for thermal insulation and insulating backfill to limit heat loss from buildings, for insulation to limit frost penetration beneath roads, as porous bitumen additives, as a means of absorbing seismic waves and for slope stabilisation (http://www.etra.eu.com).

The addition of rubber in a wide range of applications in civil engineering is based upon the unique characteristics of tyre rubber as listed below:

1 High durability constituents of tyres, such as carbon black and antioxidants, enhance the resistance to wear, chemical decomposition and sunlight.
2 Moisture absorption – they are relatively impervious to absorption.
3 Low compacted dry density and thermal conductivity – a tyre is a poor thermal conductor so they are a better thermal insulator than soil or aggregates.
4 High hydraulic conductivity.
5 High compressibility, enough to absorb vibrations.
6 Low acoustic insulation.

Finally, reuse of tyre rubber in the applications mentioned above can lead to the achievement of an environmental goal, which is the protection of the environment by recycling this kind of solid waste. At the same time, the use of large volumes of waste tyres as a substitute for natural aggregates (sand, gravel, etc.) represents a great advantage from the point of view of sustainability in construction, while the tyre mountain would cease to exist.

9.6 Sustainability issues and life cycle assessment

The public, governments and industry are all greatly interested in green design and engineering approaches towards better environmental quality and sustainable development. A life cycle assessment (LCA) is a detailed analysis dealing with the interaction between a product and the environment. In particular, LCA calculates raw materials and energy used in order to produce a particular product (inputs) and the negative impacts of the resulting release of pollutants into the environment and, as a result, impacts on human health (outputs). LCA is conducted in order to produce more ‘green’ products with the least environmental impact. This can be achieved with studies on the effects of each phase of the LCA on the environment. At the same time, these studies can help producers to take conservative action aimed at making the environmental impact less harmful.

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There are several studies employing the LCA framework or methodology that have focused on passenger vehicle tyres (Amari *et al*., 1999; Krömer *et al*., 1999). In general there are five stages in the LCA of a tyre (Krömer *et al*., 1999).

1 *Extraction of raw materials*. A tyre is made up of many components which come from different sources such as plants (natural rubber), minerals (silica, metal reinforcements) and petroleum (synthetic elastomers, carbon black, chemicals). Approximately 6.9% of the overall resource requirement in the life of a tyre is consumed in the phase of extracting raw materials.
2 *Production in tyre plants.* Approximately 4.8% of the total resources expended in the life of a car tyre are used in the production stage.
3 *Distribution and transportation.* Between the various life stages – during which the constituents of a tyre undergo changes – tyres must be transported. The consumption of resources is lowest in this phase of the tyre's life (~0.2%).
4 *Use on the road.* Tyres are used to absorb road surface irregularities, so as the rubber compounds of a tyre are being deformed they heat up and dissipate part of the energy transmitted by the engine to the environment. Moreover, in operation tyres are subjected to constant wear due to tread abrasion. Eventually the tyre forfeits its functional value due to lack of sufficient tread depth. In general, a car tyre is withdrawn from service after 35 000–45 000 km while the service life of a truck tyre increases to 180 000–200 000 km (http://www.etra.eu.com). As far as energy consumption is concerned, approximately 88% of all the resources consumed in the life of a tyre are required for the use of the tyre by the car.
5 *Utilisation of worn tyres after the end of their service life, recycling and waste management.* Incinerating an average passenger car tyre provides enough energy to power a 60 W light bulb for more than 40 days. Other options such as re-grooving and re-treading could result in a reduction of total life cycle energy by both displacing raw material use and extending the service life of non-tread components.

In order to eliminate the environmental impact of the life cycle of a tyre, several recommendations should be carried out in each phase of the LCA. Raw materials acquisition for a car tyre is characterised by a high water requirement. The use of polyester, which has already replaced rayon to a certain extent, results in a reduction in the water requirements. Moreover, this phase is characterised by a high incidence of waste. The use of synthetic fibres instead of steel cord could reduce the amount of waste generated, assuming that the environmental impact from the production of fibres does not cancel out the benefits of waste reduction.

The negative impact during the tyre production phase has more to do with energy generation than with the production itself. Therefore it is not possible to influence this phase in any way.

Tyre use is accompanied by high consumption of energy and resources. The

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partial substitution of silica for carbon black as a filler could be a solution to the development of tyres with lower rolling resistance (Krömer *et al.*, 1999).

Corti and Lombardi (2004) used LCA in order to compare different processes for the end-of-life treatment of worn tyres – such as substitution of conventional fuels by tyres in cement kiln production, combustion in a conventional waste-to-energy process and two processes of reusing tyres as a filling material based on a cryogenic and a mechanical pulverisation process. Results showed that the use of tyres as fuel in cement kilns and combustion in a conventional waste-to-energy process are very satisfactory in terms of reducing the negative effects associated with the use of onventional fuels, with the first one to be better than the second one. The other two filling material processes showed worse results because of the high energy consumption related to the pulverisation processes.

9.7 Conclusions

Waste tyre management is a serious global concern. Millions of waste tyres are generated and stockpiled every year, often in an uncontrolled manner, causing a major environmental problem. As tyres are durable and not naturally biodegradable, they remain in dumpsites with little degradation over time, presenting a continuing environmental hazard. Furthermore, sites available for disposal of tyres are getting fewer, while legally, landfilling of worn tyres of any size has been forbidden since the end of July 2006. Therefore, it is crucial to find ways for their alternative utilisation by means of recycling.

Rubber tyres, in different shapes and sizes can be used in many civil and non-civil engineering applications – such as in the production of rubber composites, as a fuel in cement kilns, by incineration for the production of electricity, as an aggregate or additive in cement products, in road construction, as lightweight fill for embankments or as backfill material for retaining walls.

The use of crumb rubber and tyre granules in Portland cement concrete has been the subject of many research projects in recent years. The results of these studies show that concrete modified with tyre rubber can be used in applications where mechanical properties are not of prime importance. However, the permeability and chloride ion penetration are reduced; while the impact and crack resistance are improved.

Moreover, tyre rubber can be used as a bitumen modifier or as aggregate in asphalt mixtures. This can be done either by the wet or by the dry process. Pavements made of rubberised asphalt mixed with aggregates have been constructed widely with great success. Such sections have better skid and rutting resistance, and improved fatigue cracking resistance, while their service life can be greater than that of conventional sections. Moreover, it is possible to lay pavements made of rubberised asphalt under a wide range of climatic conditions, as mentioned by many researchers.

Tyre chips are advantageous for use in geotechnical applications because of

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their low density and high durability, shear strength and thermal insulation; in many cases they are also cheaper compared with other fill materials. The use of tyre rubber as a lightweight geomaterial for embankments or as backfill against retaining walls is very promising and should be promoted. Thus, large volumes of waste tyres can be consumed.

In conclusion, tyre rubber can be used in a substantial number of civil engineering works. It has good potential for development but this depends largely on the ability of the building and construction designers involved to convince the authorities and the relevant constructors of the advantages of these applications. Although more research needs to be done in all the sectors mentioned above, the addition of even small amounts of tyre rubber in some applications could enable the large volumes of stockpiled tyres to be eliminated, while conserving natural resources.

9.8 References

Ahmed I. and Lovell C.W. (1993), "Rubber soils as lightweight geomaterial", *Transportation Research Record*, **1422**, 61–70.

Airey G.D., Collop A.C. and Singleton T.M. (2001), "Rheological and cohesive properties of bitumen cured in crumb rubber", in Proceedings of the International Symposium of Concrete Technology, University of Dundee, Eds R.K. Dhir, M.C. Limbachiya and K.A. Paine, *Recycling and Reuse of Used Tires*, 281–298.

Airey G.D., Mujibur M.M. and Collop A.C. (2003), "Absorption of bitumen into crumb rubber using the basket drainage method", *International Journal of Pavement Engineering*, **4**(2), 105–119.

Airey G.D., Collop A.C. and Mujibur M.M. (2004), "Mechanical properties of crumb rubber modified asphalt mixtures", in 3rd Eurasphalt and Eurobitume Congress, Vienna.

Albano C., Camacho N., Reyes J., Feliu J.L. and Hernández M. (2005), "Influence of scrap rubber addition to Portland I concrete composites: Destructive and non-destructive testing", *Composite Structures*, **71**, 439–446.

Amari T., Themelis N.J. and Wernick I.K. (1999), "Resource recovery from used rubber tires", *Resources Policy*, **25**, 179–188.

ASTM (1994), ASTM D653-90, Standard technology relating to soil, rock and contained fluids, *Annual Book of ASTM Standards*, Vol. 04.08, American Society for Testing and Materials, West Conshohocken, PA, USA.

ASTM (2003), ASTM D4318-00, Standard test methods for liquid limit, plastic limit, and plasticity index of soils, *Annual Book of ASTM Standards*, Vol. 04.08, pp. 582–595, American Society for Testing and Materials, West Conshohocken, PA, USA.

ASTM (2004), ASTM D 6270-98, Standard practice for use of scrap tires in civil engineering applications, Re approved Edition 2004, American Society for Testing and Materials, West Conshohocken, PA, USA.

Benazzouk A., Douzane O, Langlet T., Mezreb K., Roucoult J.M. and Quéneudec M., (2007), "Physico-mechanical properties and water absorption of cement composite containing shredded rubber wastes", *Cement and Concrete Composites*, **29**, 732–740.

Bosscher P.J., Edil T.B., Eldin N.N. (1992), "Construction and performance of a shredded waste tire test embankment", *Transportation Research Record*, **1345**, 44–52.

www.EngineeringEBooksPdf.com

Cetin H., Fener M. and Gunaydin O. (2006), "Geotechnical properties of tire-cohesive clayey soil mixtures as a fill material", *Engineering Geology*, **88**, 110–120.

Chiu C.-T. (2008), "Use of ground tire rubber in asphalt pavements: Field trial and evaluation in Taiwan", *Resources, Conservation and Recycling*, **52**(3), 522–532.

Choubane B., Sholar G.A., Musselman J.A. and Page G.C. (1999), "Ten-year performance evaluation of asphalt-rubber surface mixes", *Transportation Research Record*, **1681**, 10–18.

Corti A. and Lombardi L. (2004), "End life tyres: Alternative final disposal processes compared by LCA", *Energy*, **29**, 2089–2108.

CWA (2002), CEN Workshop Agreement 14243-2002, "Post-consumer tyre materials and applications", CEN, Brussels.

Edil T.B, Bosscher P.J. and Eldin N.N. (1990), "Development of engineering criteria for shredded or whole tires in highway applications", Department of Civil and Environmental Engineering, University of Wisconsin-Madison, WI, USA.

Edil T.B. and Bosscher P.J. (1994), "Engineering properties of tire chips and soil mixtures", *Geotechnical Testing Journal*, **17**(4), 453–464.

Edil T.B. (2004), "A review of mechanical and chemical properties of shredded tires and soil mixtures", in Geotechnical Special Publication No. 127, Eds A.H. Aydilek and J. Wartman, *Recycled Materials in Geotechnics*, pp. 1–21, ASCE, Reston, VA, USA.

Eldin N.N. and Senouci A.B. (1993), "Rubber-tire particles as concrete aggregates", *ASCE Journal of Materials in Civil Engineering*, **5**(4), 478–496.

Epps J.A. (1994), "Use of recycled rubber tires in highways", NCHRP Synthesis of Highway Practice No. 198, Transportation Research Board, Washington DC, USA.

European Waste Catalogue (2002), Section 16, part 16 01 03, http://www.environment-agency.gov.uk/commondata/acrobat/ewc.pdf.

Fedroff D., Ahmad S. and Savas B.Z. (1996), "Mechanical properties of concrete with ground waste tire rubber", *Transportation Research Board*, **1532**, 66–72.

Fernandes Jr. J.L., Bertollo S.A.M., Bernucci L.L.B. and E. de Moura, (2002), "Laboratory evaluation of dense asphalt mixtures modified with addition of rubber", in 3rd International Conference on Bituminous Mixtures and Pavements, J&A Publishers, Thessaloniki, Greece.

Foose G., Benson C.H. and Bosscher P.J. (1996), "Sand reinforced with shredded waste tires", *Journal of Geotechnical Engineering*, **122**(9), 760–767.

Gesoglu M. and Güneyisi E. (2007), "Strength development and chloride penetration in rubberised concretes with and without silica fume", *Materials and Structures*, **40**, 953–964.

Ghazavi M. (2004), "Shear strength characteristics of sand-mixed with granular rubber", Technical Note, *Geotechnical and Geological Engineering* **22**, 401–416.

Hataf, N. and Rahimi, M.M. (2005), "Experimental investigation of bearing capacity of sand reinforced with randomly distributed tire shreds", *Construction and Building Materials*, **20**(10), 910–916.

Heitzman M. (1992), "Design and construction of asphalt paving materials with crumb rubber modifier", *Transportation Research Record*, **1339**, 1–8.

Humphrey D.N. and Sandford T. (1993), "Tire chips as lightweight sub grade fill and retaining wall backfill", in Proceedings of the Symposium on Recovery and Effective Reuse of Discarded Materials and By-products for Construction of Highway Facilities, Federal Highway Administration, p. 5.55–5.68.

Humphrey D. (1995), "Civil engineering applications of chipped tires", North Platte, Omaha, NE, USA.

www.EngineeringEBooksPdf.com

Hunt E.A. (2002), "Crumb rubber modified asphalt concrete in Oregon", Oregon Department of Transportation, OR, USA.

Kettab R. and Bali A. (2004), "Modified bituminous concrete using rubber powder", in Proceedings of the International Conference organized by the Concrete and Masonry Research Group, Kingston University, London, Thomas Telford, pp.163–170.

Khalid H.A. and Artamendi I. (2002), "Exploratory study to evaluate the properties of rubberized asphalt modified using the wet and dry processes", 3rd International Conference on Bituminous Mixtures and Pavements, J&A Publishers, Thessaloniki, Greece, pp. 15–25.

Khaloo A.R., Dehestani M. and Rahmatabadi P. (2008), "Mechanical properties of concrete containing a high volume of tire-rubber particles", *Waste Management*, available online 26 March 2008.

Khatib Z.K. and Bayomy F.M. (1999), "Rubberized Portland cement concrete", *ASCE Journal of Materials in Civil Engineering*, **11**(3), 206–213.

Khosla N.P. and Trogdon J.T. (1990), "Use of ground rubber in asphalt paving mixtures", Technical Report, Department of Civil Engineering, North Carolina State University, Raleigh, NC, USA.

Krömer S., Kreipe E., Reichenbach D. and Stark R. (1999), "Life cycle assessment of a car tire", Report for Continental AG, Germany.

Lee H.S., Lee H., Moon J.S. and Jung H.W. (1998), "Development of tire-added latex concrete", *ACI Materials Journal*, **95**(4), 356–364.

Lee J.H., Salgado R., Bernal A. and Lovell C.W. (1999), "Shredded tires and rubber-sand as lightweight backfill', *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, **125**(2), 131–141.

Li G., Stubblefield M.A., Garrick G., Eggers J., Abadie Ch. and Huang B. (2004), "Development of waste tire modified concrete", *Cement and Concrete Research*, **34**, 2283–2289.

Minnesota Pollution Control Agency (1990), "Illinois Scrap Tire Management Study", Springfield, IL, USA.

Naik T.R. and Singh S.S. (1991), "Utilization of discarded tires as construction materials for transportation facilities", Report No. CBU-1991-02, UWM Centre for By-products Utilization, University of Wisconsin-Milwaukee, Milwaukee, WI, USA, p. 16.

Oikonomou N., Stefanidou M. and Mavridou S. (2006), "Improvement of the bonding between rubber tire particles and cement paste in cement products", in 15th Conference of the Technical Chamber of Greece, Alexandroupoli, Greece, 25–27 October (in Greek), pp. 234–242.

Oikonomou N., Mavridou S. and Kazakopoulos A. (2007), "Study of asphalt mixtures modified with tire rubber", in Proceedings of the 4th International Conference on Bituminous Mixtures and Pavements, Thessaloniki, Greece (in Greek), Vol. 1, pp. 465–477.

Pais J.C., Sousa J.B., Saam R. and Pereire P.A.A. (2001), "Effect of crumb rubber origin on asphalt hot mix laboratory performance",in 2nd International Symposium on Maintenance and Rehabilitation of Pavements and Technological Control, 29 July–1 August 2001,Auburn, AL, USA, PP. 1–10.

Park J.K., Kim J.Y. and Edil T.B. (1996), "Mitigation of organic compound movement in landfills by shredded tires", *Water Environment Research*, **68**(1), 4–10.

Pierce C.E. and Williams R.J. (2004), "Scrap tire rubber modified concrete: Past, present and future", in Proceedings of the International Conference Organized by the Concrete and Masonry Research Group, Kingston University-London, Eds M.C. Limbachiya and J.J. Roberts, *Sustainable Waste Management and Recycling: Used-Post-Consumer Tyres*, Thomas Telford, pp. 1–16.

www.EngineeringEBooksPdf.com

Punith V.S., Thyagaraj M.N. and Veeraragavan A. (2002), "Studies on tensile strength characteristics of dense bituminous macadam mix with crumb rubber as modifier", in Proceedings of the 3rd International Conference on Bituminous Mixtures and Pavements, Thessaloniki, Greece, pp. 547–556.

Raghavan D., Huynh H. and Ferraris C.F. (1998), "Workability, mechanical properties and chemical stability of a recycled tire rubber-filled cementitious composite", *Journal of Materials Science*, **33**(7), 1745–1752.

Rahman M.M., Airey G.D and Collop A.C. (2004), "Laboratory investigation to assess moisture sensitivity of dry process CRM asphalt mixtures", in Proceedings of the International Conference Organized by the Concrete and Masonry Research Group, Kingston University-London, Eds M.C. Limbachiya and J.J. Roberts, *Sustainable Waste Management and Recycling: Used-Post-Consumer Tyres*, Thomas Telford, pp. 151–162.

Reddy K.R. and Marella A. (2001), "Properties of different size scrap tire shreds: implications on using as drainage material in landfill cover systems", in the Seventeenth International Conference on Solid Waste Technology and Management, October 2001, Philadelphia, PA, USA.

Rostami H., Lepore J., Silverstraim T. and Zundi I. (1993), "Use of recycled rubber tires in concrete", in Proceedings of the International Conference on Concrete 2000, University of Dundee, Ed. R.K. Dhir, pp. 391–399.

Segre N. and Joekes I. (2000), "Use of tire rubber particles in addition to cement paste", *Cement and Concrete Research* **30**(9), 1421–1425.

Siddique R. and Naik R.T. (2004), "Properties of concrete containing scrap-tire rubber – an overview", *Waste Management*, **24**, 563–569.

Tatlisoz N., Benson C.H. and Edil T.B. (1997), "Effects of fines on mechanical properties of soil-tire chip mixtures", in ASTM STP 1275, T*esting Soil Mixed with Waste or Recycled Materials*, Eds M.A. Wasemiller and K.B. Hoddinott, ASTM West Conshohocken, PA, USA, pp. 93–108.

Topçu I.B. (1995), "The properties of rubberized concrete", *Cement and Concrete Research*, **25**(2), 304–310.

Tortum A., Celik C. and Aydin A.C. (2005), "Determination of the optimum conditions for tire rubber in asphalt concrete", *Building and Environment*, **40**, 1492–1504.

Turatsinze A., Bonnet S. and Granju J.-L. (2005), "Mechanical characterization of cement-based mortar incorporating rubber aggregates from recycled worn tyres", *Building and Environment*, **40**, 221–226.

Eleazer W.E. II, Barlaz M.A. and Whittle D.J. (1992), "Resource recovery alternatives for waste tires in North Carolina", Civil Engineering Department, North Carolina State University, NC, USA.

Yoon S., Prezzi M., Siddiki N.Z. and Kim B. (2006), "Construction of a test embankment using a sand-tire shred mixture as fill material", *Waste Management*, **26**, 1033–1044.

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10

Durability of sustainable concrete materials

J. BAI
University of Glamorgan, UK

Abstract: This chapter considers various aspects of the durability of sustainable concrete materials. It examines the important causes of material deterioration and discusses measures to prevent such damage. The chapter begins by reviewing the technological background for durability and addressing the reasons for durability problems. The chapter identifies the effect of the use of sustainable concrete materials on durability and examines the processes involved in building defects and failures from a materials point of view.

Key words: durability, freeze–thaw, abrasion, sulfate attack, chloride ingress, efflorescence, sustainability.

10.1 Introduction

In spite of the improved understanding of many of their common causes and consequences, material failures are still of great concern to the building and civil engineering construction industry. Freezing and thawing in temperate regions with repeated freeze–thaw cycles can cause severe deterioration of concrete. This freeze–thaw process induces large stresses in concrete leading ultimately to its damage. The damage is accelerated, particularly in pavements, by the use of de-icing salts, often resulting in severe scaling at the surface. Sulfates in soil and groundwater are resisted by using suitable cementitious materials and a properly proportioned concrete mixture subjected to proper quality control. Other physical degradations such as abrasion and cracking can cause concrete surfaces to wear away.

Recent years have seen changes in environmental legislation relating to the disposal of industrial waste materials. These changes have resulted in a growing interest in the use of industrial by-products and recycled materials – e.g. fly ash (FA), ground granulated blast-furnace slag (GGBS) and waste-paper sludge ash (WSA) – to partially replace Portland cement in concrete, and recycled concrete as an alternative to aggregates. An advantage of such utilization of waste materials is the contribution towards the conservation of natural resources; however, the reuse of waste materials could add further complication to durability problems.

This chapter outlines the durability of sustainable concrete materials. It examines the important causes of material deterioration and discusses how to prevent

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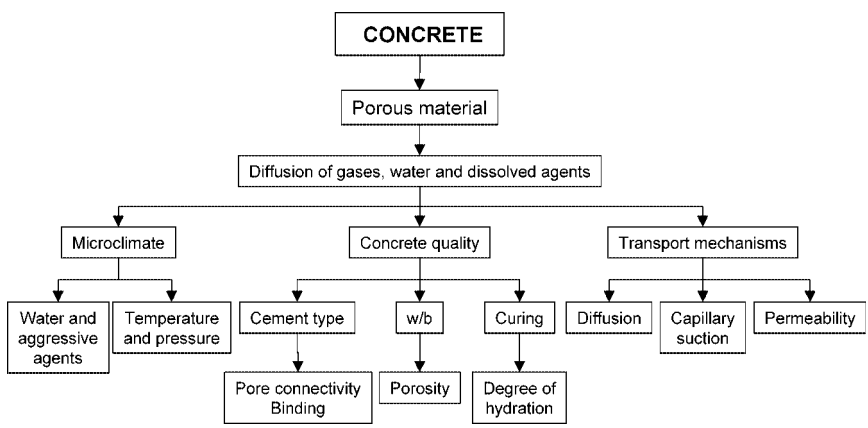
such damage. The chapter begins by reviewing the technological background for durability and addressing the reasons for durability problems. The chapter identifies the effects of using sustainable concrete materials on durability and examines the processes involved in the occurrence of building defects and failures from a materials point of view.

10.2 The nature of concrete durability

The durability of concrete is defined as its ability to resist deterioration processes that may occur as a result of weathering action (interaction with its external environment) (Cai and Liu, 1998; Alexander *et al*., 2007; Pade and Guimaraes, 2007; Yoon *et al*., 2007; Song, 2008), or reactions that may occur between the constituent materials or their reaction with internal contaminants present (Fernandes *et al*., 2004; Owsiak, 2004; Kockal and Turker, 2007). The deterioration is largely the result of physical (cracking, frost, attrition and fire) (Poon *et al*., 2001; Felicetti, 2006; Litorowicz, 2006; Valenza *et al*., 2007) or chemical phenomena (ingress of aggressive fluids, gases and ions, e.g. sulfate, acid, sea water) occurring within or through the concrete surface (Hobbs and Taylor, 2000; Bai *et al*., 2003; Brown *et al*., 2004; Muralidharan *et al*., 2005).

Concrete is porous in its nature. Some aspects of concrete durability involve the penetration of certain forms of aggressive agents. Hence the durability of concrete is mostly associated with its permeability and/or diffusion (Verbeck, 1982; Mehta and Monterio, 1993). Figure 10.1 shows the nature of concrete durability. Inadequate durability can be due to external factors and/or internal causes within the concrete. The ability to resist the flow of fluids through the porous medium is primarily governed by microclimate parameters (aggressive agents, temperature and pressure, etc.), concrete quality and transport mechanisms. The intrinsic properties of concrete affecting permeation are the porosity of the hardened



10.1 Nature of concrete durability.

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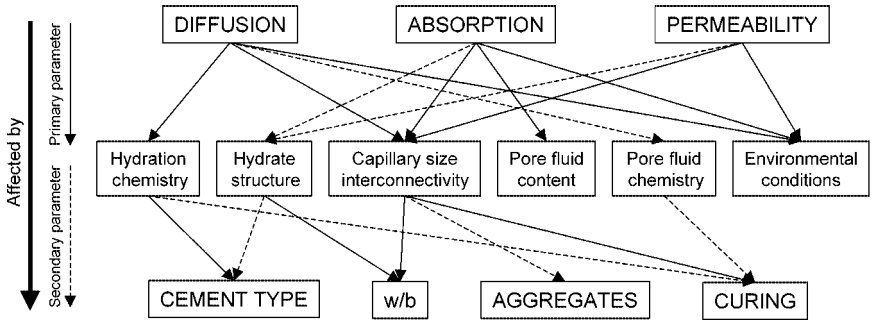

10.2 Factors affecting concrete permeability.

cement paste (Leemann *et al*., 2006; Swider *et al*., 2007), the relative size of the pores (Pradhan *et al*., 2005) and the degree of continuity of these pores (Holly *et al*., 1993). Higher water to binder ratios (w/b) result in an increase in pore volume, hence an increase in permeation (Neville, 1995, p. 492). Figure 10.2 shows the primary and secondary parameters affecting permeation of concrete; these parameters can all hence have an adverse effect on the durability of the concrete. Some excellent references are readily available on the transport mechanisms of gases, fluids and ionics in concrete (Neville, 1995; Nilsson, 1996; Zaharieva *et al*., 2003). Basheer *et al.* (2001) provide a comprehensive review of assessment of the durability of concrete from its permeation properties.

10.3 Durability of sustainable construction materials

10.3.1 Freeze–thaw resistance

Various concepts have been proposed to explain the deterioration of materials due to frost action. It is now generally recognized that there are two types of deterioration due to freezing and thawing cycles: internal cracking and surface scaling (Powers, 1945, 1975; Litvan, 1972). Powers (1945) developed a well-known hydraulic pressure theory attributing frost damage in cement paste to stresses caused by hydraulic pressure in the pores. As the water in the capillary pores freezes there is an increase in volume. If there is no space for the ice to expand into because the pores are full of water, the expansive forces will cause disruption of the pores. If the water within the pores contains dissolved salts in varying concentrations, this means that not all the water will freeze at the same time. These differences in ionic concentrations result in the formation of osmotic pressures (Powers and Helmuth, 1953). Litvan (1972) and other investigators (Radjy, 1968; Setzer, 1976) have analyzed the phenomenon using basic thermodynamic considerations. They consider that the water adsorbed on the surface or contained in the smaller pores cannot freeze due to the interaction between the surface and the water. Because of the difference in vapor pressure of this unfrozen and much

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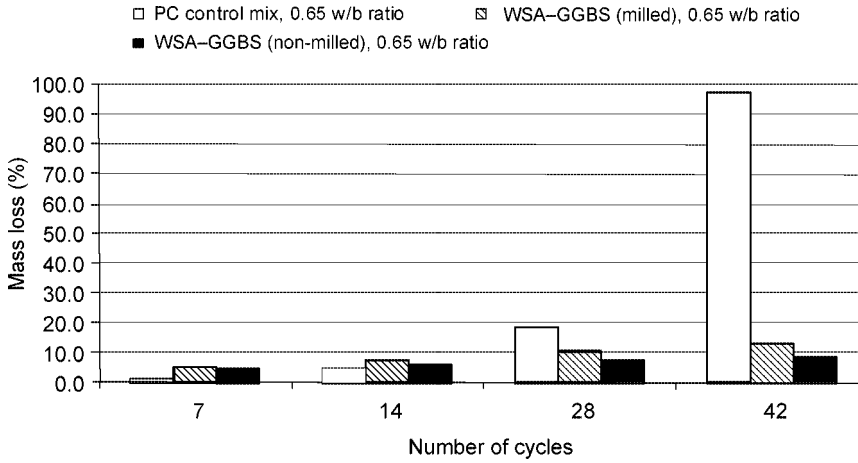

10.3 Mass loss of Portland cement (PC) control, WSA–GGBS milled and unmilled mixtures after 7, 14, 28 and 42 freeze–thaw cycles (Bai *et al.*, 2007).

cooled liquid and the bulk ice in the surroundings of the paste system, there will be migration of water to locations where it is able to freeze, such as the larger pores or the outer surface. The process leads to partial desiccation of the paste and accumulation of ice in crevices and cracks. The freezing could also form a semi-amorphous solid (non-crystalline ice), resulting in great internal stresses and ultimately breaking up.

The way to prevent the internal cracking and disruption that can occur due to freezing and thawing cycles is to add air-entraining admixtures to the concrete resulting in the formation of small discrete air bubbles within the capillary network. The air voids act as reservoirs of air into which the ice can expand without causing disruption of the capillaries. This has been confirmed as the most effective way of minimizing the damage from frost attack by laboratory data and field experience (Neville, 1995, p. 547). Proper air-entrainment, with appropriate volume and spacing factors, will dramatically improve the durability of concrete exposed to moisture during cycles of freezing and thawing. Entrained air also improves the concrete's resistance to surface scaling caused by chemical de-icers.

Yüksel (2007) reported that resistance to freeze–thaw increased when fine aggregate was replaced by non-ground blast furnace slag and bottom ash at levels of up to 20%. Gökçe *et al.* (2000) reported that the freeze–thaw durability of concrete produced from fine materials of waste concrete aggregate was higher than that of concrete produced from normal sand. Hardened concrete incorporating FA or GGBS has similar or better performance except at early ages compared with Portland cement CEM I (Dhir *et al.*, 1998; Blackledge, 2002). Figure 10.3 shows from that the Portland cement control mixture failed (over 90% loss of mass) under freeze–thaw attack before the 42nd cycle, whereas unmilled and milled

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wastepaper sludge ash (WSA)–GGBS mixes performed well. The unmilled mix had slightly higher resistance to freeze–thaw than the milled mixture.

Edwards (1991) and Lehrsch (1998) reported that frost leads to breakdown of concrete and formation of soil aggregates. Porosity has a major influence on the freeze–thaw durability of stone and aggregates. The total pore volume, the pore size and distribution, and the degree of saturation all contribute to freeze–thaw durability (Litvan, 1980). A rock that has less than 1% water absorption is generally considered to be frost-resistant. It is, however, the finer pores, measuring about 1 μm and less, that are most important for the frost resistance of rocks (Lindqvist *et al.*, 2007).

Gökçe *et al*. (2000) reported results of freeze–thaw testing that showed that of concrete produced from waste concrete aggregates with air content was less durable, but that the freeze–thaw durability of concrete produced from fine materials of waste concrete aggregates was higher than that of concrete produced from normal sand.

Fibers can provide an adequate internal restraining mechanism and allow the concrete system to perform crack control functions. Therefore, randomly distributed fiber in a concrete mixture restrains the tensile stress owing to volume changes of the frozen water, and reduces the freeze–thaw damage to the concrete.

Exterior masonry walls are exposed to severe weather conditions, such as freeze–thaw action, which affect the durability of masonry units. As the water in moist units, freezes, it produces pressure in the pores of the unit. If the pressure developed exceeds the tensile strength of the unit, the cavity will dilate and rupture. The accumulative effect of successive freeze–thaw cycles and disruption of the unit can eventually cause expansion and cracking, scaling and crumbling of the unit. The effect of frost on the durability of the units is affected by the moisture content of the units at the start of freezing, the rate of freezing and thawing, and the number of freeze–thaw cycles. It is important that brick should possess good durability. One method to improve the freeze–thaw characteristics of brick is to increase the compactness of the brick and thus reduce the quantity of pores and also the diameter of the pores (Zhao, 2006). Another method is to optimize the formulation and curing regime to obtain hydration products with better freeze–thaw characteristics. Masonry units must comply with the European Standard (EN 771-1:2003) specifying the characteristics and performance requirements for masonry units manufactured from clay for use in masonry construction for building and civil engineering. The appropriate materials subjected to severe exposure conditions should be selected and protected properly; for example, consideration of cappings, copings, and sills in areas where freezing conditions can occur. Earth-retaining walls, where saturation with freezing will occur can be considered as being subject to severe exposure.

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10.3.2 Abrasion resistance

Abrasion can cause concrete surfaces to wear away, which can be a particular problem in industrial floors. Particles of sand, gravel or other solid flooding waste in flowing water can erode the surfaces of structures – such as dams, weirs, tunnels and water pipelines. Hydraulic structures can be made from a range of materials from large rocks and concrete to obscure items such as wooden timbers or tree trunks.

The wearing resistance of concrete is the ability of its surface to resist being worn away by rubbing and friction (Laplante *et al,*, 1991). Wearing of floors and pavements can result from production operations, or from foot or vehicular traffic. The action of the abrasive materials carried by water on hydraulic structures leads to erosion (ACI Committee 210, 1998). Wearing resistance is closely related to compressive strength at the wearing surface (Dhir *et al*., 1991). As the paste wears, the fine and coarse aggregates are exposed, and abrasion and impact will cause additional degradation that is related to aggregate-to-paste bond strength and hardness of the aggregate.

Concretes with fine recycled aggregates have greater abrasion resistance than the normal concrete (Evangelista and de Brito, 2007). This may be related to the fact that abrasion resistance is deeply connected with the bond between the cement paste and the fine aggregates, which is better when recycled aggregates are used. Brito *et al.* (2005) replaced coarse natural aggregates with recycled aggregates of ceramic origin, and achieved better abrasion resistances as the replacement ratio increased.

Test results (Yen *et al.*, 2007) have indicated that concrete mixtures where up to 15% of the cement has been replaced by FA had similar abrasion–erosion resistance to concrete without FA. Beyond levels of 15% cement replacement, the abrasion–erosion resistance decreased with increasing cement replacement. Concrete reinforced with fibers shows higher abrasive resistance (Horszczaruk, 2005). The resistance is 30% higher than that of non-reinforced concrete. Felekoglu *et al.* (2007) reported that steel fiber (156 kg/m^3) addition decreased weight loss due to abrasion by 42% and improved the 28 days flexural strength by 19%.

10.3.3 Cracking

Cracks occur in plastic concrete or in hardened concrete and the causes of cracking are many (Fig. 10.4). In fresh concrete plastic shrinkage cracking occurs when the concrete is subjected to a very rapid loss of moisture caused by a combination of factors – including air and concrete temperatures, relative humidity and wind velocity at the surface of the concrete (Cohen *et al.*, 1990). During the concrete consolidation period, the plastic concrete may be locally restrained by reinforcing steel or formwork. This local restraint may result in voids and/or cracks (settlement cracking) adjacent to the restraining element (Price, 1982; Kronlöf *et al*., 1995).

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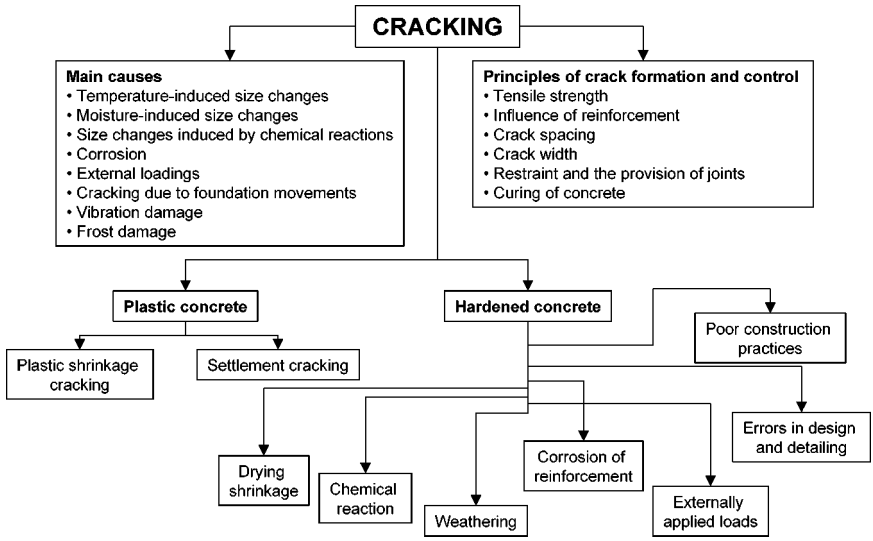

10.4 Causes of cracking.

The weathering processes that can cause cracking include freezing and thawing, wetting and drying, and heating and cooling. Size changes induced by chemical reactions can be very disruptive.

In order to prevent and minimize cracks in concrete, it is important to identify the causes of cracks. The major factors controlling ultimate drying shrinkage of concrete, for example, include relative humidity, aggregate type and content (or paste content), water content and water to cement (w/c) ratio. The rate of moisture loss and shrinkage of a given concrete is influenced by the size of the concrete member, the relative humidity, the distance from the exposed surface and drying time. The disruptive character of cracking from some kinds of chemically induced size changes potentially impairs the life and the structural serviceability of an affected construction. These chemical changes include corrosion of metals, sulfate attack, hydration and carbonation. Designers, specifiers and surveyors should therefore be particularly vigilant in identifying the risks associated with the use of recycled materials. In general, the design strategy would be to avoid the use of susceptible materials or of susceptible combinations of materials, to ensure that service conditions are not favorable to reactions, and to protect susceptible materials, where appropriate, from conditions favoring reactions.

10.3.4 Alkali–silica reaction

The alkali–silica reaction has received much attention and the first to be recognized involves a reaction between the OH^- ion associated with the alkalis (Na_2O and K_2O) from the cement and other sources, with certain siliceous constituents

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that can be present in the aggregate. This phenomenon was referred to as an alkali–aggregate reaction but is more properly designated as an alkali–silica reaction. The alkali–silica reaction adversely affects the appearance and serviceability of a structure. The corrosion reaction is an expansive reaction leading to eventual spalling of the concrete cover (Vidal *et al.*, 2007).

Gress *et al.* (2000) carried out extensive research on investigating techniques and procedures for the assessment of the alkali silica reactivity (ASR) expansion potential for concrete made from recycled concrete aggregate (RCA). The expansion of concrete cubes was found to be significantly accelerated compared with that of a standard prism. Sealing the prisms in evacuated plastic bags with water was also found to accelerate ASR expansion effectively.

Glass is unstable in the alkaline environment of concrete and could cause deleterious alkali–silica reaction problems. Taha and Nounu (2008) reported that glass powder as cement replacement used in concrete as a pozzolanic amorphous material, can contribute to the formation of hydration products and the C–S–H gel. Moreover, the results of this study showed that when pozzolanic glass powder was used in concrete as a cement replacement, the ASR expansion was significantly reduced even at high alkali contents. The presence of pozzolanic glass powder in concrete as a cement replacement leads to changes in the concentration of hydroxide ions in the pore solution, which is considered to be directly reasponsible for reducing the risk of ASR expansion.

Not all aggregates are susceptible to deleterious ASR. However, aggregate selection must avoid aggregates containing high levels of reactive minerals or rocks. Use of pozzolanic materials is an effective option to minimize the potential for deleterious ASR deterioration as this can reduce the pH values of the concrete pore solution.

10.3.5 Sulfate attack

Sulfate attack is the most common form of chemical attack that the concrete is subjected to. Sulfates are commonly found in soil, aggregates, sea water and cements. The chemical consequences of sulfate attack on concrete components are detailed below (Neville, 1995; Taylor, 1997; Hewlett, 1998; Skalny *et al.*, 1998).

1 The formation of ettringite (calcium aluminate trisulfate), resulting in an increase in solid volume, leading to expansion and cracking

$$2(3CaO.Al_2O_3.12H_2O) + 3(Na_2SO_4.10H_2O) \Rightarrow$$
$$3CaO.Al_2O_3.3CaSO_4.31H_2O + 2Al(OH)_3 + 6NaOH + 17H_2O$$

2 The formation of gypsum (calcium sulfate dihydrate), leading to softening and loss of concrete strength

$$Ca(OH)_2 + Na_2SO_4.10H_2O \Rightarrow CaSO_4.2H_2O + 2NaOH + 8H_2O$$

Protection against sulfate attack can be achieved by using concrete with low

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permeability, using cements with a low C_3A content and blends of Portland cement with pozzolans (thus reducing the available $Ca(OH)_2$). Proper placement, compaction, finishing and curing of concrete are essential to minimize the ingress and movement of water, which is the carrier of the aggressive salts. Recommended procedures for these operations are found in the Building Research Establishment (BRE) Special Digest 1 (BRE, 2005). Krammart and Tangtermsirikul (2004) indicated that the expansions of municipal solid waste ashes and calcium carbide waste cements in sodium sulfate solution were lower than those of the control cement when it was exposed to sulfate solution.

There are many factors affecting sulfate attack and also factors that mitigate the attack. In general three approaches are adopted: (a) preventing sulfates from penetrating into concrete; (b) consuming as much $Ca(OH)_2$ as possible in the hydrated cement matrix through the use of pozzolans such as FA and GGBS; (c) using cement with low C_3A.

The first approach is very important and can be achieved by producing impermeable concrete in order to stop or slow the penetration of sulfates into the concrete, thus extending the service life of the concrete. For concrete structures in contact with sulfate-bearing soils, protective linings such as the various proprietary self-adhesive membranes, or protective coatings – such as bitumens, tars and epoxy resins – may also be applied on exterior surfaces.

Pozzolans such as FA (Chindaprasirt *et al.*, 2004; Zuquan *et al.*, 2007), silica fume (Roy *et al*., 2001; Ganjian and Pouya, 2005), metakaolin (Bai *et al.*, 2002; Khatib and Hibbert, 2005) and GGBS (Gollop and Taylor, 1996; Higgins, 2003;) can be employed to effect improvement in the resistance of concrete to sulfate attack. The effect of pozzolans is that the pozzolanic reactions consume $Ca(OH)_2$, which is needed for reaction with sulfates. In the meantime, blended cement concrete has less $Ca(OH)_2$ due to the replacement of cement with pozzolans.

Finally, the formation of ettringite can be minimized by using sulfate-resisting cement, which has a lower C_3A content.

10.3.6 Chloride-induced degradation and steel corrosion

It is generally established that hydrated Portland cement in mortar and concrete is susceptible to attack by sea water, which contains both chloride and sulfate. The principal outcomes are a significant loss of strength, due primarily to decalcification of the C–S–H gel, and diffusion of chloride ions into the concrete, which can initiate corrosion of steel reinforcement. Partial replacement of Portland cement by pozzolans (such as FA, GGBS and metakaolin) can retard these processes (Bai *et al.*, 2003; Al-Otaibi, 2008).

Chlorides can come from a number of different sources, such as de-icing salts, use of unwashed marine aggregates, and sea water. Chloride ions cause localized breakdown of the passive film that initially forms on steel as a result of the alkaline nature of the pore solution in concrete. After initiation of the corrosion process, the

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accumulation of corrosion products (iron oxides and hydroxides), occupying a volume several times larger than that of the original iron (Tuutti, 1982) leads to internal stresses that result in cracking and spalling of the concrete cover.

Resistance to chloride ingress is mainly dependent upon the cement or blended cement with pozzolans and the w/c ratio, with aggregate quality being a secondary factor (Lindvall, 2007). Compressive strength is included as an indirect control on these parameters (BS 8500-1:2006) (BSI, 2006)). Through careful design and good construction practices, the protection provided by Portland cement concrete to embedded reinforcing steel can be optimized. Bai *et al.* (2003) reported that significant reductions in chloride penetration depths occur when Portland cement is partially replaced with FA and metakaolin. These reductions increase with both increasing total replacement level and increasing exposure time. This is attributed to the relative changes in intrinsic diffusivity and chloride binding capacity with age exhibited by the different binder compositions. The quality and depth of concrete in the cover zone are all important in minimizing the risk of corrosion. Khatib and Mangat (2002) investigated the influence of high-temperature and low-humidity curing on chloride penetration in concrete containing cement replacement materials. Higher chloride penetration resistance was observed when cement is partially replaced with either FA or silica fume.

Ann *et al.* (2008) reported that FA and GGBS were used to compensate for the loss of strength and durability of concrete containing recycled aggregate. As a result, 30% FA and 65% GGBS concretes showed increases in compressive strength to the levels of those of control specimens cast with natural granite gravel. Replacement with FA and GGBS was effective in raising the resistance to chloride ion penetration into the concrete body, measured by a rapid chloride ion penetration test based on ASTM C 1202-91. It was found that the corrosion rate of 30% FA and 65% GGBS concretes was kept at a lower level after corrosion initiation, compared with the control specimens.

For plain concrete, the presence of chlorides is not generally a cause for concern in the UK. However, for concrete containing reinforcement, the presence of chlorides is potentially very serious and this has been responsible for the damage of many structures. In most cases, concrete provides very good protection to embedded steel owing to a number of physical and chemical phenomena. It is only under specific conditions that this protection will break down and corrosion occurs. Concrete cover in combination with the chemical resistance are the main factors influencing the effectiveness of concrete against corrosion initiation. High alkalinity of the concrete pore fluids (pH > 12.5), owing to calcium hydroxide (CH) produced from cement hydration, provides conditions that leave embedded steel in a thermodynamically stable or passive and non-corroding condition. The destruction of the passive conditions involves two processes that are mainly responsible for the occurrence of corrosion: the ingresses of carbon dioxide (carbonation) and chloride ions coupled with the presence of oxygen and water. Under these conditions the ferrous ions (Fe^{2+}) released from the anode combine

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with the hydroxyl ions (OH^-) from the cathode, in the presence of water and oxygen to produce rust (ferric hydroxide, $Fe(OH)_2$). This is an expansive reaction leading to eventual spalling of the concrete cover and a reduction in the area of the steel section at the anodic site. The depth of concrete cover is important in minimizing the risk of steel corrosion. Concrete quality can be enhanced by reducing the permeability (Andrade *et al.*, 2006).

10.3.7 Efflorescence

Efflorescence is a deposit of salts, usually white, formed on a surface, the substance having emerged in solution from within either concrete or masonry and subsequently precipitated by evaporation. It occurs most readily in porous concrete near the surface. Efflorescence is not normally damaging, but it is aesthetically undesirable. Dow and Glasser (2003) developed a physicochemical model to explain the origin of efflorescence and quantify the key features of its formation. Brocken and Nijland (2004) investigated the efflorescence process and its relevant parameters and reported that efflorescence on masonry is generally formed by (hydrated) Na^-, K^-, calcium sulfates or carbonates. Single and double salts commonly encountered are thenardite, Na_2SO_4, glaserite, $K_3Na\ (SO_4)_2$ and syngenite, $K_2Ca\ (SO_4)_2{\cdot}H_2O$. In mortar, sulfate generally originates from the calcium sulfate (gypsum, anhydrite, hemihydrate) added to control setting. Efflorescence of calcium carbonates, notably calcite, $CaCO_3$ (formed by the reaction of $Ca(OH)_2$ with CO_2), often occurs on the surfaces of masonry or concrete elements. Efflorescence of gypsum occurs as a white foggy deposit on the surface of clay bricks. Efflorescence and wash-out of lime typically occurs on masonry units. During wetting, rain runs off the masonry surfaces and cause excessive wetting of the mortar joints. This facilitates dissolution of lime in the pore water of the mortar joints and prevents carbonation of this lime.

Most efflorescence can be washed away by high-pressure water. Efflorescence can be limited or prevented through proper drainage and concrete sealers can also prevent efflorescence from reoccurring. The use of lime and GGBS in mortar mixtures would effectively eliminate efflorescence in masonry structures.

10.4 References

ACI Committee 210 (1998). Erosion of concrete in hydraulic structures, in *ACI Manual of Concrete Practice, Part 1*, American Concrete Institute, Farmington Hills, MI.

Alexander, M.G., Mackechnie, J.R.,Yam, W. (2007). Carbonation of concrete bridge structures in three South African localities. *Cement and Concrete Composites*, **29**(10), 750–759.

Al-Otaibi, S. (2008). Durability of concrete incorporating GGBS activated by water-glass. *Construction and Building Materials,* **22**(10), 2059–2067.

Andrade, C., Martínez, I., Castellote, M., Zuloaga, P. (2006). Some principles of service life calculation of reinforcements and in situ corrosion monitoring by sensors in the radio-

www.EngineeringEBooksPdf.com

active waste containers of El Cabril disposal (Spain). *Journal of Nuclear Materials*, **358**(2–3), 82–95.

Ann, K.Y., Moon, H.Y., Kim, Y.B., Ryou, J. (2008). Durability of recycled aggregate concrete using pozzolanic materials. *Waste Management*, **28**(6), 993–999.

Bai, J., Wild, S., Sabir, B.B. (2002). Sorptivity and strength of air-cured and water-cured PC-PFA-MK concrete and the influence of binder composition on carbonation depth. *Cement and Concrete Research*, **32**(11), 1813–1821.

Bai, J., Wild, S., Sabir, B.B. (2003). Chloride ingress and strength loss in concrete with different PC–PFA–MK binder compositions exposed to synthetic seawater. *Cement and Concrete Research*, **33**(3), 353–362.

Bai, J, Kinuthia, J., Wild, S., O'Farrell, M., Mozaffari, E., Ng'ang'a, A.M. (2007). The development of a rapidly setting pipe-bedding material from waste sludge ash (wsa), Veolia project final report, Wolverhampton, UK.

Basheer, P.A.M, Nolan, É. (2001). Assessment of the durability of concrete from its permeation properties: a review. *Construction and Building Materials*, **15**(2–3), 105–114.

Blackledge, G.F. (2002). *Concrete Practice*, Third edition (Revised by R.A. Binns), British Cement Association, Camberley, Surrey.

Brito, J. de, Pereira, A.S., Correia, J.R. (2005). Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates. *Cement and Concrete Composites*, **27**, 429–433.

Brocken, H. Nijland, T.G. (2004). White efflorescence on brick masonry and concrete masonry blocks, with special emphasis on sulfate efflorescence on concrete blocks. *Construction and Building Materials*, **18**(5), 315–323.

Brown, P., Hooton, R.D., Clark, B. (2004). Microstructural changes in concretes with sulfate exposure. *Cement and Concrete Composites*, **26**(8), 993–999.

BRE (Building Research Establishment) (2005). *Concrete in Aggressive Ground*, Special Digest 1, Third edition, Building Research Establishment, Watford, UK.

BSI (British Standards Institutes) (2006). BS 8500-1:2006, *Concrete – Complementary British Standard to BS EN 206-1 – Part 1: Method of Specifying and Guidance for the Specifier*, British Standards Institution, London.

Cai, H., Liu, X. (1998) Freeze–thaw durability of concrete: ice formation process in pores. *Cement and Concrete Research*, **28**(9), 1281–1287.

Chindaprasirt, P., Homwuttiwong, S., Sirivivatnanon, V. (2004). Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar. *Cement and Concrete Research*, **34**(7), 1087–1092.

Cohen, M.D., Olek, J., Dolch, W.L. (1990). Mechanism of plastic shrinkage cracking in portland cement and portland cement-silica fume paste and mortar. *Cement and Concrete Research*, **20**(1), 103–119.

Dhir, R.K., Hewlett, P.C., Chan, Y.N. (1991). Near surface characteristics of concrete abrasion resistance. *Materials and Structures*, **24**(2), 122–128.

Dhir, R.K., McCarthy, M.J., Magee, B.J. (1998). Impact of BS EN 450 PFA on concrete construction in the UK. *Construction and Building Materials*, **12**(1), 59–74.

Dow, C., Glasser, F.P. (2003). Calcium carbonate efflorescence on Portland cement and building materials. *Cement and Concrete Research*, **33**(1), 147–154.

Edwards, L.M. (1991). The effect of alternate freezing and thawing on aggregate stability and aggregate size distribution of some Prince Edward Island soils. *Journal of Soil Science*, **42**, 193–204.

Evangelista, L., de Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*, **29**(5), 397–401.

www.EngineeringEBooksPdf.com

Felekoglu, B., Türkel, S., Altuntas, Y. (2007). Effects of steel fiber reinforcement on surface wear resistance of self-compacting repair mortars. *Cement and Concrete Composites*, **29**(5), 391–396.

Felicetti, R. (2006). The drilling resistance test for the assessment of fire damaged concrete. *Cement and Concrete Composites*, **28**(4), 321–329.

Fernandes, I., Noronha, F., Teles, M. (2004). Microscopic analysis of alkali–aggregate reaction products in a 50-year-old concrete. *Materials Characterization*, **53**(2–4), 295–306.

Ganjian, E., Pouya, H.S. (2005). Effect of magnesium and sulfate ions on durability of silica fume blended mixes exposed to the seawater tidal zone. *Cement and Concrete Research*, **35**(7), 1332–1343.

Gökçe, A., Nagataki, S. Hisada, M., Saeki, T. (2000). Durability of recycled aggregate concretes subjected to freezing and thawing: Impact of crushed concrete characteristics, II. In: International Symposium, *Cement and Concrete Technology in the 2000s*, vol. 1, 6–10 September. Istanbul, Turkey, pp. 371–381.

Gollop, R.S., Taylor, H.F.W. (1996). Microstructural and microanalytical studies of sulfate attack. IV. Reactions of a slag cement paste with sodium and magnesium sulfate solutions. *Cement and Concrete Research*, **26**(7), 1013–1028.

Gress, D.L., Kozikowski, R.L., Eighmy, T.T. (2000). Accelerated ASR testing of recycled concrete. In: Proceedings of WASCON 2000, Waste Management Series, vol. 1, pp. 221–233, Elsevier, New York.

Hewlett, P.C. (1998). *Lea's Chemistry of Cement and Concrete*, Fourth Edition, John Wiley & Sons, Inc., New York.

Higgins, D.D. (2003). Increased sulfate resistance of ggbs concrete in the presence of carbonate. *Cement and Concrete Composites*, **25**(8), 913–919.

Hobbs, D.W., Taylor, M.G. (2000) Nature of the thaumasite sulfate attack mechanism in field concrete. *Cement and Concrete Research*, **30**(4), 529–533.

Holly, J., Hampton, D., Thomas, M.D.A. (1993). Modelling relationships between permeability and cement paste pore microstructures. *Cement and Concrete Research*, **23**(6), 1317–1330.

Horszczaruk, E. (2005). Abrasion resistance of high-strength concrete in hydraulic structures. *Wear*, **259**(1–6), 62–69.

Khatib, J.M., Hibbert, J.J. (2005). Selected engineering properties of concrete incorporating slag and metakaolin. *Construction and Building Materials*, **19**(6), 460–472.

Khatib, J.M., Mangat, P.S. (2002). Influence of high-temperature and low-humidity curing on chloride penetration in blended cement concrete. *Cement and Concrete Research*, **32**(11), 1743–1753.

Kockal, N.U., Turker F. (2007). Effect of environmental conditions on the properties of concretes with different cement types. *Construction and Building Materials*, **21**(3), 634–645.

Krammart, P., Tangtermsirikul, S. (2004). Properties of cement made by partially replacing cement raw materials with municipal solid waste ashes and calcium carbide waste. *Construction and Building Materials*, **18**(8), 579–583.

Kronlöf, A., Leivo, M., Sipari, P. (1995). Experimental study on the basic phenomena of shrinkage and cracking of fresh mortar. *Cement and Concrete Research*, **25**(8), 1747–1754.

Laplante, P., Aitcin, P.C., Vezina, D. (1991). Abrasion resistance of high performance concrete. *Journal of Materials in Civil Engineering*, **3**(1), 19–28.

Leemann, A., Münch, B., Gasser, P., Holzer, L. (2006). Influence of compaction on the

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interfacial transition zone and the permeability of concrete. *Cement and Concrete Research*, **36**(8), 1425–1433.
Lehrsch, G.A. (1998). Freeze–thaw cycles increase near-surface aggregate stability. *Soil Science*, **163**, 63–70.
Lindqvist, J.E., Åkesson, U., Malaga, K. (2007). Microstructure and functional properties of rock materials. *Materials Characterization*, **58**(11–12), 1183–1188.
Lindvall, A. (2007). Chloride ingress data from field and laboratory exposure – Influence of salinity and temperature. *Cement and Concrete Composites*, **29**(2), 88–93.
Litorowicz, A. (2006). Identification and quantification of cracks in concrete by optical fluorescent microscopy. *Cement and Concrete Research*, **36**(8), 1508–1515.
Litvan, G.G. (1972). Phase transitions of adsorbates; IV, Mechanism of frost action in hardened cement paste. *Journal of the American Ceramic Society*, **55**(1), 38–42.
Litvan, G.G. (1980). Freeze–thaw durability of porous building materials. *ASTM STP 691 Durability of Building Materials and Components*, pp. 455–463, ASTM, West Conshohocken, PA.
Mehta, P.K., Monterio, P.J.M. (1993). *Concrete Structure, Properties and Materials*, vol. 2, p. 548, Prentice Hall, NJ.
Muralidharan, S., Vedalakshmi, R., Saraswathi, V., Joseph, J., Palaniswamy, N. (2005). Studies on the aspects of chloride ion determination in different types of concrete under macro-cell corrosion conditions. *Building and Environment*, **40**(9), 1275–1281.
Neville, A.M. (1995). *Properties of Concrete*, Fourth Edition, Prentice Hall, NJ.
Nilsson, L.O. (1996) HETEK, Chloride penetration into concrete, State-of-the-art, transport processes, corrosion initiation, test methods and prediction models, Report No. 53, Road Directorate, Copenhagen, Denmark.
Owsiak, Z. (2004). Alkali–aggregate reaction in concrete containing high-alkali cement and granite aggregate. *Cement and Concrete Research*, **34**(1), 7–11.
Pade, C., Guimaraes, M. (2007). The CO_2 uptake of concrete in a 100 year perspective. *Cement and Concrete Research*, **37**(9), 1348–1356.
Poon, C.-S., Azhar, S., Anson, M., Wong, Y.-L. (2001). Strength and durability recovery of fire-damaged concrete after post-fire-curing. *Cement and Concrete Research*, **31**(9), 1307–1318.
Powers, T.C. (1945). Working hypothesis for further studies of frost resistance of concrete. *ACI Journal*, *Proceedings*, **41**(4), 245–272.
Powers, T.C. (1975). Freezing effects in concrete. In: *Durability of Concrete, SP-47*, pp. 1–11, American Concrete Institute, Farmington Hills, MI.
Powers, T.C., Helmuth, R.A. (1953). Theory of volume changes in hardened cement paste during freezing. *Proceedings of the Highway Research Board*, **32**, 285–297.
Pradhan, B., Nagesh, M., Bhattacharjee, B. (2005). Prediction of the hydraulic diffusivity from pore size distribution of concrete. *Cement and Concrete Research*, **35**(9), 1724–1733.
Price, W.H. (1982), Control of cracking during construction, *Concrete International: Design and Construction*, **4**(1), 40–43.
Radjy, F.F. (1968). A thermodynamic study of the system hardened cement paste and water and its dynamic mechanical response as a function of temperature. PhD Thesis, Department of Civil Engineering, Stanford University.
Roy, D.M., Arjunan, P., Silsbee, M.R. (2001). Effect of silica fume, metakaolin, and low-calcium fly ash on chemical resistance of concrete. *Cement and Concrete Research*, **31**(12), 1809–1813.
Setzer, M.J. (1976). A new approach to describe frost action in hardened cement paste and

www.EngineeringEBooksPdf.com

concrete. In: Proceedings of the Conference on *Hydraulic Cement Pastes – Their Structure and Properties*, Sheffield, UK, pp. 313–325, *British Cement and Concrete Association*, Camberley, Surrey.

Skalny, J., Diamond, S., Lee, R.J. (1998), Sulfate attack, interfaces and concrete deterioration. In: Proceedings of RILEM, 2nd International Conference on *The Interfacial Transition Zone in Cementitious Composites*, A. Katz, A. Bentur, M. Alexander, and G. Arliguie, eds, NBRI Technion, Haifa, pp. 141–151.

Song, H.-W., Lee, C.-H., Ann, K.Y. (2008). Factors influencing chloride transport in concrete structures exposed to marine environments. *Cement and Concrete Composites*, **30**(2), 113–121.

Swider, P., Conroy, M., Pédrono, P., Ambard, D., Mantell, S., Søballe, K., Bechtold, J.E. (2007). Use of high-resolution MRI for investigation of fluid flow and global permeability in a material with interconnected porosity. *Journal of Biomechanics*, **40**(9), 2112–2118.

Taha, B., Nounu, G. (2008). Using lithium nitrate and pozzolanic glass powder in concrete as ASR suppressors. *Cement and Concrete Composites*, **30**(6), 497–505.

Taylor, H.F.W. (1997). *Cement Chemistry*, Second Edition, Thomas Telford, London.

Tuutti, K. (1982). Corrosion of steel in concrete, CBI Fo4. 82, Swedish Cement and Concrete Research Institute, Stockholm, Sweden.

Valenza, J.J., George, I.I., Scherer, W. (2007). A review of salt scaling: II. Mechanisms. *Cement and Concrete Research*, **37**(7), 1022–1034.

Verbeck, G. (1982). *Pore structure – Significance of Tests and Properties of Concrete and Concrete Making Materials*. ASTM Special Technical Publication No. 169A, pp. 211–219, ASTM, West Conshohocken, PA.

Vidal, T., Castel, A., François, R. (2007). Corrosion process and structural performance of a 17 year old reinforced concrete beam stored in chloride environment. *Cement and Concrete Research*, **37**(11), 1551–1561.

Yen, T., Hsu, T.-H., Liu, Y.-W., Chen, S.M. (2007). Influence of class F fly ash on the abrasion-erosion resistance of high-strength concrete. *Construction and Building Materials*, **21**(2), 458–463.

Yoon, I.-S., Çopuroglu, O., Park, K.-B. (2007) Effect of global climatic change on carbonation progress of concrete. *Atmospheric Environment*, **41**(34), 7274–7285.

Yüksel, I., Bilir, T., Özkan, Ö. (2007). Durability of concrete incorporating non-ground blast furnace slag and bottom ash as fine aggregate. *Building and Environment*, **42**(7), 2651–2659.

Zaharieva, R., Buyle-Bodin, F., Skoczylas, F., Wirquin, E. (2003). Assessment of the surface permeation properties of recycled aggregate concrete. *Cement and Concrete Composites*, **25**(2), 223–232.

Zhao, F., Xiao, J., Liu, H. (2006). Autoclaved brick from low-silicon tailings: preparation and discussion. In: Proceedings of the 3rd International Conference on *Energy and Environment Materials ICEEM-3*, Guangzhou, China, p. 137.

Zuquan, J., Wei, S., Yunsheng, Z., Jinyang, J., Jianzhong, L. (2007). Interaction between sulfate and chloride solution attack of concretes with and without fly ash. *Cement and Concrete Research*, **37**(8), 1223–1232.

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11

Nanotechnologies for sustainable construction

M. R. GEIKER and M. M. ANDERSEN
Technical University of Denmark, Denmark

Abstract: This chapter seeks to highlight key aspects and recent trends in the development and application of nanotechnology to facilitate sustainable construction, use and demolition of buildings and infrastructure structures, i.e. 'nanoconstruction'. Nanotechnology is not a technology but a very diverse technological field that covers many application areas. The chapter therefore aims to provide a framework for addressing relevant issues of green nanoconstruction and to bring an overview and illustrative examples of current early developments.

Key words: sustainability, eco-innovation, construction, buildings, nanotechnology.

11.1 Introduction

Despite the enormous and still rising research and development (R&D) investments in nanotechnology worldwide, it is still at an early stage of development; much nanoscience is still pre-commercial (Wood *et al.*, 2003; BMBF, 2004; Luther, 2004; Lux Research, 2004; Willems and van den Wildenberg, 2004; Aitken *et al.*, 2006; Build-NOVA, 2006; Hullmann, 2006).

The hype (extensive focus, debate and fantasising) related to nanotechnology is considerable, with grand expectations of nanotechnology to restructure the world atom by atom. There are especially high expectations for nanotech's *eco-innovative* ('green', sustainable) potential. It is difficult to find a nanoreport or policy document where major environmental benefits are not a main or important claim (see, for example, Nanoforum, 2003; NSET, 2003; EC, 2004; Luther, 2004; Royal Society, 2004; European Parliament Scientific Technology Options Assessment Committee, 2007; Schmidt, 2007). At the same time, concerns regarding possible environmental and health risks related to nanotechnology are increasingly being addressed by scientists, companies and policy makers (Colvin, 2002; Arnall, 2003; Nanoforum, 2004; Royal Society, 2004; Aitken *et al.*, 2006; Friends of the Earth Germany, 2007). There is, however, as yet much uncertainty both as to the environmental opportunities and risks related to nanotechnology (Andersen and Rasmussen, 2006).

The construction sector was among the first to be identified as a promising application area for nanotechnology back at the beginning of the 1990s; but

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appears that the fragmented and conservative construction industry is falling behind other sectors in applying nanotechnology (Gann, 2003). The really big multinational construction companies with large R&D departments are taking the lead in developing *nanoconstruction*, but the majority of construction companies, universities and other knowledge institutions have little insight and experience with nanotechnology (CRISP/SPRU, 2003; Bartos *et al*., 2004; Zhu *et al*., 2004, Luther and Zweck, 2006; Andersen and Molin, 2007). When talking about eco-innovation in nanoconstruction, we are therefore still dealing much with potentialities (Andersen and Molin, 2007; Green Technology Forum, 2007).

This chapter seeks to highlight key aspects and recent trends in the early development and application of eco-innovative nanotech solutions in the construction sector. Nanotechnology is not a technology but a very diverse technological field covering many application areas. The chapter therefore aims to provide a framework for addressing relevant issues of green nanoconstruction and to bring an overview with illustrative examples of current developments.

11.2 Nanotechnology and sustainable construction

11.2.1 Defining nanotechnology

Nanoscience and nanotechnology are the understanding and control of matter at a nanoscale, which is a billionth part of a metre (10^{-9}) (US National Nano Initiative, www.nano.gov). The significance of the nanoscale is not only the small scale, but also the fact that materials obtain new properties at this level. The size range of nanotechnology is normally limited from 100 nm down to the molecular level (approximately 0.2 nm) because in this range materials have significantly different properties to the bulk properties. This is mainly due to two reasons. First, nanomaterials have a large surface area, which can make materials more chemically reactive and affect their strength and electrical properties. Second, quantum effects can begin to dominate the behaviour particularly at the lower end of the nanoscale, which affects the optical, electrical and magnetic behaviour of materials.

Concerning nanoproduction methods, two main routes can be distinguished, entailing a very wide range of techniques (Luther, 2004):

(a) *the top down approach* – entails the fabrication of nanoscale structures by applying specific machining and etching techniques (e.g. lithography, ultra-precise surface figuring);
(b) *the bottom up approach*, also referred to as 'molecular nanotechnology' – entails controlled assembly of atomic and molecular aggregates into larger systems (e.g. clusters, organic lattices, supramolecular structures and synthesised macromolecules).

However, research into nanoscale structures, and even technologies based on nanoscale structures are nothing new. In addition, nanomaterials are not only

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Table 11.1 List of strategic research priorities as stated by ECTP in the Strategic Research Agenda (ECTP, 2005)

A: Meeting client/user requirements	
A1	Healthy, safe and accessible indoor environment for all
A2	A new image of the cities
A3	Efficient use of underground city space
A4	Mobility and supply through efficient networks
B: Becoming sustainable	
B1	Reduce resource consumption (energy, water, materials)
B2	Reduce environmental and manmade impacts
B3	Sustainable management of transport and utilities networks
B4	A living cultural heritage for an attractive Europe
B5	Improve safety and security
C: Transformation of the construction sector	
C1	A new client-driven, knowledge-based construction process
C2	ICT and automation
C3	High-added-value construction materials
C4	Attractive workplaces

Source http://www.ectp.org/documentation/ECTP-SRA-2005_12_23.pdf.

manmade, but exist in nature too. What led to a nanotechnological breakthrough during the 1990s was the development and application of new sophisticated instruments to observe, measure and manipulate processes at the nanoscale level. Before these tools, R&D at the nanoscale was experimental trial and error (Royal Society, 2004). An example of an old green nanotechnology is heterogeneous catalysis for air purification, which is a 30–40 year old established technology where the trial and error-based initial development is increasingly being replaced by a nanoscientific approach (Andersen and Rasmussen, 2006).

11.2.2 Sustainable construction

In recent years, sustainability issues have become increasingly important for the further development of the construction sector. This may be illustrated by the strategic priorities of the European Construction Technology Platform (ECTP) (see Table 11.1). 'Becoming sustainable' is given considerable attention. According to ECTP, sustainable development in construction encompasses resource efficiency, environmental impact, utility networks, the cultural heritage and safety issues.

The environmental agenda is increasingly moving from the more general sustainable development agenda towards the micro (business and consumer) eco-innovation agenda. Eco-innovations are innovations that create value on the market while pursuing reductions in net environmental impacts. With the EU Environmental Technologies Action Plan (ETAP) of 2004 new policy signals were sent in the simultaneous pursuit of environmental and competitiveness goals.

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ETAP created a renewed political interest in pursuing eco-innovations as a business opportunity, breaking with a 35 year tradition of treating the environment as a burden to business (Kemp and Andersen, 2004; Kemp *et al.*, 2004). The EU is in the lead in developing such eco-innovation policies under the slogan 'clean, clever and competitive' (the Lisbon process), but also several Asian countries and the United States are moving fast ahead, illustrating that the climate agenda is becoming truly global (Andersen, 2008a, 2008b; Reid and Miedzinski, 2008).

This policy perspective seeks to address the specific challenges that different sectors and types of companies face when they are eco-innovative. Sustainable construction has recently been identified as one of the six 'lead markets' for innovation in the EU and one out of four eco-innovation policy priority areas (EC, 2006, 2008a, 2008b). This underlines the considerable interest in promoting eco-innovation in the construction sector and, moreover, a policy interest in addressing the barriers to innovation in this traditionally conservative sector.

Such an innovation-oriented policy initiative is of great importance if the high-tech nanotechnology is to achieve a wider uptake in the generally low-tech and little innovative construction sector. Nanotechnology may potentially contribute to making the construction sector both more clever and clean, and improving the innovation capacity and competitiveness of the sector (Andersen, 2006; Andersen and Rasmussen, 2006). Generally, nanotechnology offers opportunities for meeting many of the challenges addressed by the ECTP strategy. These include: (A) meeting the user requirements both in terms of developing smart, fashionable and efficient buildings and cities, and an improved indoor environment; (B) achieving a high resource efficiency and even contributing to environmental remediation and energy production; as well as (C) renewing the sector in making it more knowledge based and automated.

11.3 Green nanotechnology for construction

The great diversity of nanotechnologies means that it is not easy to grasp or delimit what green nanotechnology entails or what it could mean for construction. The high environmental expectations for nanotechnology are related to some fundamental features of nanotechnology. Nanoforum (2004), for example, argues that self-assembly, i.e. the attempt to mimic nature's intrinsic way of building on the nanometre scale, molecule by molecule through self-organisation, has eco-potential because it is extremely efficient (Nanoforum, 2004, p. 39). Another Nanoforum report points to the energy efficiency of nanoparticles. The most relevant effect of nanoparticles for applications is the large amount of atoms exposed on the surface compared with the bulk material. The large surface area leads to a high reactivity thereby, for example, increasing absorption rates for light and facilitating reaction processes at reduced temperatures and with less materials loss (Nanoforum, 2003, p. 89).

Potentially, the atom-by-atom construction of materials leads to optimised

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Table 11.2 Overview – nanorelated areas and their relevance for the construction sector (after Andersen and Molin (2007))

	Relevance for the construction sector (main topics)	
Nanorelated research and technology areas	Applications	Important environmental properties
1 Nanostructured materials		
(a) Nanoporous materials, including cement- and wood-based materials (b) Polymers (c) Composites (d) Other materials	Construction materials in general Insulation materials Load-carrying materials	Strength:weight ratio Durability Performance under fire Impact on indoor climate Energy efficiency Resource efficiency Recyclability Degradability
2 Nanostructured surfaces as coatings and thin films		
(a) Chemically modified surfaces (b) Physically modified surfaces	Everywhere in buildings and civil works	Strength and toughness Durability including aesthetics Impact on indoor climate Hygiene Maintainability Environmental remediation, see point 6 below
3 Nanooptics		
(a) Planar lightwave circuits (b) Photonic crystal fibers (c) Light-emitting diodes (LEDs and OLEDs) (d) Integrated optical sensors	Integrated functions in general Electrical and lighting systems Climate control	Energy efficiency Fire and other safety factors
4 Nanosensors and electronics		
For monitoring and transmission (a) Biosensors (b) Optical sensors (c) Chemical sensors (d) Gas sensors (e) Microorganism detection (f) Electroactive materials	Monitoring and control everywhere in buildings and civil works	Embeddedness Durability Maintainability Resource efficiency
5 Nanointegrated energy production and storage		
(a) Solar cells (b) Fuel cells (c) Other	Heating and cooling systems Building envelope Electricity supply	Energy self-sufficiency and efficiency in buildings and utility systems
6 Nanointegrated environmental remediation		
(a) Catalytic cleaning (b) Other separation and purification processes	Air purification in buildings and infrastructures Water systems (supply and waste) Waste systems	Environmental remediation in general Indoor climate, including cleaning and hygiene Degradability Resource efficiency Substitution of hazardous materials

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tailoring of materials and products without dangerous and messy by-products. An important feature of relevance for nanoconstruction is that nanotechnology allows the design of materials with multifunctional properties. A single nanomaterial can replace several traditional ones. Nanocomposites can be made strong, light, electrically conductive and fireproof. Nanocoatings can be self-cleaning, de-polluting and antimicrobial. For additional discussions on green nanotech opportunities, see Nanoforum (2003), Andersen and Rasmussen (2006), Green Technology Forum (2007) and Scientifica (2007).

The major goal of a recent Danish report (Andersen and Molin, 2007) was to identify the potential of nanotechnology to meet the needs and solve the problems of the construction sector, including the environmental challenges. In this work, six 'nanopillars' emerged that systemise the potential of nanotechnology in relation to the construction industry.

1 Nanostructured materials.
2 Nanostructured surfaces.
3 Nanooptics.
4 Nanosensors and electronics.
5 Nanointegrated energy production and storage.
6 Nanointegrated environmental remediation.

Table 11.2 gives an overview of nanoresearch and technology areas and their construction relevance. The overview illustrates the great variety and scope of nanotechnology, the many emerging technological areas and the broad application opportunities which address almost all aspects of construction. In Section 11.5 we illustrate some of these technologies and potentials.

Nanotechnology may potentially offer many novel environmental and improved solutions in construction. More importantly this goes not only for improving production processes, materials and components for new-builds, but there are also major, and unique, potentials for eco-innovative renovation of existing buildings which is a key challenge for sustainable construction. In addition, environmental improvements in the operation phase may be considerable. It is likely that many of the novel solutions are in an early stage of development, others are fully commercial. Generally, most nanotechnologies are targeted at other applications than construction, mainly more knowledge-intensive areas such as medicine, food and military (Luther, 2004; Andersen and Rasmussen, 2006; Malinowski *et al*., 2006). Many of these quite generic nano-technologies could well be adapted to or directly applied in the construction sector (Andersen and Molin, 2007). However, further development is needed to address the specific problems and environmental requirements of the construction sector.

A Danish analysis shows a generally weak demand for nanotechnology in the construction sector:

> The overall picture of the demand for, knowledge of, and views on

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> nanotechnology in the construction sector is that knowledge and expertise are currently too fragmented to allow for a substantial uptake, diffusion and development of nanotechnological solutions in the construction industry. At present, only very vague ideas of the possible benefits can be identified among key agents of change such as architects, consulting engineers and facility managers. Furthermore the demand side will be reluctant about introducing nanotechnological materials until convincing documentation about functionalities and long-term effects is produced. A need for documentation of the consequences for health and safety is evident (Andersen and Molin, 2007, p. 32).

Two recent consultancy reports on green nanoconstruction (Green Technology Forum, 2007; Scientifica, 2007) identify a wide range of products that are already commercially available worldwide, illustrating that much is beginning to happen in this area. According to these reports, barriers for the wider development of green nanoconstruction are considerable and lie mainly in four areas: (a) the lack of knowledge of nanotech opportunities in the construction sector; (b) reluctance of the sector towards (radical) innovation; (c) the high costs of some, but not all, nanotechnologies; (d) public concern about nanorisks.

A wider use of nanotechnologies will require the use of more science-based innovation processes than is usually the case in construction and necessitates new learning modes. The cost-conscious industry and users will, in some cases, need to consider more costly products which may, however, lead to savings when viewed from a life cycle perspective. The risk issues may turn out to be the most critical element for the wider adoption of nanotechnologies in construction, see also Section 11.4 below.

11.4 Health and environmental risks

When exploring the potential applications of nanotechnology, resulting in improved and sustainable processes and materials, new risks and uncertainties should be taken into account and thorough environmental assessments covering the entire life cycle should also be undertaken. Until recently there has been very little attention and research focusing on nanorelated risks (Andersen and Rasmussen, 2006). This has changed dramatically in later years and increasing attention is now being paid by authorities. In the US National Nanoinitiative, by far the biggest nanoresearch programme globally, it is stated that 'increasing knowledge of the environmental, social and human health implications of nanotechnology is crucial' (NSET, 2003, p. 32). In its proposal for a European strategy on nanotechnology, the EU Commission (EC, 2004, p. 20) also emphasises the potential risk to human health and the need for research and precautions. Several surveys are underway around the globe for an overview of these see Chapter 7 of Nanoforum (2004).

Concerns regarding nanotechnology are particularly related to the following issues.

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- The particles' ultra-fine size and large surface area, crystalline structure and reactivity, which could facilitate transport in the environment or the body that could be harmful and difficult to control because of the particles' interactions with other elements. Some manufactured nanoparticles will be more toxic per unit of mass than larger particles of the same chemical.
- The 'invisible' size of the particles being developed. Such particles could accidentally enter into the food chain, initially causing damage to plants and animals while eventually becoming a hazard to humans. The expected wide-reaching spread of nanomaterials in products and the environment could make them difficult to contain and control (EC SANCO, 2004; Nanoforum, 2004; Royal Society, 2004; Aitken *et al*., 2006).

The evaluation of risks related to nanoparticles is complicated by the fact that they already exist widely in the natural world, e.g. as a result of photochemical and volcanic activity or particles created by plants and algae. Some of these are highly toxic. They have also been created for thousands of years by man as a by-product of cooking and combustion and, more recently, vehicle exhaust. The question is then whether manufactured nanoparticles or the use of nanoparticles in new ways present new risks? The most significant conclusion of the recent risk studies is a likely health risk related particularly to *free nanoparticles* that may penetrate into the brain, lungs and other tissues and possibly cause cancer and other deceases. Nanotubes have properties quite similar to asbestos fibres, which raises suspicion of a similar toxicity (Colvin 2002; Arnall, 2003; EC SANCO, 2004; Luther, 2004; Nanoforum, 2004; Royal Society, 2004; Tsuji *et al*. 2006; Friends of the Earth Germany, 2007).

Most of the risk studies, however, focus on health and safety aspects, whereas environmental assessments on nanoproducts are still rare. The Royal Society report concludes that 'there is virtually no information about the effect of nanoparticles on species other than humans or about how they behave in the air, water or soil, or about their ability to accumulate in the food chains' (Royal Society, 2004, the summary). They recommend that until more is known the release of nanoparticles and nanotubes to the environment should be avoided as far as possible, and that a precautionary principle should be applied.

An important point is that risk issues and environmental impacts related to nanotechnologies vary considerably due to the great diversity of nanotechnologies. Many nanotechnologies are quite harmless but may be considered risky owing to the 'nano' prefix. It is therefore necessary to undertake environmental and health assessments of individual products or product groups.

For hazard identification, Hansen *et al*. (2007) recently suggested that nanomaterials should be categorised depending on the location of the nanoscale structure in the system. This leads to a division of nanomaterials into three main categories: (I) materials that are nanostructured in the bulk; (II) materials that have nanostructure on the surface; and (III) materials that contain nanostructured

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particles. These main categories were further divided into nine subcategories and combined with the inherent physical and chemical properties relevant for each particular category of nanomaterial to form a hazard identification scheme. This scheme is given in Table 11.3. As can be observed, not all the properties apply to all the different categories. Hansen *et al*. (2007) recommend that the location of the nanoscale structure in the system, as well as the nine relevant physical and chemical properties of the nanomaterials identified as hazardous descriptors, be included in, for instance, the Material Safety Data Sheets.

When it comes to nanoconstruction specifically there seems to be limited general research both on risk issues and overall environmental assessments. The Green Technology Forum Report mentioned has, surprisingly, very little information on the possible risks or net environmental impact of the identified nanoconstruction products that are claiming to be green (Green Technology Forum, 2007). As it is now, risk and environmental assessments may be found in the various specific nanoareas rather than in the nanoconstruction area in general. At present, the environmental effects should therefore be considered as potential impacts that we need to know more of. We may conclude that there are still major uncertainties related to nanotechnology risks and overall environmental assessments owing to lack of knowledge.

11.5 Selected examples of green nanoconstruction

This section seeks to give some illustrative examples of the application of eco-innovative nanosolutions for sustainable construction within the six suggested nanopillars (see Section 11.3). Some of the examples are still in the experimental stage, illustrating the current very early development of nanotechnology. The examples are to a high degree based on direct inputs from nanoscientists or companies. The cases are in need of thorough environmental assessments during the life cycle in order to evaluate their environmental impacts fully.

11.5.1 Nanostructured materials

Nanostructured materials as nanoporous materials (e.g. cement- and wood-based products, polymers and composites) are used as both load-carrying and non-load-carrying construction materials. The impact on sustainability depends on, for example, the strength to weight ratio and the durability (Drzal *et al*. 2004). Two examples are given here: the first concerns high-performing insulation materials based on aerogels; the second, green (energy and resource efficient) cement. Insulation materials contribute substantially to the energy efficiency of buildings. Hence, high-performance insulation materials have been increasingly demanded in recent years due to a worldwide requirement for CO_2 reduction. Concrete is the most widely-used construction material and even minor improvements have a large impact on the sustainability of construction.

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Table 11.3 Hazard identification scheme illustrating the relevant inherent physical and chemical properties in comparison to each of the categories proposed by Hansen *et al.*, 2007

Material and category		Chemical composition	Size	Shape	Crystal structure	Surface area	Surface chemistry	Surface charge	Solubility	Adhesion
Bulk	Ia	+	–	–	–	/	/	/	+	+
Multiphase	Ib	+	+	+	–	+	+	–	+	+
Structured surface	IIa	+	+	+	–	+	+	–	+	+
Film	IIb	+	+	–	–	–	+	–	+	+
Structured film	IIc	+	+	+	–	–	+	–	+	+
Surface bound NPs	IIIa	+	+	+	+	+	+	+	+	+
NPs suspended in liquids	IIIb	+	+	+	+	+	+	+	+	+
NPs suspended in solids	IIIc	+	+	+	+	+	+	+	+	+
Airborne NPs	IIId	+	+	+	+	+	+	+	+	+

+ Property expected to be relevant for hazard identification of the nanomaterial.
– Property not expected to be relevant for hazard identification of the nanomaterial.
/ Not possible to determine the property for this type of nanomaterial.
NP, nanoparticle.

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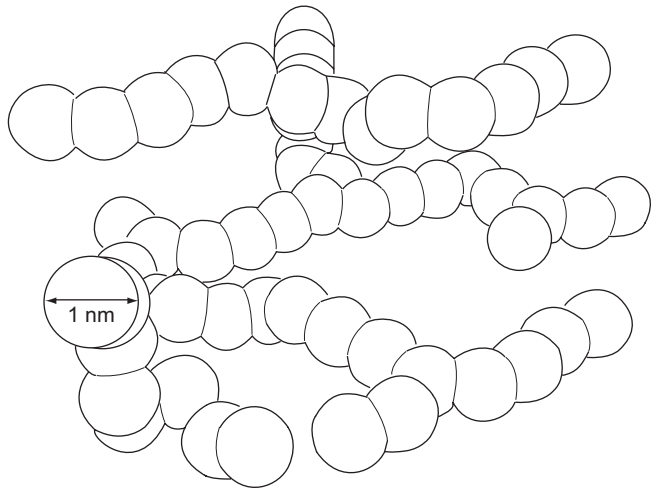

11.1 A schematic representation of the nanoporous structure of an SiO_2 aerogel. Courtesy of M. Koebel, EMPA, *Switzerland.*

Example 1.1 High-performing insulation materials based on aerogels

A major contribution to this example was provided by M. Koebel, S. Brunner, T. Glättli, K. Ghazi Wakili of EMPA – Materials Science & Technology, Switzerland.

Vacuum insulation panels – a micro- or nanoporous core material that is vacuum-packaged in a metal/polymer multilayer laminate foil – take full advantage of the fact that they are the most powerful bulk insulation systems available today, with a thermal conductivity up to 10 times lower than that of mineral wool fibre. The first commercially available products have been implemented in the construction of new buildings. However, they are extremely fragile to mechanical damage/puncturing and show significant ageing.

Aerogel insulation falls in the same class as conventional microporous materials, but with much smaller pore sizes of the order of 10 nm (10^{-8}) as compared with a mean pore size in conventional insulation of tens of microns (10^{-5}). In addition, aerogels exhibit a low structural conductivity owing to their unique combination of low density, high porosity (~90%) and specific surface area (>600 m^2/g). A schematic representation of the nanoporous structure of an SiO_2 aerogel is shown in Fig. 11.1. The material consists of SiO_2 particles of roughly 1 nm diameter which condensate during the gelification step to form a three-dimensional network.

Two companies are already producing SiO_2 aerogel insulation on an industrial scale. However, since such products are expensive compared with conventional solutions, silica aerogels are still a market niche in the insulation sector. Further development is needed as to a sustainable production technology which features a

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continuous process, recycling of solvents and unreacted raw materials, as well as cost minimisation – for example by using the smallest possible amounts of hydrophobisation agents and solvents. Owing to its translucent character, aerogels also find application in translucent roofing insulation, a small market associated with low- or zero-energy houses and demonstrator or prestige buildings.

There are significant uncertainties connected with the market potential and speed of growth of such niche markets and competition is already a step ahead. Rising oil prices and an increasing focus on energy efficiency as a policy target may result in a brighter future for high-performance insulation products.

Example 1.2 Green cement of the future based on nanotechnology

A major contribution for this example was obtained from Jesper Sand Damtoft, Aalborg Portland A/S, Denmark.

Significant advances are being made by using nanoscience to create fundamental knowledge of cementitious systems and using this to develop more energy- and resource-efficient concrete and other cement-based materials. Concrete is the most widely-used construction material because it is inexpensive, uses relatively little energy during manufacture and can be made from local materials. Concrete is an artificial rock, composed of readily available materials such as crushed rock, gravel and sand bound with a cementitious binder. The global cement production exceeds 2 billion tonnes and the demand is continuously increasing as a consequence of the need for infrastructure, industry and housing in high growth economies such as China and India. The biggest challenge with regard to sustainability is the CO_2 emission from the cement production: 0.8 tonne CO_2/tonne cement or approximately 5% of the world's anthropogenic CO_2 emissions. The goal for the cement industry is therefore to meet the increasing demand for cement while reducing CO_2 emissions and keeping the high quality.

Since Roman times, virtually all concrete has been made by using calcium silicate-based binders. Today, these binders are produced by burning raw materials such as limestone, clay and sand, in a cement kiln at 1450–1500 °C to produce Portland cement. Portland cement is composed of artificial calcium silicate minerals, where minor elements in solid solution determine the crystal structure and hence reactivity. The minerals react with water to form nanoporous products. The nanoporosity will, together with the nanostructure of the hydrated phases, to a large degree determine the properties of the hardened concrete.

The addition of micro- and nanosized particles to cementitious mixtures may result in a more homogeneous and finer pore structure. The cement paste structure and porosity can, for example, be engineered by addition of non-pozzolanic layer silicates having specific particle shapes and surface properties (e.g. charge and specific surface area). This seems mainly to be due to the growth of calcium silicate hydrates (C-S-H) on the clay particle surfaces where the nanostructure of the C-S-H seems to depend on the size, shape and charge of the clay particles. In

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addition, the clay particles act as nucleation sites and increase the cement's reaction rate (Lindgreen *et al.*, 2008).

It is the aim of a project carried out jointly by iNANO, Århus and Aalborg Universities, GEUS and Aalborg Portland to use nanoscience to develop the green cement of the future that will be produced with lower CO_2 emissions, but at the same time having improved properties. The project is supported by the Danish Advanced Technology Foundation. The overall objective is to reduce CO_2 emissions by 30%. This will be realised by the development of new functionalised nanoparticles based on natural abundant materials which combined with the further chemically optimised base cement provides the basis for totally new cement types and building materials with reduced embodied energy consumption and CO_2 emissions, as well as higher strengths and improved durability. For example, increased energy efficiency in the cement production is obtained though the introduction of impurities lowering the energy needed for formation of the most important cement constituent, the clinker mineral alite. In addition, the so-called 'mineralised clinker' that is formed has advantages with regard to the production of limestone filler cements, since 15–20% limestone may be added while maintaining the same strengths as unmineralised pure Portland cement; this allows the clinker content in the concrete to be reduced which directly lowers the CO_2 emission (Borgholm *et al.*, 1995).

11.5.2 Nanostructured surfaces

Nanostructured surfaces have the potential to be of major environmental benefit in construction, not least because of the opportunities for renovating existing buildings and infrastructure. A wide variety of nanotechniques exist giving rise to a range of different properties. Surfaces can be made hard and durable thereby improving both their functionality and sustainability. In addition, dirt-repellent, electrically conducting and antibacterial properties may be obtained. Hard and antistatic (i.e. dust repellent) surfaces may be obtained by ultraviolet (UV) curing of special binders, see Example 2.1 below. Self-cleaning surfaces may be obtained through the lotus effect – where the self-cleaning properties arise as a result of the hydrophobic, water-repellent double structure of the surface – or by the application of photocatalytic substances (TiO_2 (anatase)). See also the description of self-cleaning properties in Section 11.5.6.

Example 2.1 Ultraviolet-hardening painting for strong and durable surfaces

A major contribution to this example was provided by Per Møller of The Technical University of Denmark (personal communication, 2008).

Some binders have the ability to cure instantly when exposed to UV light. The UV curing process for paint provides improved physical and chemical properties in polymeric materials and produces superior results in bonding, surface finish and

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durability. In particular, it is possible to obtain an elastic coating by careful selection of the binders. UV curing is used on many types of substrates, including plastics, wood, metal and glass.

Solvent-borne paints are composed of a resinous binder, pigments, fillers and a solvent. After application to the substrate the solvents evaporate and the coating dries. The evaporated solvents are generally flammable and toxic. Solvent emissions are often a big problem environmental problem for the paint industry. In contrast, the UV curing process achieves the transition from liquid to solid by means of chain-addition polymerisation. This polymerisation is triggered by the reaction of a low concentration of an ingredient called a photo initiator, which absorbs and reacts with reactive chemical groups in the binder caused by the UV light.

In UV-curable coatings, the resin binder is replaced by a formulation of liquid monomers and oligomers, which are induced to crosslink by the reaction of the photo initiator. To make paint, pigments may be dispersed in the liquid formulation. The coating is completely reactive and the thickness that is applied wet is essentially the same as the thickness after curing. In UV paints, the pigment does not enter into the crosslinking reaction but is interlocked with the polymer. There is no mass transfer and no evaporation of solvents – the wet formulation simply becomes dry following exposure to a UV light source.

Typically, the radiant energy produced by the UV lamp is focused by a reflector onto the coating and the UV energy striking the surface causes the photo initiator to trigger the polymerisation reaction. The material is usually solidified or dried when it exits the UV cure zone. The time and space required for the curing process is much less than required for thermal drying methods. Because the process relies on UV light to initiate the cross linking of molecules, UV paint does not evaporate any solvents nor heat the substrate.

UV-cured paint surfaces are currently used in construction for flooring and furniture, where the hardening process can be controlled and undertaken in an inert atmosphere.

11.5.3 Nanooptics

Lighting is a heavy user of energy, and is responsible for 10–12% of electricity consumption; using less energy in lighting will reduce its environmental impact. Light emitting diodes (LEDs) is one of the areas that is frequently highlighted when referring to the eco-potential of nanotechnology. Innovation in LEDs may be supported by nanoinnovations in illuminating materials and smart windows, compare the discussion on nanostructured surfaces above, as well as requirements to overall building design for a renewal of lighting systems (Boyce *et al.*, 2003).

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Example 3.1 Light emitting diodes and optical sensors for intelligent and energy-efficient lighting systems

A major contribution to this example was provided by Carsten Dam Hansen of DTU Fotonik, The Technical University of Denmark.

LEDs are in a rapid stage of development; the light emission is now so strong that LEDs can be used for general illumination. The successful application of LEDs for general illumination is forecasted to provide significant economic and environmental benefits. Today, LEDs can be found in many applications requiring coloured light – such as signs, traffic signals, decorative and architectural lighting, and automobile daylight running lights and brake lights. Recent advances in nanotechnology, compound semiconductor materials and enhanced manufacturing techniques are enabling a new generation of blue, green and white LEDs.

The advantages of LEDs are many, such as their low maintenance cost, tuneability, compact size and robustness, but they also have environmentally important features such as longevity, high energy efficiency and not containing any environmentally harmful substances. In the user phase, energy consumption is low compared with incandescent bulbs. LEDs need only about 20% of the power required by a normal bulb in order to produce the same amount of white light. The longevity in the user phase results in considerably reduced production of light sources (one LED replacing around 50 incandescent bulbs with short longevity). LEDs are also environmentally friendly in the waste phase, as the content of heavy metals is low (e.g. no mercury), and they emit no UV light, in contrast to fluorescent lamps. Since LEDs now are able to produce white light of high quality in addition to high energy efficiency, they can be expected to replace conventional lighting technology, and such a switch would result in substantial energy savings. Recent estimates suggest that under the US Department of Energy's (DOE) accelerated schedule, solid-state lighting could displace general illumination light sources such as incandescent and fluorescent lamps by 2025, decreasing energy consumption for lighting by 29% and saving 3.5 quadrillion BTUs (DOE website, http://www.netl.doe.gov/ssl/2008).

Commercial LEDs have reached and surpassed the energy efficiency of incandescent lamps with a luminous efficacy of around 50 lm/W for warm white LEDs and approximately 90 lm/W for cool white LEDs. High-power CW (continuous-wave) operation in laboratories has shown efficiencies of 99 and 129 lm/W for warm and cold white LEDs, respectively. With the improved LED materials of the future, luminous efficacy is expected to reach 150 lm/W; thus, LEDs are expected to surpass the energy efficiency of fluorescent lamps (Optics.org, 2007).

Nanotechnology plays a major part in the development of new enhanced LEDs, with higher energy efficiency but also higher total luminous flux. Novel growth technologies using nanoscale patterning are employed for improved substrates and precise layering of semiconductor materials, see for example Wang *et al*. (2008). Developments in LED technology are taking place globally, driven mainly by

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large companies in the United States, Japan and Germany, and research institutes like Sandia National Laboratories. An upcoming research area is the development of new LED-based flexible intelligent lighting systems in buildings. In these systems the LEDs combined with optical sensors seek to follow the rhythm of daylight, changing the strength and colour of the light in order to imitate natural light.

11.5.4 Nanosensors and electronics

Electronics (ICT) and in particular sensors are increasingly seen as central for the development of smart and resource-efficient houses, utility systems and cities. Nanotechnology plays an important role in the quest for still smaller and more efficient chips. Much of nanoresearch is focusing on developing electroactive materials such as polymer-based lightweight, cheap and corrosion-proof nanocomposites with a high electrical conductivity. Wireless, tiny nanosensors and actuators in buildings are likely to be key components in the future of such intelligent systems. Most of these sensors are currently based on micro- rather than nanotechnology but developments are rapid in this area. A wide range of sensors exist: biosensors, optical sensors, chemical sensors and gas sensors. The example below focuses on wireless sensors in buildings. See also Example 3.1 above.

Example 4.1 Embedded wireless sensors in buildings

A major contribution to this example was received from Jens Møller Jensen of Danfoss Ventures A/S, Denmark.

Wireless sensors in buildings can in general be divided into application areas, for example: monitoring and controlling the interior environment, monitoring and controlling resources, monitoring the state of construction elements and monitoring the exterior environment. Nanotechnology presents opportunities for improvement of electronic sensors in many different fields of technology. Not only may the actual sensing elements, i.e. the specific electronic component measuring the parameter in question, be greatly improved, but also the remaining parts of the electronic sensors can benefit from nanotechnologies. Overall, we are likely to see electronic sensors applied in fields and applications that have previously not been feasible. This is indeed the case with wireless sensors, for which five parameters are key to widespread application: functionality, durability, power management, size and cost.

In the case of sensor elements, two variants of nanotechnology appear to be the major focus, namely carbon nanotubes and nanoengineered surfaces. Nanoscale carbon tubes that are made sensitive to specific molecules allow the production of sensor elements that are electrically sensitive to specific chemical substances. This may range from simple compounds such as water and simple gases affecting the condition of a structural element or the quality of the environment to complex

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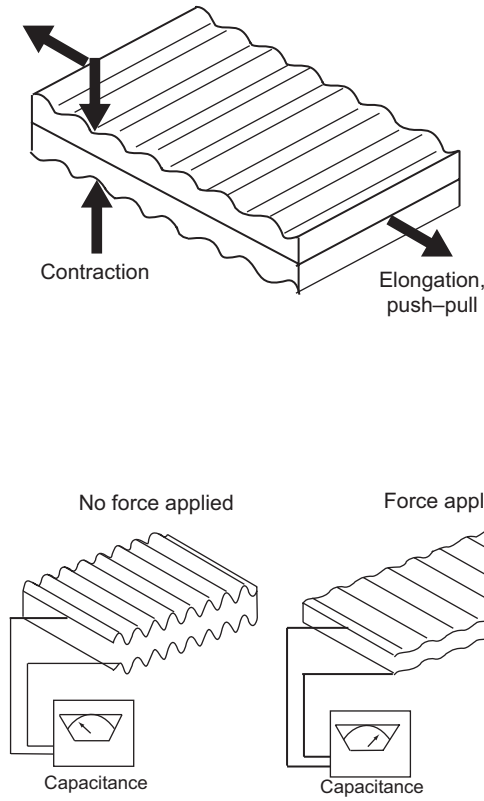

11.2 Conceptual Dielectric Electro Active Polymer (DEAP) sensor in action. Courtesy of Danfoss PolyPower A/S, Denmark.

molecules related to, for example, volatile organic compounds or even explosives. Nanoengineered surfaces will eventually enable sensor elements to be produced that can withstand exposure to substances and environments that the sensors based on current technologies cannot endure.

Another example of novel nanoengineered sensor elements is a polymer that can act for example, as an electrical sensor for dimensional changes in construction elements and buildings. This polymer was recently presented by Danfoss PolyPower A/S on an industrial scale, see Figs 11.2 and 11.3. The polymer material, called DEAP (Dielectric Electro Active Polymer), can act as a sensor, an actuator or an energy generator depending on the application and may thus be seen in many other applications related to sustainable construction.

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11.3 Industrial production of DEAP sensor. Courtesy of Danfoss PolyPower A/S, Denmark.

The remaining parts of electronic sensors which serve to process output from the sensor elements – i.e. sensor front-end electronics, processing circuitry, wireless communication circuitry etc. – will benefit from nanotechnology to reduce, for example, power consumption, performance and physical size.

11.5.5 Nanointegrated energy production and storage

Nanotechnology offers new opportunities for generating energy de-centrally and integrated in buildings as well as for storing energy on-site. Thereby, energy loss in transmission may be reduced and novel energy sources may be developed. Nanotechnology may also contribute to new ways of storing energy through, for example, improved materials for hydrogen storage, new super capacitors, improved efficiency in batteries, etc. However, major developments are not expected in the near future (Walsh, 2007).

Nanotechnology is mainly relevant for the development of micro-fuel-cell plants which show promising developments for on-site energy production, although still in the early stages of development. In addition, nanotechnology is leading to important advances in many solar technologies, not only leading to greater efficiencies but also to new types of products. One of the newest and most

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revolutionising developments is polymer solar cells, also known as organic thin films, a technology that will be further highlighted below.

Example 5.1 Polymer solar cells

A major contribution to this example was provided by Frederik Krebs and Torben Damgaard Nielsen of Risø-DTU, Denmark.

Polymer solar cells primarily based on polymers and nanoparticles can be used for many applications – small electronic gadgets, off-grid community power generation, or power plant energy production – if technology development allows for it. One of the most interesting areas of use is building integration of photo voltaic cells (BIPV). The polymer solar cells are of great interest from an architectural viewpoint because they are very cheap, made of environmentally harmless materials, thin, light and highly flexible. This opens up many more building applications compared with the traditional silicon-based solar cells because of the possibility of integrating or adapting the solar cells to most shapes and surfaces, e.g. in facades, roofs, curtains and windows. Entire buildings could become solar collectors.

Polymer solar cells or 'plastic solar cells' are basically semiconducting materials made from organic molecules. They are similar to silicon-based solar cells in function but different in material. Although in recent years polymer solar cells have received massive attention, it is still a technology at the research level and thus is not commercially available.

The polymer solar cell is a layered structure consisting of, as a minimum, a transparent front electrode, an active layer – which is the actual semiconducting polymer material – and a back electrode printed onto a plastic substrate. The active layer is between 150 and 200 nm thick, resulting in a significantly lower use of materials compared with a traditional silicon solar cell. The use of cheap, abundant materials like plastics and aluminium and the possibility of processing the active material using existing cost-effective and low-energy printing or coating techniques results in a significantly lower price than silicon-based solar cells and less environmental impact. Also, the polymer solar cell has environmental advantages compared with other solar cells. Compared with silicon-based solar cells the production is more energy efficient, and they do not have the problems with heavy metals and chemicals that other (nano) solar thin films have.

As a promising energy technology for the future, polymer solar cells have improved remarkably in recent years and power conversion efficiencies of up to 6.5% were reported for small area devices (1–10 mm^2) (Kim *et al.*, 2007). Unfortunately, these values have not yet been sustained for the long lifetimes needed for commercial maturity.

A team of researchers at Risø-DTU recently achieved more than one year's lifetime for one material under normal operating conditions and 8000–10 000 hours under accelerated conditions (1000 W/m^2, AM 1.5G (air mass 1.5 global

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illumination), 72 °C) (Krebs and Norman, 2007). Efficiencies of 2.22% for a small module with an area of 10 cm^2 area and of 2.45% for an area of 2 cm^2 were recorded for another material. These are significant developments, but a lifetime of several years, efficiencies of 4–8% and a stable, large-scale production process must be achievable before commercial application is within reach. The research today is focused on improving efficiency through experimenting on a nanoscale or simply a zig-zag muster that combines the different materials in the photovoltaic layer. Nanotechnology has mostly illuminated the importance of having as much contact surface as possible between the different components of the photovoltaic layer.

Risø-DTU recently produced 2100 solar cells of approximately 100 cm^2, 1.5–3 V, 1 mA and with a lifetime of several months at a printing facility by using existing screen printing equipment. These solar cells were used for demonstration and product integration during the summer of 2008. It is believed to be the first large-scale production and public offering of polymer solar cells. Although results are promising, it will take years before building integration into buildings is possible.

11.5.6 Nanointegrated environmental remediation

Nanotechnology opens up new opportunities for undertaking environmental remediation in buildings themselves – i.e. handling or removing residuals from air, water and solid wastes at the site of consumption – thereby potentially reducing or avoiding waste and pollution. In addition, nanotechnologies may have significant effects on environmental remediation in civil works such as water systems (supply and sewage systems) and transport infrastructure. Expectations are considerable when it comes to the potential for air purification: buildings that could clean the air within them and also around them, self-cleaning roads, etc. Equally high are the expectations for water purification, where considerable commercial development is already taking place through nanoscale filters with charged membranes, and various nanoparticles targeted at specific pollutants. To date, solid waste treatment has not received much attention but there are interesting potentials including possible de-centralised solutions (Casser *et al*., 2003, 2007; Casser, 2004, 2005; Gray, 2005; Andersen and Rasmussen, 2006; Gurol, 2006; Mann, 2006; Wiesner, 2006; Green Technology Forum, 2007; Watts, 2008).

Example 6.1 Self-cleaning and pollution control by photocatalysis

A major contribution to this example was provided by Per Møller of The Technical University of Denmark and Gian Luca Guerrini of the CTG Italcementi Group.

TiO_2 (anatase) is one of the three mineral forms of titanium dioxide, the other two being brookite and rutile. Anatase is photocatalytically active under UV light and can exhibit self-cleaning, air cleaning and disinfecting properties under

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exposure to UV radiation. Photocatalytic activity is the ability of a material to create an electron–hole pair as a result of exposure to UV radiation:

$$TiO_2 \text{ (anatase)} + hv \rightarrow \text{electron(cb)} + h^+vb$$
$$h^+vb + OH^- \rightarrow \cdot OH$$
$$h^+vb + H_2O \rightarrow \cdot OH + H^+$$
$$\text{electron(cb)} + O_2 \rightarrow O_2^-$$
$$\text{electron(cb)} + h^+vb \rightarrow \text{heat}$$

where hv is a photon (light), h^+vb is an electron–hole, electron(cb) is the valence band, ·OH is a hydroxyl radical, and O_2^- is a super-oxide ion. Oxygen acts as an electron acceptor and the generated free hydroxyl radical (·OH) is a very efficient oxidiser of organic matter. TiO_2 (anatase) is increasingly being used in construction materials and household goods to provide integrated environmental remediation (Cassar, 2004, 2005; Strini *et al*., 2005; Dienemann and Declerk, 2006; Baglinoni and Cassar, 2007).

The system comprising TiO_2 (anatase) and cement has been studied to alleviate environmental pollution through the use of construction materials containing photocatalysts and to maintain the aesthetic characteristics of concrete structures, particularly those based on white cement. In May 2006, the Italcementi Group launched the industrial-scale production and marketing of photocatalytic cement-based products manufactured with the TX Active® principle. The concept was used for the first time in 1996 for the production of the precast blocks to be used for the realisation of the three imposing sails in the church 'Dives in Misericordia' in Rome, which is designed by Richard Meier and was inaugurated in 2003. The main objective of this work was the realisation of a unique structure where prolonged maintenance of the white colour could be achieved (Cassar *et al*., 2003; Guerrini *et al*., 2007).

Self-cleaning properties using photocatalysis can also be applied for self-cleaning windows, e.g. in the BIOCLEAN self-cleaning glass from Saint Gobain and the Activ™ from Pilkington: a transparent coating of hydrophilic and photocatalytic mineral material (anatase) on the outside of the glass harnesses the power of both sun and rain to remove dirt and grime efficiently. Exposure to the UV rays present in daylight triggers the decomposition of organic dirt and prevents mineral dirt from adhering to the surface of the glass. It also makes the glass 'hydrophilic', meaning that when it rains the water sheets across the glass, without forming droplets, rinsing away the broken down dirty residues.

In addition to providing self-cleaning surfaces, TX Active®-based materials (and other construction materials with TiO_2, see below) seek to reduce organic and inorganic pollutants that are present in the air, e.g. through the following chemical reaction for oxidation by hydroxyl radicals, ·OH:

$$NO_2(g) + \cdot OH = HNO_3$$
$$SO_2(g) + 2(\cdot OH) = H_2SO_4$$

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An interesting aspect of TiO_2–cement composites is that there is a clear synergy between the cement and the TiO_2 that makes cement an ideal substrate for environmental photocatalysis. Many photo-oxidizing compounds such as NO_2 and SO_2 are acidic. The alkaline cement matrix is particularly suitable for fixing both the polluting reagent and the photo-oxidation products at its surface. Estimates according to Italcementi are that in a large city such as Milan, covering 15% of visible urban surfaces with products containing TX Active® principle would enable a reduction in pollution of approximately 50%. Several pilot applications have already demonstrated the effectiveness of de-pollution activity with NO*x* reductions measured at 20–60% as a function of lighting conditions (Plassais and Guillot, 2006; Guerrini and Peccati, 2007).

A broad list of the current applications of photocatalytic cement-based materials includes: concrete pavements (paving blocks and tiles, white topping); roofing tiles; indoor and outdoor paints, renderings and plasters; precast panels; and coatings in tunnels (see Figs 11.4 and 11.5). In Italy in 2006, photocatalytic surfaces produced with cement-based materials amounted to approximately 400 000 m^2, equivalent to 56 football fields, whereas horizontal applications (paving blocks, industrial pavements, white topping, etc.) amounted to approximately 200 000 m^2. At a European level, the 2007 estimate for horizontal surfaces is over 1 million m^2 (Cassar *et al*., 2007). According to the Italcementi Group, the market is growing strongly and is moving into the ready-mix concrete and precast sectors.

As far as indoor applications are concerned, the Maxit Group has a gypsum-based product line based on photocatalysis (Maxit Airfresh®), which seeks to mitigate air pollution, especially in the indoor environment. The use of such indoor materials is still limited. For use on existing structures, the potential of TiO_2-impregnated sealers for preparation of photocatalytically active concrete has recently been demonstrated (Watts, 2008).

Several questions still remain unanswered (see, for example, Gurol (2006)). Topics of current investigations include: the evaluation of kinetics and the formation of intermediates or by-products during the photocatalytic degradation of volatile organic compounds (VOCs) or more complex organic substances; the assessment of long-term performances (functional durability); the effectiveness of dedicated modified TiO_2 for de-polluting actions in indoor environments; and the health risk assessment of photocatalytic materials which, for example, is investigated within the framework of the broader study of nanomaterials and nanotechnologies in the EU-funded Nanosafe2 project (NanoSafe, 2008).

A matter of concern, especially in connection with indoor use, is the risk of degradation of organic matter into hazardous products such as the production of ozone and free radicals from VOCs. A recent case illustrates the importance of a proper health risk assessment: in April 2008, Nanocover, a handy-man product for self-cleaning windows, was removed from the Danish market based on arguments given by Møller (2008a, 2008b) that the active component TiO_2 (anatase) implies

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11.4 Tunnel: photocatalytic coating and dedicated UV lighting system (Rome, Italy). Courtesy of G. L. Guerrini, CTG Italcementi Group.

11.5 Photocatalytic road made from paving blocks (Italy). Courtesy of G. L. Guerrini, CTG Italcementi Group.

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a high health risk due to its powerful oxidation capability (see, for example, Kubota *et al*. (1994)). The product was earlier accepted based on a report prepared for the European Commission on cream with TiO_2 (rutile), which has other properties than TiO_2 (anatase) (P. Møller, personal communication, 2008).

11.6 Sources of further information and advice

The early stage of development of nanotechnology in general and more specifically in construction means that the related literature and activities are limited. Literature focusing on nanoconstruction is equally sparse to date. However, within this literature, green nanoconstruction is dealt with quite substantially, which underlines the importance of the eco-innovative nanopotential (see Gann, 2003; Bartos *et al*., 2004; Zhu *et al*., 2004; Luther and Zweck, 2006; Mann, 2006; Andersen and Molin, 2007; Zhi and Gao, 2008). These analyses are a mixture of overview consultancy reports and more scientific analyses looking into trends and innovation dynamics. The main literature on green nanoconstruction is recent and is limited to Green Technology Forum (2007) and Scientifica (2007). These are consultancy reports that give a good overview of commercial green nanoconstruction products but contain limited critical analyses. Nanorisks is a topic in its own right and a key source of information is the Royal Society (2004). Non-governmental organisations are often engaged in this, see Friends of the Earth Germany (2007).

There are numerous websites on nanotechnology. A good entrance to relevant further sources of information is to visit the webpages of various nanoconstruction initiatives and programmes. Andersen and Molin (2007) bring an overview identifying nine foreign or international initiatives that focus in various ways on the opportunities that nanotechnologies may bring to the construction sector. These initiatives range from research projects to permanent research and/or dissemination networks, demonstration activities and private or public laboratories dedicated specifically to nanoconstruction research and product development. The initiatives are briefly described in Table 11.4. In addition, a RILEM Technical Committee 197-NCM Nanotechnology in construction materials, was established in 2002 with the objective of, among other things, producing a State-of-the-art Report and a survey of existing and potential applications in construction (Bartos *et al.*, 2004). The only activity with a specific green orientation is the Green Nordic NanoCon (GNNC) project, as shown in Table 11.4.

11.7 Conclusions

The chapter has shown a range of potential nanotechnonologies applicable for construction and with promising environmental impacts. Some are already commercial, many are underway. Several nanotechnologies are none the less interesting because they point to some novel solutions for achieving sustainable buildings and cities. They are especially relevant because many can be used in existing buildings

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Table 11.4 Overview – initiatives (year 2007) to support application of nanotechnology in construction (Andersen and Molin, 2007)

Name	Country/region	Thematic focus	Mode of organisation	Range	Goals and main activities
NRC-IRC	Canada	Cement and concrete, bitumen, fire protection, indoor air quality and insulation	Research centre/ governmental agency	National	Product development, exploitation of intellectual property rights
NanoCem	Europe	Cementitious materials	Network	Europe	Fundamental research
NANOCOM	Scotland	Construction materials	Research centre/ university	National	Fundamental research
NANOC	Spain	Development of various nanomaterials (high-performance material, nano-/microstructures, modelling materials)	Research centre/ private company	International	Exploitation of intellectual property rights
RENAC	Spain	Nanoparticles, nano-composites, sensors and basic nanotechnology	Network	Valencian community, Spain	Fundamental research, exchange of resources, commercial exploitation of nanotechnologies
Nano House	Australia	Roof, paint, coating, glass, lighting, energy	Network	International	Demonstration and development of nanotechnologies
Glass House	Australia	Glass	Network	International	Demonstration and development of nanotechnologies
Nanoarchi-tecture.net	US	Various nanoconstruc-tion activities and cases	Web portal	US/international	Dissemination towards architects
GNNC (Green Nordic NanoCon)	Denmark, Sweden, Finland	All green nano-construction, company cases in window chain	Research and dissemination project	Nordic	Innovation research, dissemination towards companies, scientists and policy makers

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and structures and not only in new builds. Much nanoscience and technology development today is, however, not directed at the construction sector and this may inhibit or slow down the introduction of green nanoconstruction. Much more knowledge is needed about the possible opportunities, including commercial values and industrial trends, durability, and wider environmental assessment and risk issues.

11.8 Acknowledgements

The data for this chapter are mainly based on three projects: the Green NanoTechnology Foresight sponsored by the Danish EPA; the NanoByg project sponsored by Realdania, Denmark; and the Green Nordic NanoCon project sponsored by the Nordic Innovation Centre. We also thank the scientists and companies that have provided direct information for the examples in Section 11.5, as well as Anders Baun and Stig Olesen, at The Technical University of Denmark, for commenting on the general risk aspects.

11.9 References

Aitken RJ, Chaudhry MQ, Boxall ABA and Hull M (2006), 'Manufacture and use of nanomaterials: current status in the UK and global trends', *Occupational Medicine,* **56**(5), 300–306.

Andersen MM (2006), 'Embryonic innovation – path creation in nanotechnology', *DRUID Conference*, Copenhagen, 18–20 June, *www2.druid.dk/conferences/viewpaper.php?id=703&cf=8.*

Andersen MM (2008a), 'Review: System transition processes for realising sustainable consumption and production', in Tucker A, Charter M, Vezzoli C, Sto E and Andersen MM (Eds) *System Innovation for Sustainability* 1, Green Leaf Publishing, Sheffield, pp. 320–344.

Andersen MM (2008b), 'Eco-innovation – towards a taxonomy and a theory', *DRUID Conference*, Copenhagen, 18–20 June, *www2.druid.dk/conferences/userfiles/file/June_13b.pdf.*

Andersen MM and Rasmussen B (2006), *Environmental Opportunities and Risks from Nanotechnology*, Risoe-Report 1550-EN, Risø National Laboratory, Roskilde, Denmark.

Andersen MM and Molin M (2007), *NanoByg: A survey of Nanoinnovation in Danish Construction*, Report number Risoe-R-1234(EN), Risø National Laboratory, Roskilde, Denmark, http://www.risoe.dk/rispubl/reports/ris-r-1602.pdf.

Arnall AH (2003), *Future Technologies, Today's Choices: Nanotechnology, Artificial Intelligence and Robotics; A technical, political and institutional map of emerging technologies*, Greenpeace Environmental Trust, London, UK.

Baglioni P and Cassar L (Eds) (2007), 'Photocatalysis, environment and construction materials – TDP 2007', in *International RILEM Symposium on Photocatalysis, Environment and Construction Materials*, Florence, Italy, RILEM PRO 55.

Bartos PJM, Hughes JJ, Trtik P and Zhu W (Eds) (2004), *Nanotechnology in Construction* XVI, Springer, Berlin.

BMBF (Federal Ministry of Education and Research) (2004), *Nanotechnology Conquers*

www.EngineeringEBooksPdf.com

Markets: German Innovation Initiative for Nanotechnology. http://www.bmbf.de/pub/nanotechnology_conquers_markets.pdf.

Borgholm HE, Herfort D and Rasmussen S (1995), 'A new blended cement based on mineralised clinker', *World Cement*, **8**, 27–33.

Boyce P, Hunter C, Howlett O (2003), *The Benefits of Daylight through Windows*, Lighting Research Centre, Rensselaer Polytechnic Institute. http://www.lrc.rpi.edu/programs/daylighting/pdf/DaylightBenefits.pdf.

Build-NOVA (2006), *Characteristics of the Construction Sector – Technology and Market Tendencies*, Europe INNOVA EC, Bruxelles.

Cassar L (2004), 'Photocatalysis of cementitious materials, clean buildings and clear air', *MRS Bulletin*, May 29, 328–331.

Cassar L (2005), 'Cementitious materials and photocatalysis', *Betonwerk+Fertigteil-Technik*, **1**, 10–16.

Cassar L, Pepe C, Tognon G, Guerrini GL and Amadelli R (2003), 'White cement for architectural concrete, possessing photocatalytic properties', in *11th International Congress on Chemistry of Cement*, Durban, South Africa, vol. 4, p. 2012.

Cassar L, Beeldens A, Pimpinelli N and Guerrini GL (2007), 'Photocatalysis of cementitious materials', in *International RILEM Symposium on Photocatalysis, Environment and Construction Materials*, Florence, Italy, RILEM PRO 55, pp. 131–146.

Colvin V (2002), *Nanotechnology: environmental impact*, Presentation at National Center for Environmental Research (NCER), U.S. EPA.

CRISP/SPRU (2003), *The Emperor's New Coating: New Dimensions for the Built Environment: The Nanotechnology Revolution*, CRISP, London, www.crisp-uk.org.uk/REPORTS/NanoReportFinal270103.pdf.

Dienemann W and Declerk P (2006), 'Self-cleaning concrete cladding panels', *Betonwerk+Fertigteil-Technik*, **2**, 14–16.

Drzal LT, Mohanty AK, Burgueno R and Misra M (Eds) (2004), *Biobased Structural Composite Materials for Housing and Infrastructure Applications: Opportunities and Challenges*. Proceedings of the NSF Housing Research Agenda Workshop, 12–14 February, Orlando, Florida.

EC (2004), *Towards a European Strategy for Nanotechnology*, European Commission, http://cordis.europa.eu/nanotechnology/actionplan.htm.

EC (2006), *Putting Knowledge into Practice: A Broad-Based Innovation Strategy for the EU*, COM (2006) 502 final, Brussels, http://eur-lex.europa.eu/LexUriServ/site/en/com/2006/com2006_0502en01.pdf.

EC (2008a), *Coordinated Action to Accelerate the Development of Innovative Markets of High Value for Europe – The Lead Markets Initiative Brussels*, MEMO/08/5, 7 January, Brussels, http://ec.europa.eu/enterprise/leadmarket/leadmarket.htm.

EC (2008b), *Eco-innovation – When Business Meets the Environment*, Call for proposals 2008, CIP Eco-innovation and pilot and market replication projects, http://ec.europa.eu/environment/etap/ecoinnovation/index_en.htm.

EC SANCO (2004) *Nanotechnologies: A Preliminary Risks Analysis*, report on the basis of a workshop organised in Bruxelles on 1–2 March by the Health and Consumer Protection Directorate General of the European Commission (SANCO), European Communities, Bruxelles.

ECTP (2005), *Strategic Research Agenda for the European Construction Sector: Achieving a sustainable and competitive construction sector by 2030*, European Construction Technology Platform, EC, Brussels, http://www.ectp.org/.

European Parliament Scientific Technology Options Assessment Committee (2007), *The*

www.EngineeringEBooksPdf.com

Role of Nanotechnology in Chemical Substitution, http://www.nanowerk.com/spotlight/spotid=2212.php.

Friends of the Earth Germany (BUND) (2007), *For the Responsible Management of Nanotechnology*, discussion paper, 12 April, http://www.bund.net/lab/reddot2/pdf/bundposition_nano_03_07.pdf.

Gann D (2003), *A Review of Nanotechnology and its Potential Applications for Construction*, SPRU/CRISP, http://www.crisp uk.org.uk/REPORTS/LongNanotech240203.pdf.

Gray S (2005), *Nanotechnology Applications in Water Management*, http://www.nanovic.com.au/downloads/water_management.pdf.

Green Technology Forum (2007), *Nanotechnology for Green Building*s, Indianapolis, greentechforum.net.

Guerrini GL and Peccati E (2007), 'Photocatalytic cementitious roads for de-pollution', in *International RILEM Symposium on Photocatalysis, Environment and Construction Materials*, Florence, Italy, RILEM PRO 55, pp. 179–186.

Guerrini GL, Plassais A, Pepe C and Cassar L (2007), 'Use of photocatalytic cementitious materials for self-cleaning applications', in *International RILEM Symposium on Photocatalysis, Environment and Construction Materials*, Florence, Italy, RILEM PRO 55, pp. 219–226.

Gurol MD (2006), *Photo-catalytic Construction Materials and Reduction in Air Pollutants*, report, Environmental Engineering, San Diego State University, http://www.csus.edu/calst/government_affairs/reports/PHOTO-CATALYTIC.pdf.

Hansen SF, Larsen BH, Olsen SI and Baun A (2007), Categorization framework to aid hazard identification of nanomaterials', *Nanotoxicology*, **1**, 243–250.

Hullmann, A (2006), *The Economic Development of Nanotechnology – An Indicator Based Analysis*, ftp://ftp.cordis.europa.eu/pub/nanotechnology/docs/nanoarticle_hullmann_nov2006.pdf.

Kemp R and Andersen MM (2004), *Strategies for Eco-Efficiency Innovation*, strategy paper for the Informal Environmental Council Meeting, 16–18 July, Maastricht, VROM, Den Haag.

Kemp R, Andersen MM and Butter M (2004), *Background Report about Strategies for Eco-Innovation*, background report for the Informal Environmental Council Meeting, 16–18 July, Maastricht, VROM, Den Haag.

Kim K, Liu J, Namboothiry, MAG and Carroll DL (2007), 'Roles of donor and acceptor nanodomains in 6% efficient thermally annealed polymer photovoltaics', *Appl. Phys. Lett.* 90, 163511, Doi:10.1063/1.2730756.

Krebs FC and Norrman K (2007), 'Analysis of the failure mechanism for a stable organic photovoltaic during 10 000 h of testing', *Progress in Photovoltaics: Research and Applications*, **15**, 697–712.

Kubota Y, Shuin T, Kawasaki C, Hosaka M, Kitamura H, Cai R *et al.* (1994), 'Photokilling of T-24 human bladder cancer cells with titanium dioxide', *British Journal of Cancer*, **70**, 1107–1111.

Lindgreen H, Geiker M, Krøyer H, Springer S and Skibsted J (2008), 'Microstructure engineering of Portland cement pastes and mortars through addition of ultrafine layer silicates', *Cement and Concrete Composites*, **30**, 686–699, doi:10.1016/j.cemconcomp.2008.05.003.

Luther W (2004), *International Strategy and Foresight Report on Nanoscience and Nanotechnology*, VDI Technologiezentrum for Risoe National Laboratory, Düsseldorf.

Luther W and Zweck A (2006), *Anwendungen der Nanotechnologie in Architektur und*

www.EngineeringEBooksPdf.com

Bauwesen, Zukünftige Technologien Consulting der VDI Technologiezentrum GmbH, Band 62, April , Düsseldorf.

Lux Research (2004), *The Nanotech Report*, New York.

Malinowski N, Luther W, Bachmann G, Hoffknecht A, Holtmannspötter D and Zweck A (2006), *Nanotechnologie als wirtschaftlicher Wachstumsmarkt: Innovations- und Technikanalyse*, Zukünftige Technologien Consulting der VDI Technologiezentrum GmbH, Band 53, Düsseldorf.

Mann S (2006), *Nanotechnology and Construction*, Nanoforum, www.nanoforum.org.

MCH NanoSolutions (2007), *Self-Cleaning Buildings Thanks to Nanotechnology and Green Chemistry*, press release, 1 August, http://www.pr.com/press-release/46970.

Møller P (2008a), 'Professor: Forbyd farligt nanocover med det samme', in *Ingeniøren*, Ed. T. Djursing, 15 April,10:38, http://ing.dk/artikel/87229.

Møller P (2008b), 'Professor: Rensende vægmaling risikerer at gøre mere skade end gavn', in *Ingeniøren*, Ed. M. Nyvold, 24 April, 12:42, http://ing.dk/artikel/87566.

Nanoforum (2003), *Nanotechnologies Help Solve the World's Energy Problems*, Nanoforum, www.nanoforum.org.

Nanoforum (2004), *Benefits, Risks, Ethical, Legal and Social Aspects of Nanotechnology*, Nanoforum, www.nanoforum.org.

NanoSafe (2008), EU NanoSafe Project webpage, www.nanosafe.org/.

NSET (2003), *The National Nanotechnology Initiative: Research and Development Leading to a Revolution in Technology and Industry: Supplement to the Presidents FY 2004 Budget*, National Science and Technology Council, Washington, DC

Optics.org (2007) 'High-power LED breakthrough from Cree', http://optics.org/cws/article/industry/31163, 18 September.

Plassais A and Guillot L (2006), 'De-polluting activity assessment of photocatalytic cement-based materials: from laboratory to real scale testing', in *10th International Symposium on Concrete Roads* (Brussels/Belgium, 18–22 September.

Reid A and Miedzinski M (2008), *Eco-Innovation: Final Report for Sectoral Innovation Watch*, SYSTEMATIC Eco-Innovation Report 2008, Technopolis Group.

Royal Society (2004), *Nanoscience and Nanotechnologies: Opportunities and Uncertainties,* The Royal Society and The Royal Academy of Engineering, http://www.nanotec.org.uk/finalReport.htm.

Schmidt KF (2007), *Green Nanotechnology*, Woodrow Wilson International Center for Scholars Project on Emerging Nanotechnologies, http://www.nanotechproject.org/116/4262007-green-nanotechnology-its-easier-than-you-think.

Scientifica (2007), *Nanotech: Cleantech – Quantifying The Effect of Nanotechnologies on CO_2 Emissions*, http://www.cientifica.eu/index.php?option=com_content&task=view&id=73&Itemid=118.

Strini A, Cassese S and Schiavi L (2005), 'Measurement of benzene, toluene, ethylbenzene, and o-xylene gas phase photodegradation by titanium dioxide dispersed in cementitious materials using a mixed flow reactor', *Applied Catalysis B*, **61**, 90–97.

Tsuji JS, Maynard AD, Howard PC, James JT, Lam CW, Warheit DB and Santamaria AB (2006), 'Research strategies for safety evaluation of nanomaterials, Part IV: risk assessment of nanoparticles', Nanotechnology peer review workshop summary, www.epa.gov/OSA/pdfs/nanotech/nanotechnology-peer-review-workshop-summary-report-final-070706.pdf.

Walsh B (2007), *Environmentally Beneficial Nanotechnologies*, Oakdene Hollins for Department for Environment, Food and Rural Affairs, May, www.defra.gov.uk/environment/nanotech/policy/pdf/envbeneficial-report.pdf.

www.EngineeringEBooksPdf.com

Wang C, Chen L, Chen C, Cheng Y, Ke M, Hsieh M, *et al.* (2008), 'GaN nanorod light emitting diode arrays with a nearly constant electroluminescent peak wavelength,' *Optics Express*, **16**, 10549–10556.

Watts MJ (2008), 'Photocatalysis of 4-chlorophenol mediated by TiO_2 fixed to concrete surfaces', *Solar Energy*, **82**(3), 206–211.

Wiesner MR (2006), 'Responsible development of nanotechnologies for water and wastewater treatment', *Water Science & Technology*, **53**(3), 45–51, http://www.iwaponline.com/wst/05303/wst053030045.htm.

Willems and van den Wildenberg (2004), *NRM Nanoroadmap Project*, work document on Nanomaterials, W&W Espana s.l.

Wood S, Geldart A, Jones RAL (2003), *The Social and Economic Challenges of Nanotechnology*, Economic & Social Research Council, Swindon, UK.

Zhi G and Gao Z (2008), 'Applications of nanotechnology and nanomaterials in construction', in *1st International Conference on Construction In Developing Countries* (ICCIDC–I), 4–5 August, Karachi, Pakistan, pp. 235–240..

Zhu W, Bartos P and Porro A (2004), 'Application of nanotechnology in construction: Summary of a State-of-the-art Report', *Materials and Structures*, **37**(9), 649–658.

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