CHAPTER 25

Sustainable Materials in Building and Architecture

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Abstract
Construction remains one of the most intensive material consumers. The primary factors driving future material growth include increased investment in the residential and commercial sectors, increased spending by governments in infrastructure, improving liquidity in the financial markets, a softening of interest rates and ongoing industrialisation in developing economies. The building material manufacturing and supply sector is in a state of transformation, driven in large part by regulations requiring environmentally friendly or ‘green’ materials. The push for green products has spurred interest in bio-based materials, recycled materials, and the inclusion of waste materials. In addition, green building has raised performance requirements for buildings resulting in analysts forecasting a double-digit growth in green materials every year to 2013. From an environmental perspective, “green” materials would be those materials with the least ‘embodied effects’, where the word *embodied* refers to attribution or allocation in an accounting sense as opposed to true physical embodiment, and includes energy, water, and toxicity. A five-pillared strategy, based on optimising existing environmentally sound technologies and the research and development of new environmentally sound technologies, is proposed namely; optimise conventional technologies, mainstream fringe technologies, accelerate hybrid technology uptake, develop biotechnology applications, and develop nanotechnology applications. It is however highly unlikely that there will be a reduction in or a major shift away from conventional bulk materials in the short to medium term. Some new trends will emerge however, most likely in insulation materials; in a shift away from ceramic products; a shift away from zinc and copper use in piping toward PVC and other plastics; a shift toward biocomposite materials; and an uptake in recycled materials most notably in concrete (aggregate substitution), steel and aluminium. It is critical that the construction industry in general, and construction material manufacturers in particular, identify firstly, the environmental bottlenecks related to current and future material production and consumption and secondly, the technological opportunities to mitigate those environmental problems. The construction industry needs to concentrate on those environmental impacts of materials that are caused during material production (extraction, energy and water use) and end-of-life management (waste management and recycling). In some cases the in-use phase may dominate the overall environmental impacts of product life cycles because of a continuous supply of energy and/or materials during use e.g., buildings (operation, maintenance, repair).

25.1 Introduction

Most buildings up to the early 19th century, with the notable exception of prestigious public buildings, were constructed from easily available local materials. In the 19th century developments in transport modes enabled the movement of heavy and bulky materials and opened up the era of prefabricated elements and product catalogues. At the same time new materials were invented. Notwithstanding this, timber and timber-derived products, masonry units of clay and cement, concrete, steel, aluminium and glass remained and still remain the dominant materials used in construction. Recent developments in the 20th century have included plastics in a number of forms, with the most recent material development including bio-composites for construction.

Construction remains one of the most intensive material consumers: 40 per cent of materials manufactured end up in buildings.[1] Material demand is still dominated by the building sector, especially with respect to cement and fired clay.[2]

25.2 Global Industry Trends

The construction sector works with many other parties including built environment consultants, material manufacturers and suppliers, and specialist suppliers and contractors. The global construction industry grew from US$4.6 trillion ($4.6\times10^{18}$) in 2006 to US$7.5 trillion in 2010.[3] The bulk of construction expenditure is occurring in Asia in general, and China specifically.[4] It is estimated that construction output will grow by 70 per cent to US$12.7 trillion in 2020, and will account for 14.6 per cent of world industrial output.[5]

The total number of construction workers worldwide exceeded 111 million in 2001 with most employed in low- and middle-income countries.[6] In 2001 construction accounted for 7 per cent of total employment with 75 per cent of all construction workers found in developing countries: typically over 90 per cent of workers are employed in micro firms with less than 10 persons.[7]

The industry relies on close relationships with related industries specialising in building materials, including cement, plastics, wood, steel and glass, as well as innovative new construction products and systems offering higher performance characteristics especially with regard to strength, thermal and low-maintenance properties. Growth in the world market for building materials is forecast by one analyst to reach US$706.7 billion ($706.7\times10^{9}$) in 2015 although another analyst forecasts that material value will reach US$752.7 billion by 2013. [8, 9] The primary factors driving future material growth include increased investment in the residential and commercial sectors, increased spending by governments in infrastructure, improving liquidity in the financial markets, a softening of interest rates and ongoing industrialisation in developing economies.[10] The building material manufacturing and supply sector is diverse and makes a significant contribution to the industrial base of countries. The sector includes a diverse range of manufacturers (including cement, steel, aluminium, glass, and clay), suppliers (wholesale and do-it-yourself), as well as providing a large market to goods manufacturers including furniture, paint, plumbing and electrical industries.

The building material manufacturing and supply sector is also in a state of transformation, driven in large part by regulations requiring environmentally friendly or ‘green’ materials. The green building market was worth some $60 billion in 2009 in the

United States alone.[11] The push for green products has spurred interest in bio-based materials including woven floor coverings, bamboo, and cork, and recycled materials including recycled steel, aluminium, bricks, and the inclusion of waste materials such as fly-ash in concrete. In addition, green building has raised the performance requirements for fittings and fixtures such as low-flow taps, energy efficient fittings and fixtures, resulting in analysts forecasting a double-digit growth every year to 2013.[12] Some new emerging technologies, such as dynamic smart windows (that can shift from a clear to a darkened state to provide shading from the sun) and advanced insulation, like aerogels and phase-change materials, are forecast to grow into a US$829 million industry by 2020.[13] The construction sector provides an ideal test bed for scientific innovation in many ways: the risks are lower compared to the automobile or aeronautical industries, and the scale is significantly larger. Innovation need not be limited to new material either; innovation often offers more opportunities in the manner in which conventional materials are used or combined. Designers, contractors and material manufacturers and suppliers have to give consideration to both material usage and building regulations that are likely to emerge in a world dominated by calls for the reduction of carbon emissions. Building regulations are likely to embark on a pathway of increasing building performance requirements, especially with regard to energy and water efficiency, and reduced environmental impact. Net-zero buildings, and smart cities, which both react to resource consumption and occupant comfort, are emerging concepts that will provide a fertile ground for innovation in building materials.

25.3 Background and context to sustainable building and construction

The global pressures exerted on finite natural resources through 'modern'[1] consumption and production patterns and the concomitant depletion of non-renewable resources occupy a central position in the developmental strategies of governments and non-governmental organisations. These strategies flow substantially from the *Habitat Agenda* and *Agenda 21*[2].

Buildings are significant consumers of raw materials.[14] The environmental capital they contain is enormous:

- 50 percent of all resources globally go into construction;
- 45 percent of energy generated is used to heat, light and ventilate buildings and 5 percent to construct them;
- 40 percent of water used globally is for sanitation and other uses in buildings;
- 60 percent of prime agricultural land lost to farming is used for building purposes;
- 70 percent of global timber products end up in building construction;
- 40 percent of CO_2 releases come from building construction and operation;
- 40 percent of total wastes result from building and demolition activities.

Chapter 7 of *Agenda 21* promotes sustainable construction industry activities and seeks to adopt policies and technologies to enable the construction sector to meet human settlement development goals while avoiding harmful side effects on human health and the biosphere. Among the identified activities are strengthening the indigenous building

[1] The term 'modern' is used to refer to the period commencing with the industrial revolution.
[2] The importance of Agenda 21 lies in the confirmation by the General Assembly of the United Nations in 1997 that Agenda 21 remains the fundamental programme of action for achieving sustainable development.

materials industry based on inputs of locally available natural resources and enhancing the utilisation of local materials by expanding the technology platform.

A broader life-cycle approach – where the full impact of the building across its lifetime is understood – is therefore required as a starting point for "sustainable building and construction" (SBC), a term used in *Agenda 21*.[15] The main challenges that emerge to achieve sustainable construction industry activities are:[16]

- Promoting energy efficiency (energy saving measures; extensive retrofit programmes; transport aspects; use of renewable energies);
- Reducing consumption of high-quality drinking water (relying on rainwater/grey water; reducing domestic consumption with water management systems; waterless sanitation systems and use of drought resistant plants);
- Selecting materials based on environmental performance (use of renewable materials; reduction of the use of natural resources; recycling);
- Contributing to a sustainable urban development model (efficient use of land; design for long service life; the longevity of buildings through adaptability and flexibility; converting existing buildings in lieu of building new; refurbishment and technology upgrading; sustainable management of facilities; prevention of urban decay and reduction of sprawl; contributing to employment creation; cultural heritage preservation and social cohesion promotion);
- Contribution to poverty reduction; and
- Healthy and safe working environments.

Sustainable material use is thus predicated on the replacement of future flows of conventional building materials with "green" materials. From an environmental perspective, "green" materials would be those materials with the least 'embodied effects', where the word *embodied* refers to attribution or allocation in an accounting sense as opposed to true physical embodiment. In the building community the tendency is to refer only to 'embodied energy.[17] However, when investigated in a Life Cycle Assessment (LCA) study, all the extractions from and releases to nature are *embodied* effects, and there are also embodied effects associated with the making and moving of energy itself as depicted in Table 25.1.

Table 25.1: Embodied effects typically investigated in an LCA.

Inputs (extractions from nature	Outputs (releases to the environment)
Energy	Acidification
Land	Climate change (global warming)
Materials	Eutrophication
Water	Ecotoxocity
	Human toxicity
	Photo-chemical oxidant formation
	Stratospheric ozone depletion

25.4 Bulk construction material resource reserves

The raw materials that make up the bulk of materials used in construction in most cases are also those resources that are also the most plentiful on the planet. Steel is made from iron ore: iron is the most plentiful element on Earth, forming most of the outer and inner core, and it is also the fourth most common element in the Earth's crust. Notwithstanding this, the vast majority of iron ore is bound in silicate and, more rarely, carbonate minerals. The thermodynamic barriers to separating pure iron from these minerals are formidable and energy intensive: iron ore melts at about 1375 °C. The World Steel Association forecasts that steel use in 2011 will amount to 1359 Mt (1359 million tonnes) and reach a new record of 1441 Mt 2012. While iron ore reserves seem vast, some commentators suggest that reserves will run out in 64 years based on an extremely conservative extrapolation of 2% per annum growth. Cement is made by heating limestone with small quantities of other materials to 1450 °C in kilns. Cement is the basic ingredient in concrete, mortar and grout. Although individual cement companies may face shortages, cement raw materials, especially limestone, are geologically widespread and abundant, and overall shortages are not likely in the future.[18] World production in 2003 was 1860 Mt of which the bulk (880 Mt) comes from China. Clay is a naturally occurring aluminium silicate composed primarily of fine-grained materials. Clay bricks are moulded and fired at temperatures varying between 1000 °C and 1300 °C depending on the type and colour of brick required. World mine production increased from 9.66 Mt in 2009 to 10 Mt in 2010. Resources of all clays are thought to be extremely large. Aluminium is silvery white member of the boron group of chemical elements. It is the most abundant metal in the Earth's crust. Aluminium oxide has a melting point of over 2000 °C while pure cryolite, used to separate aluminium from oxygen in the oxide ores, has a melting point of 1012 °C. World smelter production increased from 37.3 Mt in 2009 to 41.4 Mt in 2010 with the largest contribution coming from China. It is believed that the world reserves for bauxite are sufficient to meet global demand well into the future.[19]

25.5 Threats facing the bulk construction material sector

The Life Cycle Assessment (LCA) concept has emerged as one of the most appropriate tools for assessing product-related environmental impacts and for supporting an effective integration of environmental concerns into economic activity. The LCA procedure investigates the whole product life cycle, from the acquisition of raw materials, through manufacture of the product, transportation and distribution, use and maintenance to disposal of the used product at the end-of-life based on multiple environmental effect categories (Table 25.2).[20] Although the main driver for LCA is sustainable development, the methodology does not as yet incorporate criteria for measuring the social and economic dimensions. The three major environmental areas of protection (AoPs) of interest to society namely, human health, ecological health and natural resources are however considered in a comprehensive manner. The LCA procedure is standardised under the ISO 14040 sub-series *Environmental Management Life Cycle Assessment*.

While resource depletion in the short to medium term would therefore appear not be a threat, a number of related threats do nonetheless exist. There are two categories of embodied effects associated with the building material life cycle, namely, outdoor environmental effects and indoor environmental effects. The outdoor environmental effects are caused by the chemical content of building materials. They can occur during any of the five generic life cycle stages (Table 25.2) and may affect any of the three AoPs. LCA measures the external embodied effects of products on the basis of the effect categories listed in Table 25.1. The indoor environmental effects manifest as human health effects such as asthma or sick building syndrome. The human health effects result from indoor air concentrations of chemical toxins off-gassed from various indoor sources including interior finishing materials.

Table 25.2: Generic life cycle stages of construction products.

1	2	3	4	5
Material extraction and processing	Construction material fabrication	On-site construction	Facility operation and maintenance	End-of-life
Forest products, coal and petroleum, plastic products, natural gas, iron, copper, zinc, aluminium, sand, stone, limestone	Timber products, fibreboard, cellulose products, steel, aluminium, appliances, wire, paint, solvents, plate glass, carpet	Foundation and site earthworks, concrete pouring, structural framing, roofing, mechanical and electrical systems, painting and cleanup	Space and water heating, space cooling, appliances, lighting. Facility improvement and maintenance materials.	Stripping reusable materials, knowck-down, site clearing, disposal.

25.5.1 Embodied Energy

The largest challenge presented to construction materials comes from the energy required to manufacture the materials. The dual crises created by the current energy scenario – energy scarcity and Greenhouse Gas (GHG) emissions – are likely to drive the development of new materials that are less energy dependent. Coal, oil and gas still remain the main sources of energy. At current global production levels proven global coal reserves are estimated to last a further 119 years.[20] In contrast proven global oil and gas reserves are equivalent to 46 and 63 years at current production levels respectively. Over 62% of oil and 64% of gas reserves are located in the Middle East and Russia. Forecasts for peak coal – the point at which the maximum global production is reached – is somewhere between 2010 and 2048.[21] Collective projections generally predict that global peak coal production may occur sometime between 2010 and 2025 at 30% above current production in the worst case scenario.[22] Peak oil, the point at which maximum petroleum is extracted, is projected by some to occur around 2020, while others believe that peak oil has already been reached. Notwithstanding the known supply, the impact of geo-political pressures will significantly influence availability and create supply uncertainties in the future.

25.5.2 Embodied Water

Water is a significant component in the production of construction materials, and electricity. Thus water shortages pose a significant threat to the production of construction materials. Peak water has been put forward as a concept to help understand growing constraints on the availability, quality, and use of fresh water resources. There is a growing view that peak water has already been reached: if present trends continue 1.8 billion people will be living with absolute water scarcity by 2025, and two thirds of the world's population could be subject to water stress.

25.5.3 Embodied toxicity

Many building material production processes contribute to widespread dispersion of toxins in the environment. Ceramic tile production has recently been linked to air pollutants which contribute to human health and ecological health effects.[23] Cement kilns contribute to airborne emissions of sulphur dioxide, nitrous oxide, mercury, dioxins and furans and particulate matter.[24] Poly Vinyl Chloride (PVC) is associated with a uniquely wide and potent range of emissions throughout its life cycle including Volatile Organic Compounds (VOCs), phthalates, heavy metals, halogenated flame retardants (HFRs) and perfluorocarbons (PFC).[25] A study analysed the environmental impact of materials for the six environmental impact types within the 'Human health' damage category for the year 2000 as well as three impact types within the 'Ecosystem quality' damage category.[26] Within the 'Human health' category the impact type 'Carcinogenic', 'Winter smog', and 'Climate change' contribute much more to the human health damage category than the other three impact types namely 'Summer smog', 'Radiation', and 'Ozone layer depletion'. In the carcinogenic category steel, paper and paperboard, and zinc contributed the most; in the winter smog category paper and paperboard, cement, steel, and lime contributed the most; and in the climate change category cement and steel contributed the most. In the 'Ecosystem quality' damage category zinc and steel contributed the most to Ecotoxicity.

With regard to building applications, non-residential and residential buildings ranked second and third respectively in terms of environmental impact. The environmental impact of the application areas reflects the demand for one or more bulk materials. The building sector uses a large amount of steel, cement and fired clay: cement ranks high on the environmental impacts for summer smog and climate change resulting in a significant impact of the building sector on these human health impacts; steel in the building sector causes carcinogenic effects; and roads and infrastructure are largely responsible for climate change effects because of the use of cement and steel. The materials included in the study accounted for roughly a quarter of the total environmental impact caused by human activities in the EU. Materials have a considerable impact on 'Carcinogenics' (24%), 'Climate change' (16%), 'Ecotoxicity' (39%) and 'Fossil fuel depletion' (28%). The largest part of the environmental problems related to materials (in particular carcinogenics, winter smog, climate change and fossil fuel depletion) is due to the production of the main bulk materials steel, cement, plastics and paper and paperboard. These therefore constitute areas where clean technologies are needed most.

25.6 A five-pillared approach to construction materials

Having regard for the challenge posed in Chapter 4(G) of Agenda 21, a five-pillared strategy, based on optimising existing environmentally sound technologies and the research and development of new environmentally sound technologies, is proposed.[27] The five pillars, which are not mutually exclusive, are to:

- Optimise existing technologies;
- Integrate environmentally sound fringe technologies into mainstream technologies;
- Accelerate hybrid technologies into mainstream technologies;
- Develop biotechnology applications for construction; and
- Develop nanotechnology applications for construction.

25.6.1 Optimise existing technologies

Optimising the use of mainstream technologies in the construction sector could assist in improving the sustainability of the sector. Some of the strategies that would help include:
Promoting dimensional co-ordination – The adoption of a set of standard metric-based modular dimensions would dramatically reduce the waste produced by the construction sector.
Off-site production and assembly – Reducing the amount of wet work done on site will greatly reduce wastage.
On-site installation techniques – The greater use of pre-assembled installations will reduce the wastage generated on site, and improve accuracy and the quality of work.
Design technology – More careful consideration of detailing, especially with regard to the sealing of joints in buildings, will reduce the heat gains and losses through leakage. Techniques include the forming of barriers between materials that are exposed to different temperatures and the contact with other more isolated materials.
Recycling – The recycling and reuse of industrial and agricultural waste materials to widen the range of building materials, reduce building product cost, ecological reduction of CO_2 footprint, as alternative new pozzolanic binders, as cement replacement, for glass ceramic manufacture and for composite manufacture continues to advance. Some countries are looking at toxicity challenges associated with the use of wastes like phosphorgypsum, municipal incinerator ashes and some coal combustion ashes. Solutions such as source reduction of toxins, oxidative destruction of persistent organics and reduction of leacheability of toxic elements by pinning them down in glass and glass ceramic matrices have been proffered.

25.6.2 Integrate environmentally sound fringe technologies into mainstream technologies

There are a number of so-called fringe technologies that are used infrequently in the construction sector, but could contribute significantly to sustainable consumption and production patterns in the sector. There would be considerable potential to increase building efficiencies if construction relied less on traditional brick construction. Contemporary drywall construction offers far greater thermal and acoustic properties than traditional brick walling, as well as offering a higher standard of finish. In addition, the construction of masonry walls, particular in multi-storeyed buildings, places the workforce at considerable health and safety risks. Great strides have been made in façade engineering: enclosing systems that are essentially prefabricated and installed on site once the superstructure of the building allows it. These systems also offer greater speed of construction with higher performance standards due to the extensive research and development inputs into jointing and fixing details. Where the use of brick is desirable (e.g. to promote labour-intensive construction for job creation purposes) the design and construction should actively pursue an energy conservation strategy that relies on the bricks' inherent thermal mass to provide a comfortable base temperature from which active heating or cooling can top up the system as required. This will require building considerably thicker walls, with fewer openings.

25.6.2 Accelerate hybrid technologies into mainstream technologies

Hybrid technologies combine two or more technologies into making a building material or building component. A structurally insulated panel (SIP) is a prime example where tow outer skins are bonded to a central insulation core to make up a single building component. Hybrid technologies can also be combined with conventional technologies: constructing the outer skin of a building with a high-performance SIP and building an inner skin of masonry construction creates a highly insulated building but having the benefits of thermal mass internally.

25.6.3 Develop biotechnology applications

Biotechnology applications in construction explore the use of bio-based and biodegradable materials, such as agricultural crops (plant and animal), as the basic raw material for construction products and materials. Current research in this field is examining the use of agricultural crops for insulation, paints, floor and wall coverings, geotextiles, thatch, reinforcement, boards, bio-composites, glues and mortar.[28] Basic science studies on developing, understanding, testing and applying fundamental principles of reinforcement to fibre/matrix engineering to enhance toughening and strengthening effects between matrix and reinforcement particles and/or fibres have been developed. Fundamental studies of polymer-polymer, polymer-fibre and polymer-particle interfaces have produced plausible theories on interfacial fracture mechanics that are based on thermodynamics. Basic science research on composites is looking at issues such as developing computational techniques to determine the extent of stress concentration due to dynamic loading, studying the effect of surface treatment of natural fibres on mechanical properties of natural fibre reinforced composites, modelling and measurement of residual stresses in composites due to differential thermal expansion between fibre and matrix, modelling dynamic stress concentration on particulate or discontinuous fibre reinforced composites and modelling of environmental degradation of composites based on chemical link density (degree of entanglement for polymers) and cohesive force variation to predict durability on the basis of short term exposure tests.[29] Significant strides have been made in these areas and fire resistance and retarding remain the challenges. The effect of fibre content on mechanical and thermal characteristics of hemp fibre reinforced 1-pentene/polypropylene copolymer composites has led to the optimisation of the composites in South Africa.

Fibre reinforced foamed concrete technology, strain-hardened cement-based composite technology, and foamed polyolefin reinforced natural fibre composite technology was also developed in South Africa. Globally, product development research produced a plethora of cement/concrete matrix composites, polymer matrix composites and bio-based composites. Monolithic roofs and structural I-beams have been produced from fibre reinforced resin matrix soya bean based materials. Design guidelines and procedures exist for applying fibre reinforced composites that take into account lack of ductility by allowing higher safety factors than for steel reinforced concrete design and have environmental exposure reduction factors for various fibre reinforced polymer systems. Product development from recycled optic fibre waste, poly(ethylene terephthalate), polyolephinic polymer wastes (including: polypropylene, polyethylene and polystyrene) have been developed. Ongoing composite projects involve reducing the cost of fibre reinforcement and related technological operations, addressing repairability, fire resistance, durability and environmental concerns associated with composites.

Biomimetics – the imitation of nature – studies the way nature addresses problems, such as the adhesive capability of a mussel. Biomimetics aims to replicate the processes of nature: just as a plant bends toward or away from the sun (phototropism), or a leaf opens and closes in response to environmental conditions, so a building will continuously respond to internal and external environmental conditions and patterns of use. Intelligent buildings make use of chemical science, like its organic counterpart, to promote life. Plants make use of carbon dioxide and water, and, through the process of photosynthesis, build up complex substances, releasing oxygen as a by-product. The use of biomimetics may lead to new adhesives that enable buildings to be glued together, instead of relying on the variable adhesive qualities of mortar. This technology requires the collaborative knowledge of biologists, physicists, chemists and engineers working in integrated teams.

25.6.4 Develop nanotechnology applications

The value of nature is only recently being appreciated as environmental capital. The attractiveness of nanotechnology is its ability to package atoms in a controlled way and package any unwanted atoms for recycling or return to their source. Current nanotechnology research focuses on design, modelling, synthesis and characterisation of a range of nanomaterials with specific properties for a range of applications. Nanolayer deposition techniques and technologies for the production of single layer carbon nanotubes are being developed. Other research interests include the purification and functionalisation of carbon nanotubes, the development of polymer nanocomposites for barrier resistance flame retardency and investigating nanostructures and properties of nanocomposites. Characterisation of nanoparticles takes centre stage. Ultra-high performance concrete and rapid strength development concrete repair nanomaterials and high performance biodegradable nanocomposites have been developed. The most widely studied nanomaterial is TiO_2. Basic science studies on the mechanism of its photocatalytic behaviour have been carried out and are now well understood. The optimal incorporation of TiO_2 into building materials such as window panes, paints, cementitious materials and tiles has led to the development of nano-scale sol-gel coating or painting of carrier substrates such as metals, ceramics, glass, polymers, concrete, wood etc to achieve a few micron thick photoactive layers. Investigations have shown that porosity, concrete aggregate size, cement to aggregate ratio, curing age, TiO_2 content and its degradation affect photocatalytic behaviour in cementitious materials. Carbonation of cement will reduce photocatalytic activity of TiO_2 containing concrete as the TiO_2 particles are closed from light. Titania solar cells are said to convert sunlight directly into electricity through a process similar to photosynthesis. Unlike silicon-based solar cells, they are said to perform well even in low light/shade and give consistent performance over a wide temperature range. Substrates do not have to be transparent. Thus titania solar cells can be vertically mounted façade panels, power generating windows of integral components of buildings.

Worldwide, nano silica fume is added to Portland cement based products to enhance strength, abrasion resistance and durability. It is also commonly used for polymer reinforcement and increases hardness, stiffness, weatherability and as fire retardant. Other nano particles of alumina, titania, fullerenes, carbon nanotubes and nano clay also increase stiffness, strength and toughness of epoxy resin polymers by inducing energy absorbing toughening mechanisms such as crack deflection, plastic deformation of the resin matrix, crack pinning, crack blunting and microcracking of the resin matrix. Global emphasis on nanomaterial manufacturing is currently on titania, fullerenes, nanotubes and fibres. Research is required to quantify any health risks that associated with exposure to nanomaterials.

The result of this development in materials science is that new and smart materials are being invented that can swell and flex, repel paint, repair themselves, adapt to the environment and capture and store the energy of the sun. Structures built from new materials have the ability to provide information to their occupants and be more environmentally sustainable. New materials like nanotubes that are one hundred times stronger than steel and one-fifth lighter, are likely to lead to fundamental new applications in energy, materials and transportation, and to significantly improve productivity. Nanotechnology can produce efficient solar cells that are as cheap as newspaper and as tough as asphalt, in fact tough enough to resurface roads so that they become solar energy collectors.[30] Nanotechnology can produce fuels from solar energy, air and water. Consumption of these fuels in nanomechanical systems will return these exact components to the air, along with some additional water vapour. The fuels are made and consumed in a cycle that produces no net pollution. In the process, it obviates the need for fossil fuels, thereby reducing carbon dioxide – and global warming. Molecular manufacturing does not require foaming activities, so the release of chlorofluorocarbons (CFCs) used in foaming plastics is ceased. Waste, including sewage and toxic waste, is made of harmless atoms arranged into noxious molecules: nanotechnology can convert these wastes into harmless forms and reconstitute them into renewable materials. Products can be made extremely durable, thereby obviating the need for disposal, or be made genuinely biodegradable, designed to decompose after use, leaving humus and mineral grit. Nanotechnology can purify the soil in the same manner that living organisms clean the environment: particular organisms or groups of organisms after all manage the ecosystem. At the core of molecular manufacturing or nanotechnology[3] is a kind of technology that many believe will replace the technological system of our current industrial world.[31] Molecular nanotechnology is defined as *"thorough, inexpensive control of the structure of matter based on molecule-by-molecule control of products and by-products"*.[32] Throughout human history, production has relied on relatively crude technology that cuts, grinds, melts, stirs, bakes, sprays and etches to make the materials that societies require to produce the products they use. Nanotechnology, by contrast, constructs materials from the smallest molecular level up.

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[3] Nanotechnology like 'modern industry' describes a huge range of technologies that have the precise arrangement of molecules at their core.

Carbon fibre also holds great promise. Carbon, along with air and water, makes up the polymers of wool and polyester, and of wood and nylon. Composite materials are increasingly used in industry in applications ranging from aircraft fuselages to Formula Grand Prix racing cars to tennis rackets because they are strong, lightweight and easily moulded into an almost endless variety of shapes. Carbon fibre is well suited to structural applications as it is extremely strong in tension – up to five times stronger than steel. It is already being used in bridge design and other civil engineering projects. Applying inexpensive solar energy, carbon dioxide can be removed directly from the air, producing oxygen and glossy graphite pebbles as a by-product. Extracting carbon from the air to reduce its level back to pre-industrial levels will remove over 300 Gt (300×10^9 tonnes) from the atmosphere and yield enough material to construct large houses for 10 billion people and have 95 percent left over.[33] Atmospheric waste is therefore capable of providing an abundant source of structural materials for the foreseeable future.

25.7Trends

It is highly unlikely that there will be a reduction in or a major shift away from conventional bulk materials in the short to medium term. Some new trends will emerge however, most likely in insulation materials (in response to energy efficiency building regulations); in a shift away from ceramic products; a shift away from zinc and copper use in piping toward PVC and other plastics; and an uptake in recycled materials most notably in concrete (aggregate substitution), steel and aluminium.

25.7.1 Trends in conventional bulk construction materials

The partial to total replacement of Portland cement by various cement extenders has been getting the attention of researchers throughout the world. The scope of extenders investigated, developed and used is wide including fly ash, rice husk ash, maize cob ash, nano-structured zonolite, nano clay cement binder (montmorillonite), metakaolin, limestone and/or dolomite fines, stronger macro-defect free glycerol plasticised PVA-calcium aluminate (secar 71) and calcium aluminate phenol resin cements. Innovative cement development for total replacement of Portland cement using geopolymers is increasing. New carbon negative magnesium-based cement that absorbs 0.6 tonnes of CO_2 per tonne of cement on hardening has been discovered. Researchers have also been looking at the basic science of pozzolanic materials for better understanding of the underlying principles. Various cement standards have been reviewed, taking account of numerous blending possibilities that are coming up. Concrete research in the world has incorporated both basic and applied science aspects. A wider range of concretes have been developed, performance evaluated and applied globally. The world's tallest building (828 m high) that is in Dubai has used high performance concrete of > 100 MPa mean strength. De-polluting, self-cleaning and photocatalytic features have also been incorporated into concrete. South Africa leads in textile concrete research and has come up with novel geotextiles for mine tunnel wall and road stabilisation. The country also leads the world in the application of continuously reinforced thin concrete road pavement emplacement and testing and in the production and use of zero-waste low cost modular concrete block building systems.

The use of advanced characterisation techniques such as mercury intrusion porosimetry, oxygen permeability, gas adsorption and electron microscopy techniques for characterisation of materials has enabled the rapid development of building materials. The use of composite panels rather than bricks in construction is increasing. The recycling and reuse of recycled materials for bricks and concrete blocks is also growing. There have also been advances in the use of alternative concrete block production processes such as autoclaving for rapid strength development.

Research on the use of adobe or earth has been wider and has even included basic science, characterisation and selection of clays for un-stabilised and stabilised earth building products. Researchers have looked at the manufacture of pozzolana for extension of Portland cement from clays using flash calcination of kaolinitic clays and unfired natural fibre reinforcement of mud bricks and their characterisation. Rammed earth construction has been extensively and successfully used for 2 to 3 storey buildings although the technology had not made headway elsewhere in spite of some of its environmental benefits.

There has been some work done on evaluation of timber frame built structures, mechanical characterisation of timber and development of formaldehyde-free polyurethane glues for laminated timber production. Transgenic trees with decreased or altered lignin content are being genetically engineered to reduce consumption of energy and chemicals for delignification and refining of wood chips. Substitution of chemical preservatives and conventional chemical glues has been achieved through the application of fungal cultures and isolated enzymes as preservatives and adhesion promoters that require less energy to produce than chemicals. Innovative water glass bonded wool wooden fibre composites and bio-glue adhesive-free board materials have also been developed. Owing to proper preservation, durability of modern wooden structures now exceeds 25 years and matches that of steel and concrete. Modular, panel and timber frame structures are now industrially manufactured - significantly lowering production cost and delivery lead time.

Higher productivity of ceramic tiles and sanitary ware has been achieved by technological advances in processing that introduced fast firing, battery pressure casting and robotic glazing systems. Large 800 x 800 mm ceramic floor tiles are now available on the market thanks to research and development. Photoactive self-cleaning and de-polluting ceramic tiles and façade systems are also available.

Glass research came up with strong, durable and insulating structural glass-mica composites, insulating foam glasses and glass ceramics from the recycling of glass cullet, vitrification and devitrification of fly ash and slag waste. The toughening of glass was achieved by molten salt diffusion, lamination with stiffer and stronger interlayer materials being developed. Glass has remained the major substrate for silicon solar panels. Glass fibre research has led to the development of zirconia coated fibres that can reinforce concrete matrices without reacting with the basic cement. Stable, durable glasses and glass fibres that do not devitrify have been developed.

The development of manufactured high specific strength light-weight steel framed buildings and, with a variety of greener cladding and infill materials is catching on. Steel encased polymer concrete, steel fibre reinforced concrete, steel fibre reinforced fly ash concrete, steel fibre reinforced metakaolin blended concrete and high strength steel fibre reinforced concrete were developed and characterised. Research on the recrystallisation behaviour of low carbon hot rolled steel strip has led to the production of stiffer steel strip from cold working of hot rolled strip that originally contains low sulphur levels. Lower

Young modulus steel strip was also developed from higher sulphur content hot rolled steel strip. Corrosion resistant nitrogen alloyed stainless steels that offer the best combination of strength and toughness of any material known to date have also been developed in South Africa. Techniques to negate nitrogen losses during welding of stainless steel to retain strength and toughness and stabilise the welding arc and reduce spatter have been developed. Basic science evaluations of the effect of concrete strength and reinforcement on toughness of reinforced concrete beams, effect of aspect ratio and volume fraction of steel fibres on mechanical properties of steel fibre reinforced concrete, strength reliability of steel-polypropylene hybrid fibre reinforced concrete, structural performance evaluation of steel fibre reinforced concrete, fatigue of steel cable stayed highway bridges and fatigue and fracture performance of cold drawn wires for pre-stressed concrete have been carried out. New non-ferrous metal products are being developed. These include a superplastic Al-Mg-Cu alloy with 700% and 25% elongation at 550^{o}C and 20^{o}C, AlMn alloy sheeting for a helium-cooled thorium high temperature reactor cooling tower and light-weight high specific strength hybrid carbon fibre reinforced plastic (CFRP)-Aluminium laminates. Short and long-term corrosion rate tests on zinc, copper, aluminium, mild steel, stainless steel and corten have been carried out at various exposure locations. The information obtained is used for long-term planning in terms of material selection, cost of corrosion, corrosion protection, durability, design, maintenance and life cycle cost analysis. Aluminium alloys now face serious competition as construction materials from a range of polymeric composites and glass reinforced plastic materials that have property advantages. Internationally there is more extensive use of recycled rather than virgin aluminium and copper products.

There has been increased and wider use of industrial minerals and rocks such as granite, basalt, basalt tuffs, limestone, dolomite, slate, dolerite, expanded perlite, pumice, exfoliated vermiculite, diatomite, bloating clays, dunite, forsterite, norite etc globally for aggregates, as dimension stone, and for the production of construction materials.

Refractories research work appears to take place largely in the private sector. Globally, the use of unshaped monolithic refractories has increased and the high alumina cement content of the castables has been dramatically reduced – to zero in some cases. The trend has also been towards the use of purer higher refractoriness materials and unfired refractories that are cured and sintered in situ.

25.7.2 Trends in bio-based construction materials

There is however great potential for crops and by-products of animal husbandry to help to reduce the environmental impact of construction. In addition to environmental benefits in production, many of the products that can be produced using renewable resources offer environmental benefits in use. The use of agricultural crops would furthermore replace a part of this material and energy consumption with lower energy and renewably sourced alternatives. In addition, wastes from agricultural crops lend themselves to safe and easy disposal with little or no environmental damage and possibly some benefits. Renewable plant materials can contribute to cutting greenhouse gases in many further ways where they substitute for fossil-based materials. The demand for industrial non-food agricultural crops (plant) and their products in Europe is generally at a very early stage. Plants can synthesise an immense range of compounds. As ‘cell factories’ they contain structures that can be used by the physical, chemical and biochemical sciences to produce useful materials such as fibres, starch, oils, solvents, dyes, resins, proteins, speciality chemicals and pharmaceuticals. Physical and chemical sciences can combine to produce new applications including fully bio-based composites such as boards in which the fibre component is made from hemp, flax or timber and the resin binder from rapeseed oil rather than the more commonly used synthetic chemical resins. Some renewable products have distinct functional advantages such as biodegradability and absence of toxicity.

The automotive industry has historically experimented with natural fibre composites – or bio-composites. It used them in 1941 to manufacture a prototype car[4] with bodywork manufactured from flax, hemp and other organic materials. Contemporary automobile manufacturers are using jute-based materials for door panels and hemp for dashboards[5]. Current interest is primarily focused on the use of bast fibres, namely hemp and flax, and certain sub-tropical fibres such as jute and kenaf. What is of particular importance with regard to applications within the automotive industry is the ability to mould complicated 3-dimensional shapes: this has a specific importance for future products in the construction industry. The United Kingdom participates in the work of IENICA through the National Non-Food Crops Centre (NNFCC).[34] The NNFCC has identified significant potential markets for renewable raw materials in four main areas:

- Chemicals – polymers and plastics, dyes, paints and pigments
- Speciality chemicals – adhesives, agrochemicals, personal specialised organics
- Industrial fibres – paper and board, composites, textile fibres
- Industrial oils – two-cycle oils, transmission fluids, lubricants

The application of agricultural crops (animal) in the manufacture of products is not as advanced as that of crops. The use of animal crops, particularly wastes, although featuring extensively in vernacular construction, has limited application in contemporary urban construction. There are a number of reasons for this:

- **Collection** – The dispersion of animal residues makes the collection difficult, certainly in terms of the volume required.
- **Health risks –** Collecting certain animal crops, such as skins and hair, poses distinct associated health risks as the raw material must generally be sourced from abattoirs.
- **Marketability** – Animal sources suffer a distinct marketing disadvantage in terms of social acceptance.

Notwithstanding these difficulties, the use of animal fibres (hair) does offer huge potential and this has therefore been included under the general fibre section.

The application of agricultural crops in construction is related to the type of crop, although it would appear that fibre is the most suitable in the short term. For the purpose of this report, crops cover all materials deliberately planted/reared on farms.

25.7.2.1 Fibre Crops

Plant fibres have a wide range of uses and are becoming an important component in the search for sustainable production and consumption patterns. There are a number of different fibres found in plants, including bast fibres, leaf fibres, seed fibres, fruit fibres and wood fibres. Fibre crops are generally divided into two categories: long fibre crops

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[4] Henry Ford, 1941

[5] Daimler Chrysler, Mercedes Benz E-and C class models

and short fibre crops. Long fibre crops include flax and hemp. Flax has been used traditionally to produce high value long fibre material for the textile industry. Development work is ongoing in this field and offers a significant body of knowledge for applications in the construction sector. Hemp has a wide range of potential uses and has established market niches using fibre, pith, seeds and seed oils.[36] Unfortunately, the presence of the psychotropic agent THC (delta 9-tetra hydrocannabinol) in fibre hemp creates a significant policing problem generally. Work is in progress in the UK to minimise the THC content and to develop visual and other simple field diagnosis tests for these types. Short fibre crops include cereal straws, miscanthus grass, canary grass and short rotation coppice. Cereal straws are by-products of the cereal industry and have been used for some time by the board and paper industries as sources of fibre. Miscanthus is a highly productive C4 grass species. Its primary market is as a biofuel, although there are a number of alternative markets for its short fibre components. Some difficulties are being experienced in overseas markets with its nomenclature and taxonomy that are undermining its applicability for future development work, which will need to be further explored for relevance within the South African context. Reed canary grass has been developed in Scandinavia as a source of short fibre for paper pulp. It is a lower productive alternative to Miscanthus and is ideally suited to low temperatures and poor soil conditions. Short rotation coppice is willow and poplar coppiced in a 3-yearly cycle. Although it too is used as a biofuel, it does offer a limited range of alternative uses.

25.7.2.2 Carbohydrates

Although all plants contain carbohydrate in one form or another, of primary interest are those in which it is stored for later extraction. The crops that are starch-producing include maize, wheat, potatoes, barley, oats, peas and, in the longer term, quinola. With regard to the physical, chemical and genetic modification of starch, wheat offers one of the biggest potential sources of renewable raw materials for industry, with products ranging from biodegradable plastics to adhesives. The paper and board industries are among the largest consumers of starch and derivatives in the non-food sector. Most of the starch is used to reinforce surface fibres and provide a smooth finish. Starch is also used in three major types of plastic: loaded products – where the starch represents a very small portion of material (10%); polymer mixtures; and thermoplastic starches (produced by extrusion).[37] One building application where starch is already used is in the manufacture of paint. It is argued that starch-based paints are as economic as synthetic coatings and could have novel properties. Starch-based paints are as strong, shiny and as liquid as synthetic paints and although they are biodegradable, do not rot after application.

25.7.2.3 Proteins

Plant proteins are an important source of raw material for both food and non-food uses, although it is mainly the structural or storage proteins such as collagen, keratin and seed proteins that are of interest for product applications. In agriculture they are sourced from seeds (soybean and pea proteins, wheat gluten) and tubers (potatoes). In addition, protein end products take the form of fibres, films or adhesives. The production of protein-based plant products for non-food products may be based upon fractionation of existing crops (wheat, barley), by current or newly developed processes (peas, soybean), or by extracting protein from existing low value by-products (rapeseed meal). Soybean and wheat protein currently offer the most important resource for protein production, with pea proteins and cottonseed proteins emerging as viable additions. Proteins are used in the manufacture of paper coatings, plywood adhesives, floor coatings, textiles and plastics.

25.7.2.4 Oils

Oils crops are principally grown for food uses although a significant proportion is used in non-food applications in the EU. Oilseed rape and soya bean cultivation dominate oil crop cultivation within the EU, although little of the soya bean production is used in non-food products. Despite considerable research activity having taken place in many European countries, significant further investigation will be required to refine and quantify specific commercial opportunities and to develop field productive types. Oil crops around the world include castor, coconut, cottonseed, groundnut, linseed, olive, palm, rape, safflower, sesame, soya and sunflower. Two species, Carmbe and Pot Marigold, are already showing commercial promise. Oilseed rape has been successfully used in the Reichstag building in Berlin as a biofuel to generate electricity. The processing potential for ricinoleic acid derived from castor in construction products includes coatings, flashing agent for pigment, polyurethane, nylon (11-nylon and 6.10-nylon), alkyd resin, polyester resin, plasticizer, hardener for epoxy resin, rust inhibitor, caulking material, adhesive, paint additive, potting and encapsulating material for electrical insulation, structural adhesive, flooring, elastomer sealant, waterproofing material, stabiliser for PVC, durable rapid dry coating and insulating varnish.[38]

Vegetable oils are currently already in use for the manufacture of:

- Gloss (oil-based) paints
- Oil modified alkyl resins which form reticulated films with variable drying times and are used extensively in paints and varnishes
- Oleoresinous varnishes

The majority of oil modified resins are based on soya oil, though sunflower is a potential direct replacement. Linseed, tung and soya oils are most commonly used in paints as they contain high levels of polyunsaturated fatty acids that aid drying. Calendula oil offers an alternative for tung oil. Linoleum – a well-known building product – is made from linseed oil, resins, wood, cork powder, calcium, vegetable pigments and hessian (jute). This material is regaining popularity as an environmentally friendly product and works well in high-tech contexts requiring a static-free environment. The solvent market is a significant market and stands to benefit from the environmental advantages offered through the use of oil crops (most solvents are very environmentally unfriendly and subject to increasingly stringent environmental regulation). Oilseed-based solvents, by contrast, are fully biodegradable, non-toxic, odourless and do not contain VOCs or PACs (Polycyclic Aromatic Carbons). Solvents are used extensively in the construction sector in products such as paints, varnishes, metal treatments, wood treatments and for treating textiles.

25.7.2.5 Other Crops

Other crops that offer potential use in the manufacture of construction products are natural latex, cork, bamboo, lavender, clary sage and thatch. Many of these crops have been used traditionally in vernacular architecture, and many are regaining popularity due to their environment-friendly characteristics, both in manufacture and in use.

25.7.3 Agricultural Crop Products

From the above it is clear that there are a number of construction products that can be made from an alternative resource such as agricultural crops. For the purposes of this study, a construction product is any component that is used in the creation of an immovable asset, both buildings and construction works.

The product areas with the greatest current impacts (in terms of quantities of agricultural material used) are:[39]

- Insulation
- Paints
- Floor coverings/internal finishes
- Geotextiles/soil stabilisation
- Thatch

The product areas that have limited current impact but offer significant future potential are:

- Boards
- Reinforcement in blocks
- Adhesives
- Sealing materials
- Reinforcement in polymer composites
- Dyes
- Structural members

Product areas that are beginning to emerge following recent research and which hold significant promise for the future, are:

- Plastics from bio-resins, and
- Polymer composites from bio-resins.

The use of crop-based materials for the applications mentioned above depend upon a number of factors, including the potential performance of the materials, their sustainable consumerism, the 'green' movement and global climate change. Environmental and consumer considerations, as well as cost drivers of crop-derived products as sources of sustainable raw materials, will continue to drive utilisation of such materials in the future.

25.8 Conclusion

It is critical that the construction industry in general, and construction material manufacturers in particular, identify firstly, the environmental bottlenecks related to current and future material production and consumption and secondly, the technological opportunities to mitigate those environmental problems. The construction industry needs to concentrate on those environmental impacts of materials that are caused during material production (extraction, energy and water use) and end-of-life management (waste management and recycling). In some cases the in-use phase may dominate the overall environmental impacts of product life cycles because of a continuous supply of energy and/or materials during use e.g., buildings (operation, maintenance, repair).

The unsustainable contemporary patterns of consumption and production are an outcome of a technology arising from the Industrial Revolution. It is therefore unlikely that the continuing use of this technology will do any more than perpetuate those patterns. However, reconciling cutting-edge technology with innovative consumption and production patterns offers a platform for achieving real progress towards the achievement of sustainable construction. Efforts to fix our current industrial system will be undermined by its inherent dependence on resource extraction. Almost everything we make requires something to be extracted and consumed from the thin layer of the Earth that supports life, and the wastes to be disposed back into this layer, often to remain in their waste state for hundreds of years. Pollution is the consequence of the application of low-level technology.

Sustainable building and construction activities will not be achieved automatically or through writing best practice based on current thinking. At best, this is a short-term palliative, albeit a necessary one. However, understanding and maximising the benefits of these new materials will require a significant commitment to research and the integration of multi-disciplinary skills. This technology relies upon the collaborative knowledge of physicists, chemists, biologists, multi-disciplinary engineers and computer programmers. Since technologies such as molecular manufacturing fall between traditional disciplines like molecular scientists and mechanical engineers, new disciplines will need to emerge to fill the gap. Up until now, the articulated alternatives have been dismissed as expensive, untested and obstructive. Cutting-edge technologies offer a clean, efficient and sustainable alternative that will yield better quality, lower cost, greater safety and restored environments, and will be economically sustainable.

References

1. B. Edwards, *Rough Guide to Sustainability*, RIBA Publications, London, 2002, pp. 5-6.
2. D. Phylipsen, M. Kerssemeeckers, K. Blok, M. Patel, and J. de Beer, *Assessing the Environmental Potential of Clean Material Technologies*, Report EUR 20515 EN, Joint Research Centre, European Communities, 2002, p. 12.
3. Global Construction Perspectives and Oxford Economics, *Global Construction 2020*, Global Construction Perspectives and Oxford Economics, London, 2010, p. 6.
4. Ibid, p. 8.
5. Ibid, p. 6.
6. ILO, *The Construction Industry in the Twenty-First Century: Its Image, Employment Prospects, and Skills Requirements,* International Labour Organisation, Geneva, 2001, p. 6.
7. Ibid, p.23.
8. GIA, “World building materials market to reach US706.7 billion by 2015”, *Report by Global Industry Analysts*, online http://www.StrategyR.com/ 2011, retrieved 28 October 2011.
9. Datamonitor, Construction Materials: Global Industry Guide, online http://www.datamonitor.com 2009, retrieved 28 October 2011.
10. GIA, “World building materials market to reach US706.7 billion by 2015”, *Report by Global Industry Analysts*, online http://www.StrategyR.com/ 2011, retrieved 28 October 2011.
11. QFinance, *Construction building and materials industry*, online http://www.qfinance.com/sector-profiles/construction-and-building-materials 2011, retrieved 28 October 2011.
12. Ibid.

13. Climate Control, “Advanced materials to lead global construction market”, *Climate Control*, online http://www.climatecontrolme.com/en/2011/08/ 2011, retrieved 28 October 2011.
14. B. Edwards, *Rough Guide to Sustainability*, RIBA Publications, London, 2002, p. 10.
15. UN, *Agenda 21*, UN Department of Economic and Social Affairs: Division for Sustainable Development, online http://www.un.org/esa/dsd/agenda21/ 1992, retrieved 28 October 2011, Chapter 7(G), p. 70.
16. Ibid, p. 70.
17. W. Trusty and S. Horst, *LCA tools around the world*, Building Design and Construction, online http://www.athenasmi.org/ retrieved 1 December 2011.
18. USGS, “Mineral Commodity Survey 2004”, *U.S. Geological Survey*, online http://minerals.usgs.gov/minerals/pubs/msc/ 2004, retrieved 28 October 2011.
19. USGS, “Mineral Commodity Survey 2011”, *U.S. Geological Survey*, online http://minerals.usgs.gov/minerals/pubs/msc/ retrieved 28 October 2011.
20. G. Keoleian, S. Blanchard, and P. Repper, Life-cycle energy, costs, and strategies for improving a single family house, *Applications and Implementation*, 2001, **4,** 135.
21. www.worldcoal.org/resources/coal-statistics/ Retrieved 26 May 2011.
22. The University of Newcastle, Australia, *Research forecasts world coal production could peak as soon as 2010*, October 28, 2009 online http://www.newcastle.edu.au/news/2009/10/28/ research-forecasts-world-coal-production-could-peak-as-soon-as-2010.html 2009, retrieved 28 October 2011.
23. N. Tikul and P. Srichandr, Assessing the environmental impact of ceramic tile production in Thailand, *Journal of the Ceramic Society of Japan*, 2010, Vol. 118, Issue 1382, p. 887.
24. groundWork, Analysis and write-up of burning alternative fuels in cement kilns, http://www.groundwork.org.za/Cement/cement%kilns%20-%20grou 2006, retrieved 1 December 2011.
25. HBN, Screening the toxics out of building materials, online http://www.healthybuilding.net/ retrieved 1December 2011.
26. D. Phylipsen, M. Kerssemeeckers, K. Blok, M. Patel, and J. de Beer, *Assessing the Environmental Potential of Clean Material Technologies*, Report EUR 20515 EN, Joint Research Centre, European Communities, 2002, pp. 16-19.
27. L. van Wyk, *Changing consumption and production patterns in the construction industry*, CSIR Technical Report, CSIR/BE/CON/IR/2006/0026/B, Pretoria, 2006, p. 17.
28. L. Van Wyk, *The use of agricultural crops, industrial waste and recycled materials in construction*, CSIR Technical Report, CSIR/PDP TH/2004/020, Pretoria, 2005, pp. 10-16.
29. J. Mapiravana, *Building Materials Research and Development Priorities*, CSIR Technical Report, CSIR/BE/CON/IR/2007/006/B, Pretoria, 2009, p 106-111
30. E. Drexler, and C. Petersen with G. Pergamint, *Unbounding the Future: the Nanotechnology Revolution*. William Morrow and Company, Inc., New York, 1991, p. 2.
31. Ibid, p. 7.
32. Ibid, p. 2.

33. Ibid, p. 2.
34. L. van Wyk, *The use of agricultural crops, industrial waste and recycled materials in construction*, CSIR Technical Report, CSIR/PDP TH/2004/020, Pretoria, 2005, p. 11.
35. E. Drexler, and C. Petersen with G. Pergamint, *Unbounding the Future: the Nanotechnology Revolution*. William Morrow and Company, Inc., New York, 1991, p. 134.
36. IENICA, *Summary Report for European Union – Fibre Crops*, Interactive European Network for Industrial Crops and their Applications, 2000, p. 29.
37. IENICA, *Summary Report for European Union* – Carbohydrate Crops, Interactive European Network for Industrial Crops and their Applications, 2000, p. 52.
38. IENICA, *Summary Report for European Union - Oil Crops*, Interactive European Network for Industrial Crops and their Applications, EU, 2000, p. 9.
39. L. van Wyk, *The use of agricultural crops, industrial waste and recycled materials in construction*, CSIR Technical Report, CSIR/PDP TH/2004/020, Pretoria, 2005, p. 16.