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Review Article

Trends and developments in green cement and concrete technology

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Abstract

The cement industry faces a number of challenges that include depleting fossil fuel reserves, scarcity of raw materials, perpetually increasing demand for cements and concretes, growing environmental concerns linked to climate change and an ailing world economy. Every tonne of Ordinary Portland Cement (OPC) that is produced releases on average a similar amount of CO₂ into the atmosphere, or in total roughly 6% of all man-made carbon emissions. Improved production methods and formulations that reduce or eliminate CO₂ emissions from the cement manufacturing process are thus high on the agenda. Emission reduction is also needed to counter the impacts on product cost of new regulations, green taxes and escalating fuel prices. In this regard, locally available minerals, recycled materials and (industry, agriculture and domestic) waste may be suitable for blending with OPC as substitute, or in some cases replacement, binders. Fly ash, Blast furnace slag and silica fumes are three well known examples of cement replacement materials that are in use today that, like OPC, have been documented and validated both in laboratory tests and in practice. The first is a by-product of coal combustion, the second of iron smelting and the third of electric arc furnace production of elemental silicon or ferro silicon alloys. This paper presents a concise review of the current state-of-the-art and standards underpinning the production and use of OPC-based cements and concretes. It outlines some of the emerging green alternatives and the benefits they offer. Many of these alternatives rely on technological advances that include energy-efficient, low carbon production methods, novel cement formulations, geopolymers, carbon negative cements and novel concrete products. Finally, the economics of cement production and the trends in the UK, US and the Gulf Cooperation Council (GCC) Region are presented, to help guide and inform future developments in cement production based on maximizing the value of carbon reduction.

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Keywords: Cement Standards; Energy; Economics; Carbon

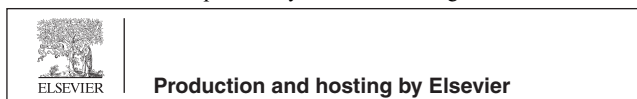
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1. Introduction

Concrete is a basic building material that will continue to be in demand far into the future. A world without concrete, and its dominant precursor, Ordinary Portland Cement (OPC), is hard to imagine. Although there are different types of concrete that have been developed for use in different applications, their common virtues are familiarity, versatility, strength, durability, wide availability, fire resistance, resistance to the elements and comparatively low cost.

OPC is a vital construction material and also a strategic commodity (Vlasopoulos, 2010). Such is our dependence on OPC that the world currently produces nearly 3.6 billion metric tonnes of the material each year (USGS Mineral Commodities Summary, 2012), with volume predicted to rise to more than 5 billion metric tonnes by 2030 (Müller and Harnisch, 2008; OECD/IEA and World Business Council for Sustainable Development, 2009). Although figures vary from country to country, around half of the world’s OPC is used to make around 11 billion metric tonnes of concrete annually; the rest is used in mortars, screeds, stucco, coatings, soil stabilization and other applications. (New Zealand Cement Holdings, 1988; Smith et al.,

2002). Today, the OPC market is dominated by China, which is attributed to 57.3% of global consumption (CEMBUREAU, 2012).

The cement industry, like the rest of the construction industry, is facing unprecedented challenges relating to energy resources, CO₂ emissions and the use of alternative materials. Worldwide, the cost of energy is rising inexorably as fuel sources deplete. This has clear, traceable impacts on the cost of producing cement and its market price; Green taxes are an additional cost that is incurred if emissions are not restricted, potentially leading to a doubling in the price of cement by 2030 (OECD/IEA and World Business Council for Sustainable Development, 2009).

Despite the incremental improvements in process efficiency that have been adopted by the cement industry in recent years, OPC production is still responsible for around 6% of all man-made global carbon emissions. The *Cement Sustainability Initiative*, developed by the World Business Council for Sustainable Development, brings together the major cement producers from across the world to try and tackle this problem (OECD/IEA and World Business Council for Sustainable Development, 2009). An important

part of the initiative is a database showing CO₂ emissions and energy performance figures for many of the significant players in the global cement industry, to promote the sharing of ideas aimed at improving these values.

The push to reduce global CO₂ emissions is backed by governments and corporations who understand that the present rate of release of this greenhouse gas into the atmosphere is a serious threat to future life and prosperity on the planet. Various authorities have introduced legislation and incentives (tax rises such as CO₂ taxes, quarrying and extraction tax, etc.) in order to regulate and reduce the activities of the industrial sectors most responsible for greenhouse gas emissions. However, the rate of increase in emissions continues almost unabated as a result of population growth and increased industrialization and economic activity in developing countries, notably in Latin America, Africa, the Middle East, India and developing countries in Asia where a three to fourfold increase in demand is projected by 2050 (OECD/IEA and World Business Council for Sustainable Development, 2009).

If the cement and concrete industries are to become sustainable and effectively contribute to emission reduction then, in addition to improvements in process efficiency and reliance on OPC blends incorporating waste materials, moving to less carbon intensive fuels, developing clinker substitutions employing other low carbon materials with cementitious properties and new low carbon and carbon-reducing cement formulations and production processes are needed.

Carbon-reducing cements, if they could be developed for commercial-scale application, probably offer the safest, most economical and elegant Carbon Capture and Storage (CCS) technology. Other approaches to CCS that require piping CO₂ emissions from cement production (and other polluting sources such as power generation), are viewed by some as the best way forward. However, widespread concerns relating to long-term reliability and high capital cost suggest that ideas such as pressurized, pumped storage of liquefied CO₂ in geological formations may be neither technically nor commercially viable. They cannot be relied on to provide a permanent solution as the risk of containment failure is simply too great.

In order to appeal to major cement manufacturing companies, an alternative cement product has to be able to generate at least the same economic value as that from an OPC production plant. At 7.6% of world cement production, the cement industry in Europe represents around 56,000 direct jobs. The average cement plant will produce around 1 million tonnes of cement per annum and cost around €150 million. Advances in automation mean that a modern plant is usually manned by less than 150 people (CEMBUREAU, 2012). Each tonne of OPC produced requires 60–130 kg of fuel oil or equivalent, depending on the cement variety and the process used, and about 110 KWh of electricity. This accounts for around 40% of the average 0.9 tonnes of CO₂ emissions per tonne of cement produced, with the

rest attributed to the calcination process, other manufacturing processes and transportation.

Concretes, on the other hand, refer to mixtures comprising coarse aggregates (such as crushed rock, ranging in size from 5 to 20 mm), fine aggregates (such as sand, ranging in diameter from 63 microns to 5 mm) and a cement binder. When mixed with appropriate quantities of water and (where required) performance-enhancing admixtures, this produces an initial fluid phase that can be shaped or cast and sets to produce a solid phase comprising a very strong, rigid concrete element or structure. Conventional Portland-clinker-based hydraulic cements (products of the calcination process) use source-materials that are cheap and abundant almost everywhere. Finding suitable alternative cements would require an investigation into their cost and profitability as well as their structural characteristics.

As alternative low-carbon cements and concretes enter the equation, three conditions will determine their success or otherwise; firstly that they are useable and perform well both short term and long term, secondly that there is sufficient information validating the capabilities of the product so that they meet engineering standards for specific functions, ranging from the making of cavity blocks to ready-mix for in situ casting of foundations, and thirdly, that there is sufficient raw material that can be transported in bulk to processing plants.

Although the ingredients for making cement are readily available in most countries, there may be opportunities to use locally sourced specific raw materials such as industrial waste, recyclable material or even earth. These materials must of course have controlled characteristics and properties that are suitable for purpose, whether it is for blending ground granulated blast furnace slag for strength enhancement or soil for producing compacted earth blocks; from the point of view of the engineer or architect, such materials are generally selected on the basis of the added functionality that they offer and their cost-effectiveness.

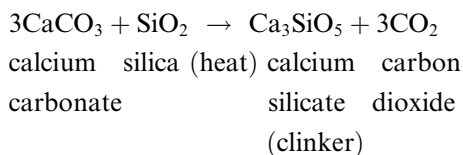
The present paper examines the production of OPC (the benchmark cement against which all cements are measured) and applicable standards. It will summarize the waste substitutes that are currently being used to reduce the carbon footprint of a range of Portland-based cements. Co-incineration of waste-derived fuels (municipal waste, sewage sludge, animal meal, waste by-products, etc.), to reduce emissions and effectively dispose of these wastes, will also be briefly discussed. Some traditional replacement cements will be briefly discussed, and the emerging, next generation of green alternative cements such as Calcium Sulfoaluminate (C\$A) cement, successfully developed and used in China since the 1970s, will be introduced.

The paper will conclude with a look at current and projected future demand for cement, highlighting the main players. A preliminary analysis of the economics of low carbon cements will be carried out and a valuation method for the carbon reduction benefits they offer is proposed.

2. Portland-based cements and other hydraulic binders

Ordinary Portland Cement (OPC) is the dominant contemporary cement. It is a mixture of compounds produced by burning limestone and clay together, in a rotary kiln, at a temperature of around 1,450 °C. Approximately 40% of cement plant CO₂ emissions are from the burning of fossil fuel to operate the kiln, 50% due to the manufacturing process and the remaining 10% are accounted for by indirect CO₂ emissions relating to transportation of the finished product and front-end production processes (World Business Council for Sustainable Development, 2012; Hendriks et al., 1999).

Cement has been used for millennia; the earliest known use of hydraulic binder was by the Macedonians of ancient Greece, and by the ancient Egyptians and Romans. The first forms of clinker-based hydraulic cements contained basic calcium compounds, for which the major raw materials are limestone (calcium carbonate) and clay (silicon oxide compounds). Calcination (from the Latin word *calcinare*) is the decomposition of calcium carbonate (limestone) to calcium oxide (lime) in order to produce basic cement. The product of calcination is usually referred to, in general, as “calcine,” regardless of the minerals undergoing thermal treatment. In the cement business it is called clinker. The calcination process for a typical modern cement clinker, where calcium carbonate and silicon oxides are combined at elevated temperature (~1,450 °C), is:



This produces a powder that will react with water and change from a paste or liquid solution into a solid mass. The finer the cement clinker is ground, the faster the reaction will be due to the increased surface area of the cement powder in contact with water.

Table 1
The primary constituents of a modern Portland cement finished clinker.

Tricalcium silicate	50%	Ca ₃ SiO ₅ or 3CaO·SiO ₂
Dicalcium silicate	25%	Ca ₂ SiO ₄ or 2CaO·SiO ₂
Tricalcium aluminate	10%	Ca ₃ Al ₂ O ₆ or 3CaO·Al ₂ O ₃
Tetracalcium aluminoferrite	10%	Ca ₄ Al ₂ Fe ₂ O ₁₀ or 4CaO·Al ₂ O ₃ ·Fe ₂ O ₃
Gypsum	5%	CaSO ₄ ·2H ₂ O

Table 2
Classification of cement types according to BS EN 197-1:2011.

CEM I Portland cement	Portland cement and up to 5% of minor additional constituents (the original OPC)
CEM II Portland composite cement	Portland cement with up to 35% of other Supplementary Cementitious Material (SCM) such ground limestone, fly ash or Ground Granulated Blast furnace Slag (GGBS)
CEM III blast furnace cement	Portland cement with a higher percentage of blast furnace slag, usually around 60% to 75%
CEM IV pozzolanic cement	Portland cement with up to 55% of selected pozzolanic constituents
CEM V composite cement	Portland cement blended with GGBS or fly ash and pozzolanic material

Portland cements are the most common Calcium–Silicate–Hydrate (C–S–H) hydraulic cements in use today. The first Portland cement was originated by the English bricklayer Joseph Aspin in Leeds in the 1800’s, after he had experimented with earlier types of cement such as Roman and other Natural cements. The composition of a typical Portland cement is ~65% calcium oxide; the rest is generally a mixture of aluminum, iron and silica.

Table 1 below lists the five main chemical compounds in cement and their average percentages by weight. These compounds develop from limestone or lime and clay as a consequence of pyroprocessing. Most hydraulic cements are based on basic calcium compounds that are easily hydrated (Gartner and Macphee, 2011). Limestone is based mainly on calcium carbonates. Alumino-silicates and calcium sulfates may be found in clay but more usually calcium sulfate has to be added directly to ground clinker.

2.1. Classification of Portland cements

In the UK and Europe the applicable standard is BS EN 197 (BSI, 2011). This is summarized in Table 2.

The pozzolans are separated into artificial pozzolans such as fly ash, silica fumes and GGBS, and natural pozzolans composed of calcium, silica and aluminum compounds such as volcanic ashes, calcinated clay and shale. Considerable latitude is permitted when specifying the amount of each pozzolan used, as can be seen in Table 3.

The American Society for Testing and Materials (ASTM) adopted a somewhat different approach when it established the C150 standard specification recognizing the 5 classifications/10 types of Portland cement listed in Table 4 (ASTM, 2012).

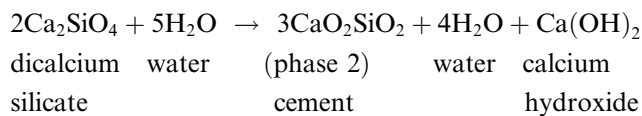
2.2. Hydration of Portland cements

Cement requires clean water to hydrate effectively. The hydration process in concrete involves the cement compounds undergoing a chemical reaction with water to produce a stable, amorphous solid hydrate. This solid phase continues to grow and expand in the presence of water and cohesively encapsulates other materials inside the matrix of hydrate solid. The chemical reaction in cement saturates the water with calcium (Ca) and hydroxide (OH) ions. The negative hydroxide ions raise the alkalinity of the cement paste to a pH > 12, effectively creating a cor-

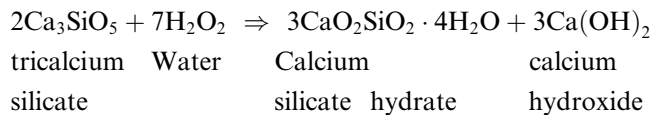
Table 3
Standard cements according to DIN EN 197-1, EN 197-4 and DIN 1164-10.

Portland cement clinker	5–100 mass%
Blast furnace slag	6–95 mass%
Natural pozzolan (trass)	6–55 mass%
Sulfate (gypsum/hemihydrate/anhydrite)	0–9 mass%
Cement additives	<1 mass%

rosive, alkaline substance. As the water becomes saturated with calcium and hydroxide ions, solid calcium hydroxide and calcium silica hydrate solids form to precipitate from the solution into the pore spaces. This process also produces heat.



The end products are the same for dicalcium and tricalcium silicates when mixed with water. The rapid reaction of tricalcium silicates in water produces more heat than the slower reaction of the dicalcium silicates in water; however both reactions produce calcium hydroxide and calcium-silicate-hydrate molecules and heat.



The main bond mechanism is not capillary force, as is often assumed, but a combination of the interlocking mechanism of microscopic hydrate solid and internal pressure due to the volume ‘filling effect’ associated with the conversion of liquid water into a solid hydrate phase and increasing the solid volume (Gartner and Macphee, 2011). The binding capacity of a hydraulic binder is thus related to the fact that the new solid phases can precipitate from a supersaturated aqueous solution in such a way as to create a significant area of solid–solid bonding interfaces in a volume that was previously filled with liquid water. A key factor governing the selection of compounds for cement is

the rate at which they can hydrate. By blending these compounds an optimum hardening rate and final strength for a specific use can be empirically determined.

Due to the nature of cement, there can be large deviations between design strength and the strength of concrete in situ; it is common practice to perform tests for such material on site or during the construction phase. Aggregates partially act as reinforcement for the hardened matrix of cement and also reduce cost by replacing a large volume of expensive cement with something similar, but of different load-bearing strength. In this sense the primary function of cement is to hold together or bind together the aggregate load bearing materials.

2.3. World Portland cement production

The production of cement varies greatly from nation to nation with the availability of materials. Where production does not satisfy demand a country can import to meet its needs. A review of recent trends in the global production of cement shows that the estimated amount of cement produced over the world was 3.6 billion tonnes – see Fig. 1, which shows that China dominates most of the market followed by Asia (CEMBUREAU, 2012). Typical cement plant capacity is expected to remain in the range of 1.5 and 2.5 million tonnes per annum (Schneider et al., 2011).

Fig. 2 shows global cement production increasing constantly from 1990 to 2050. This is to be expected as it is the second most consumed product on the planet after water. The industry is growing particularly rapidly in developing countries such as India and China that have a high demand for infrastructure and housing (World Business Council for Sustainable Development, 2009).

In the UK, cement production feeds into durable products and applications in the proportions shown in Fig. 3 (Smith et al., 2002). Articles of cement and concrete include products such as concrete building blocks and bricks, tiles, pipes, etc.

2.4. Current energy use and CO₂ emissions

Approximately 3.6 billion tons of cement is produced globally every year. A conservative estimate for every

Table 4
Classifications and types of Portland cement according to ASTM C150/C150 M.

Type I and type IA ^a	General purpose cements suitable for all uses where the special properties of other types are not required (the original OPC)
Type II and type IIA ^a	Type II cements contain no more than 8% tricalcium aluminate (Ca ₃ Al) for moderate sulfate resistance.
Type II (MH) and type II (MH)A ^a	Type II (MH) cements have moderate heat of hydration characteristic, based on a requirement that the sum of Ca ₃ Si + 4.75 Ca ₃ Al < 100% (tricalcium silicate and tricalcium aluminate), and moderate sulfate resistance properties based on a maximum Ca ₃ Al ₂ O ₆ content of 8%.
Type III and type IIIA ^a	Chemically and physically similar to type I cements except they are more finely ground to produce higher early strengths.
Type IV	Used in massive concrete structures where the rate and amount of heat generated from hydration must be minimized. It develops strength more slowly than other cement types.
Type V	Contains no more than 5% Ca ₃ Al ₂ O ₆ for high sulfate resistance.

^a The ‘A’ suffix refers to cements used to make air-entrained concrete and containing an air-entraining agent.

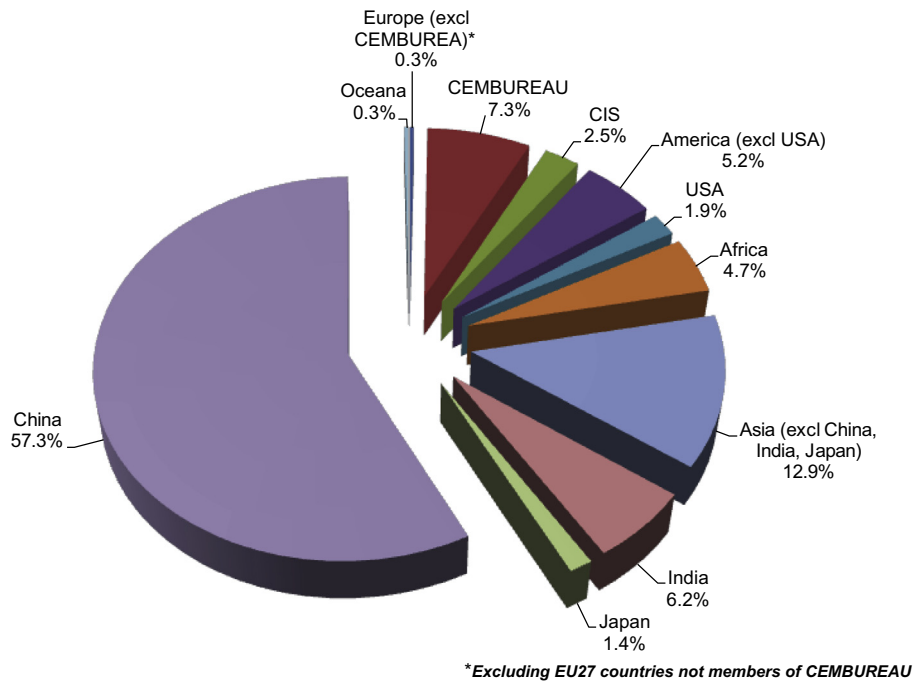


Figure 1. World Portland cement production today.

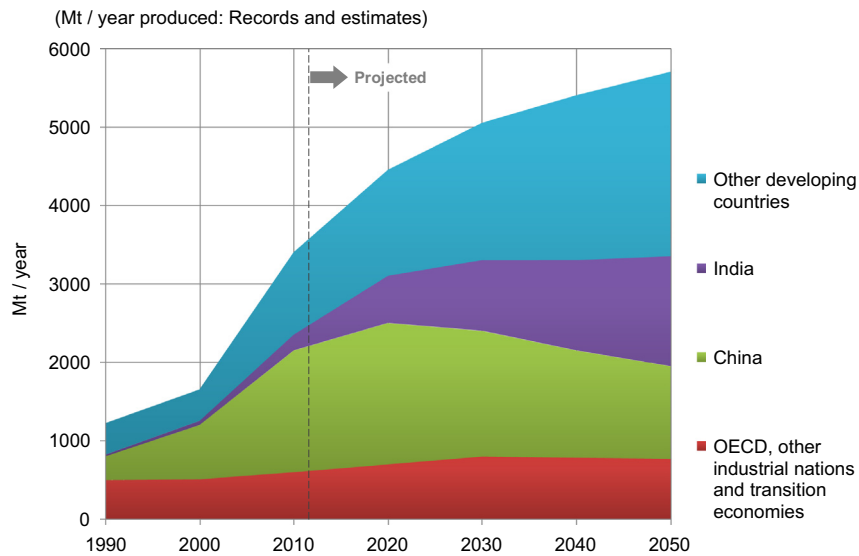


Figure 2. World Portland cement production 1990–2050.

1 kg of cement produced gives a by-product of 0.9 kg of carbon dioxide (Hendriks et al., 2004), this equates to 3.24 billion tonnes of CO₂ per year. These figures do not include CO₂ and other green house gasses emitted during the quarrying and transport of raw materials or the loading, unloading and transportation of the cement produced.

The main sources of emissions in the OPC manufacturing process are in two parts:

(i) From the calcination process as described earlier.

(ii) From the combustion fuel used to heat the raw materials to sintering temperatures (1400–1600 °C). The amount of CO₂ emission depends on the type of fuel and the particular processing method used. Kilns are fired using coal, fuel oil, natural gas, petroleum coke, biomass, waste-derived alternative fuels or mixtures of these fuels. The theoretical heat requirement for clinker-making is calculated to be about 1.75 ± 0.1 MJ per kg; however; process inefficiencies mean the actual heat requirements are higher (Hendriks et al., 2004; Norchem, 2011).

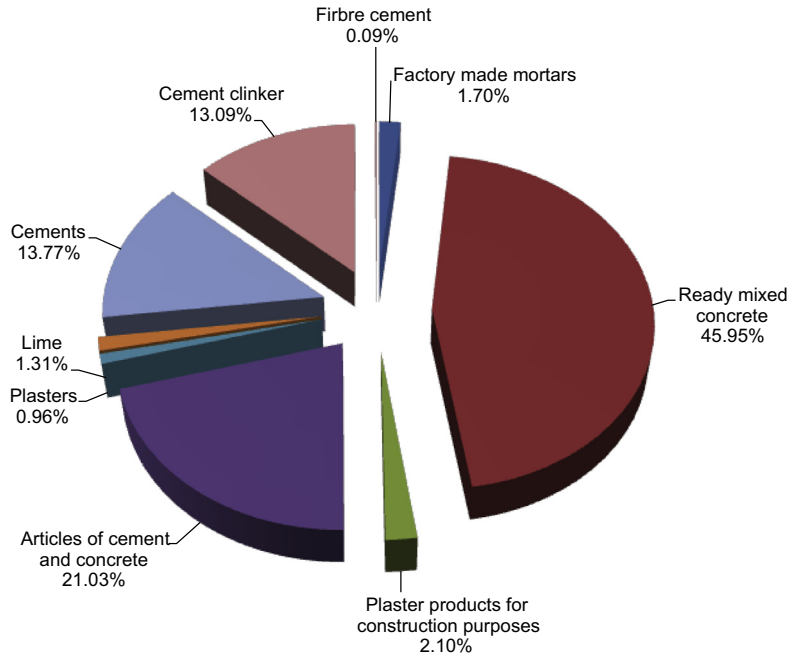


Figure 3. Cement, concrete and plaster products in the UK construction market.

The production process is diagrammatically shown in Fig. 4 (Association of Cementitious Material Producers, 2010) and the key stages are described in the rest of the section.

2.4.1. Quarrying

The production of Portland cement begins with the quarrying of raw materials. Most cement plants are situated near a limestone quarry to minimize transportation costs. Quarrying limestone involves drilling, blasting, excavating as well as crushing, screening and storing. The raw materials are milled together to achieve the right composition before being sent to the kiln for pyroprocessing. Only the operation of machinery is responsible for CO₂ emissions when quarrying for raw materials.

2.4.2. Pyroprocessing

Cement clinker is made in a rotary kiln, or long cylindrical rotary furnace that turns around once or twice every minute. Temperatures are generally around 1400–1600 °C, and energy demand varies depending on the manufacturing process (Norchem, 2011). The material undergoes the process known as calcination inside the kiln after all moisture is evaporated out, about a third of the way down the kiln. The end product size ranges from dust to big lumps of calcium silicate or clinker. See Table 5 for CO₂ emissions in kg per kg cement produced for various fuels and various clinker/cement ratios (Assumptions – Electricity use is 0.38 MJ/kg of clinker; the average emission factor of CO₂ of electricity production is 0.22 kg/MJ; fuel use is 3.35 MJ/kg of clinker (dry process) and 5.4 MJ/kg of

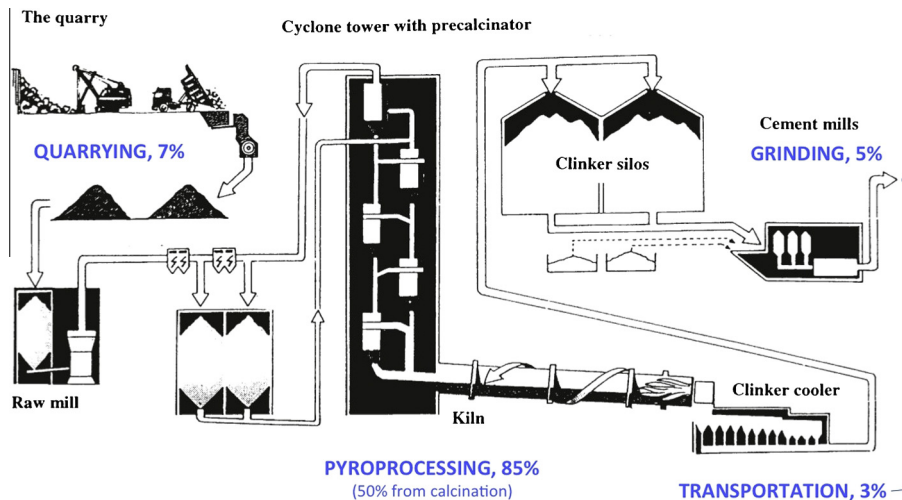


Figure 4. Share of total CO₂ emissions across the Portland cement production process.

Table 5

CO₂ emissions in kg per kg cement produced for dry and wet cement production process for various fuels and various clinker ratios (Hendriks, 2004).

Clinker ratio ^a (%)	Calcination process	Dry kiln process				Wet kiln process			
		Coal	Oil	Gas	Waste	Coal	Oil	Gas	Waste
55	0.28	0.55	0.50	0.47	0.36	0.67	0.59	0.53	0.36
75	0.38	0.72	0.66	0.61	0.47	0.88	0.77	0.69	0.47
(Portland) 95	0.49	0.89	0.81	0.75	0.57	1.09	0.95	0.90	0.57

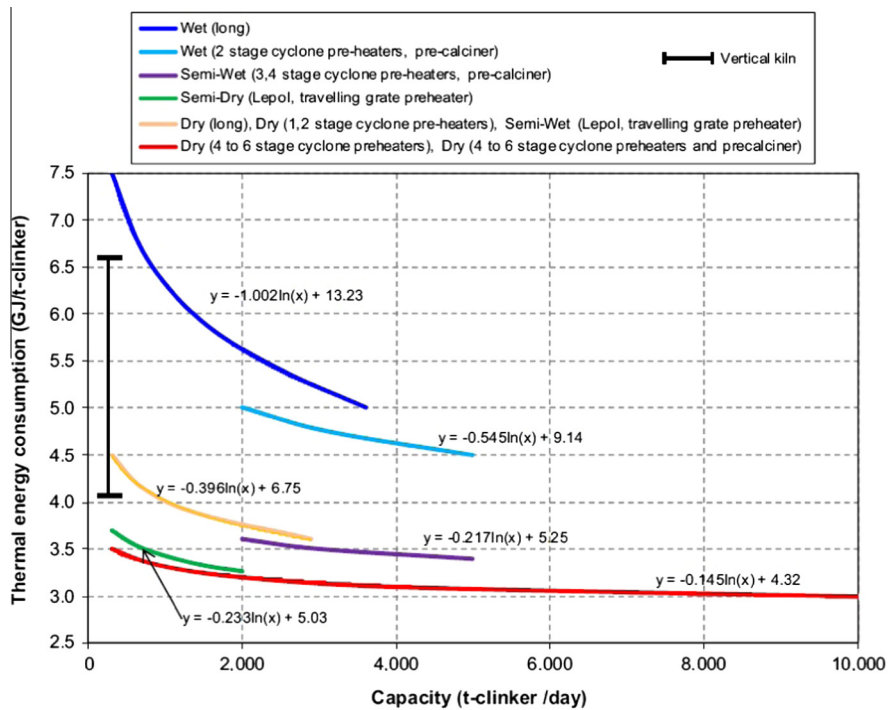
^a The ratio of Portland cement clinker to additives.

Figure 5. Energy efficiency in clinker production (Oda et al., 2012).

clinker (wet process)). It should be noted these figures assume that no CO₂ penalty is attached to materials such as slag or fly ash and some may argue they are therefore highly artificial, erring on the optimistic.

The plot in Fig. 5 spans a range of thermal energy efficiencies in Portland cement clinker production, from lowest to highest energy consumptions based on type and capacity of kiln.

According to the CSI's "Getting the Numbers Right" (World Business Council for Sustainable Development, 2009), the dry manufacturing process with preheaters and pre-calciner technology, used in a large number of cement production plants globally, had an average specific energy consumption of 3,605 MJ/t clinker in 1990 but saw a reduction of around 6% by 2006. Energy efficiency is the only element that can be managed by the industry itself but there are many factors that make this difficult. Upgrading existing plants with new technology is a costly process. If high cement performance is required, the grinding of very fine granules (for high specific surface area) will

require greater power consumption. Using clinker substitutes may reduce calcination CO₂ emissions but will generally require more heat energy. Products such as GGBS or fly ash can be used to substitute clinker in cement production either before (limited by the low lime content of the additives) or after calcination (OECD/IEA and World Business Council for Sustainable Development, 2009), however, there are limitations to this process such as availability or cost of the clinker substitute materials and there are also barriers imposed by standards and regulations.

2.4.3. Grinding

The lumps of clinker are ground up with calcium sulfate dihydrate (CaSO₄·2H₂O) or gypsum or active anhydrite to control the rate of hardening or the setting time (gypsum is also used to make Plaster of Paris, a commonly used rendering plaster). Usually about 2–10% of the ground-up Portland cement is gypsum. The final product, OPC cement is used in various ways, primarily to make mortar and concrete, cinder or cavity block.

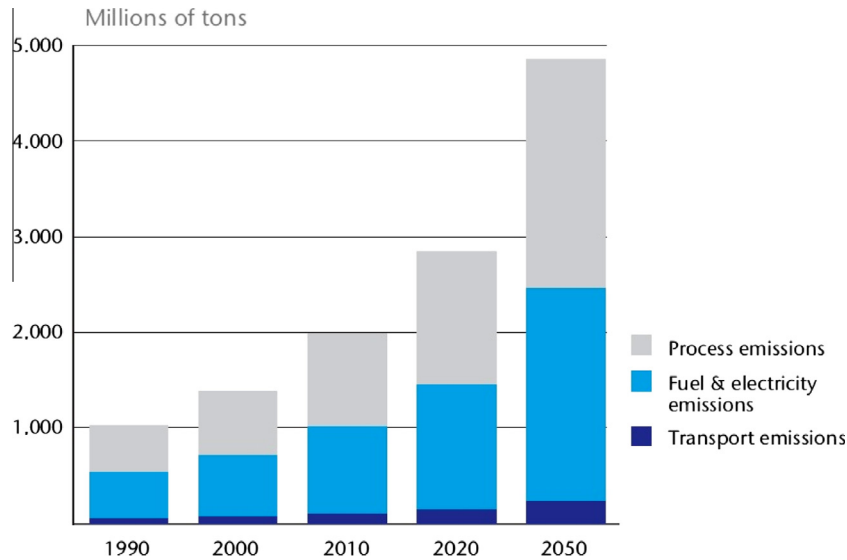


Figure 6. Projected global cement industry reference CO₂, million metric tonnes (Battelle, 2002).

2.4.4. Transportation

The cost of transporting bulk commodities greatly affects cement production. As a result, cement production plants are often located at or close to limestone quarries and customers tend to purchase cement and ready-mix concrete from as local a source as possible. Nearly 98% of U.S. cement and all readymix concrete are shipped to customers by truck (Hendriks et al., 2004). Readymix trucks typically have a carrying capacity of 6–8 cubic meters of concrete each. Barge and rail modes account for the remaining distribution. Exported cement is invariably transported by land or sea. The estimated emission rates of transport by truck, rail and ship are, respectively 0.033, 0.017 and 0.010 kgCO₂/tonne-kilometer (Lawson, 2007).

2.5. Future CO₂ emissions if we continue 'business-as-usual'

The Cement Sustainability Initiative (OECD/IEA and World Business Council for Sustainable Development, 2009) recommends how the industry can make changes on a global scale by promoting the best available efficiency technologies for new and existing production plants, increasing awareness of alternative fuels and encouraging clinker substitution. Their recommendations also include initiation of government support programmes that will help fund new industry pilot projects. Fig. 6 shows the projected CO₂ emissions from the cement industry if no changes are made to current production methods. By 2050 the emissions will have increased by almost 5 times the value in 1990. This is not a good path to be on when the world is becoming more green-aware. These initiatives will thus not only help pave the way for a 'greener' cement industry but will also be beneficial in reducing greenhouse gas taxes and ensuring the continuation of the industry in an economic climate of ever increasing costs.

The predictions in Fig. 6 were made in the year 2000 and suggest CO₂ emissions rising from around 1.4 billion to just

under 2 billion tonnes of CO₂ per year in 2010 and 4.8 billion tonnes of CO₂ per year in 2050. The CO₂ emission today (i.e., in 2012) is 3.24 billion tonnes of CO₂ per year. The original predictions have therefore underestimated the increase in CO₂ emissions by 124% – i.e., 2.24 billion as opposed to 1 billion tonnes CO₂ per year. If the exponential trend assumed in the original prediction is adjusted to accommodate the 2012 data and extrapolated over the same period of time, the cement industry emissions could conceivably rise to around 32.7 billion tonnes of CO₂ per year, more than 6 times projected and a massive 33 times 1990 levels. This would be very bad news indeed and so must clearly never be allowed to happen.

3. Novel, resource efficient cements

In order to improve energy efficiency and reduce carbon emissions, the approaches that have been adopted can be summarized under the following four main headings:

{Review and update of manufacturing processes}

Manufacturing processes in cement production have been and continue to be optimized and automated, using the best technologies available to reduce cost, emissions and increase productivity. This has led to incremental reductions in Green House Gas (GHG) emissions and has also reduced the industry's employment levels (Taylor et al., 2006). Review and update of the manufacturing process lie firmly within the domain of cement manufacturers, cement production equipment manufacturers and cement plant designers and are not for discussion here.

{Co-incineration of waste material in cement kilns}

Co-incineration of waste fuels such as wood and plastics from demolition activities, rubber tires, industrial and municipal sewage sludge, animal wastes (fats, carcasses, etc.), agricultural waste, solid waste, solvents and oils is a booming industry in some European

countries, notably Germany (Joint Research Centre, 2012). The benefits are: less conventional energy demand and cost overheads, funds paid to cement producers for disposal of waste materials that would otherwise go to landfill, and disposal of these wastes to reduce landfill. The disadvantages are increased CO₂ emissions and release into the atmosphere, if not properly (and expensively) managed, of hazardous materials like sulfur dioxide (SO₂) and other sulfur compounds, total organic compounds (TOC) including volatile organic compounds (VOCs), polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD and PCDF) and metals (including Hg, Cd, As, Pb) and their compounds. With the exception of waste biomass alternative fuels, which if used can deliver a net CO₂ emission reduction, co-incineration of waste products addresses a different sustainability agenda (management of waste).

{Supplementary Cementitious Materials (SCMs) in cement production}

This relates to the development of new concrete design guidelines that allow more SCMs to be used, to reduce CO₂ calcination. SCMs include (a) ground limestone as a filler to replace Portland cement and reduce carbon emissions, or (b) natural or artificial mineral pozzolanic compounds (Bentz, 2011). Artificial pozzolans are by-products of the iron and steel industries, classified as Recovered Mineral Components (RMCs). The benefits of adding small quantities of ground limestone are well documented (Matschei et al., 2007) and the CEM I standard permits up to 5% by weight of ground limestone to be added to the mix without loss of quality. The CEM II/A-L and CEM II/B-L standards for 'Portland limestone cement' are more liberal and permit the substitution of up to 20% and 35% by weight, respectively of ground limestone and other SCMs (CEMBUREAU, 1991).

{The development of novel, resource efficient cements}

Novel cements involve development of cement manufacturing processes that use different raw materials. The shared aim of novel cement developers is cement that emits less CO₂ and requires less energy to produce than CEM1, without reducing or compromising the efficiency of the cement. Novel cements would ideally use waste derived fuels and raw materials (Mineral Products Association, 2012). The chemical properties of some novel cements may be similar to those of Portland cement, making them ideal (easy) potential alternatives. Low carbon cements are either only in use on a limited scale in a few parts of the world, for example Calcium Sulfoaluminate Cement (CSA) in China (Lafarge has announced they will be marketing their Aether[®] CSA cement in 2014), or they are being developed by small start-up companies still looking to build pilot plants. A major objective is therefore to verify and establish technical and commercial viability, and their sustainability against Portland cements.

The remainder of the section will touch on alternative fuels and expand on the use of SCMs and development of novel, resource efficient cements.

3.1. Alternative fuel substitutes

The firing of cement clinker kilns is traditionally fueled either by coal or petroleum coke, or, to a lesser extent, alternatively by natural gas or fuel oil. Use of other fuels such as biomass can be an effective fossil fuel substitute, producing CO₂ emissions that are about 20–25% less than those of coal (OECD/IEA and World Business Council for Sustainable Development, 2009). Not only do reduced emissions make such fuels suited for cement kilns, but combustion products of inorganic compounds such as ash are also integrated into and can contribute beneficially to the clinker product.

The full range of alternative fuels used by the cement industry includes used tyres, sewage sludge, waste oil and waste derived fuels such as paper residue, plastics and textiles. Cement kilns are able to use whole or shredded tyres as a fuel, the biggest use for discarded tyres in Japan and the USA. The use of such alternative fuels in the production of Portland cement clinker is possible but it can influence the clinker properties as these fuels burn differently compared to traditional fossil fuels. This can change the temperature profile in the kiln and also affect the cooling conditions. The result is an alteration in the characteristics of the clinker that can be attributed to the porosity of the granules, burning grade of the clinker or the crystal size of the clinker phases or their reactivity.

Wastes can also alter the cement composition. For example, when tyres are co-incinerated the zinc oxide content of clinkers increases significantly. The burning of alternative fuels thus introduces different components into the kiln via ash. These can affect the performance characteristics of the cement, such as lower early strength and longer setting times (Schneider et al., 2011). However, these problems can be overcome by closely monitoring and adjusting the production process and materials to allow for the correct level of alternative fuels being burnt to be calculated and making the required compensatory changes to the composition of the raw materials fed to the kiln. This will produce high quality Portland cement clinker that conforms to cement standards. In many countries the use of alternative fuels has moved from laboratory to application (Mineral Products Association, 2012). In some European countries the average substitute rate is about 70%; in the UK it is only about 40%.

The achievement of high substitution rates faces legal and political barriers. In the UK the cement industry is primarily regulated by the Environmental Permitting Regulations (EPR) for England and Wales and Pollution Prevention and Control (PPC) for Scotland. In order to burn waste derived non-fossil fuels, a license or permit needs to be granted. To obtain this an environmental assessment has to be carried out to determine if the use of such

waste will be of greater or lesser impact than using traditional resources. However, the use of waste derived alternative fuels will generally see an increase in the associated CO₂ costs. It is likely to become difficult for the industry to source significant quantities of biomass at acceptable prices. The IEA's predictions suggest that it will only be economically viable for the cement industry to use biomass sourced alternative fuels until 2030 (OECD/IEA and World Business Council for Sustainable Development, 2009).

Alternative fuel trials such as those at Lafarge's Abergaw Works in the UK using Meat and Bone Meal (MBM) are seeking to explore the commercial and environmental benefits that using different alternative fuels can bring (Lafarge Cement UK, 2011). The plant has also used end of life tires and solid recovered fuel as a partial replacement for traditional fuels. They hope to continue using these alternative fuels on a permanent basis given the numerous benefits. Using alternative fuels may, however, be only a temporary short lived solution. In the long run a more permanent solution must be found.

3.2. Commonly used Supplementary Cementitious Materials (SCMs)

SCMs are used either as fillers or because of their pozzolanic properties. This means that the SCM particles will hydrate just as Portland cement does, but they also supply more silicate in the mixture that will react with excess hydrated lime released during the hydration of the Portland cement. In this section the most common SCMs are reviewed.

3.2.1. Ground limestone cement

Hawkins et al. (2003) presented a thorough and comprehensive review of research into the use of blended or inter-ground limestone in Portland cement. This looked at the effects of limestone use on particle size distribution, grinding, workability, hydration and setting of the cement including reaction chemistry and kinetics, heat generation, microstructure, setting time, durability, etc. Portland Limestone Cement (PLC) has been used in Europe for more than 25 years, often as an alternative to OPC in applications that do not require sulfate resistance (even though some tests have shown improved sulfate resistance for cements containing limestone). Limestone is a low cost, readily available material that is easier to grind than clinker and leads to improved particle packing and hydration. It improves workability and reduces 'bleeding' in PLC compared to OPC, but its main attributes are reduced cost and reduced CO₂ emissions. PLC containing up to 20% limestone, manufactured in accordance with current standards, can reduce energy requirements and carbon emissions by as much as 10% compared to other Portland cements while delivering comparable performance (Portland Cement Association, 2013).

3.2.2. Fly ash and pulverized fuel ash (PFA)

Fly ash and PFA are essentially one and the same; it is ash produced from coal and some other solid fuel

combustion systems. Where bottom fuel ash is left in the region of combustion, fine grained fly ash is carried with combustion flu gases and commonly collected by electrostatic precipitation. The chemical composition of fly ash tends to be a heterogeneous mixture of silicon oxides (SiO₂), aluminum oxides (AlO₃) and iron oxides (Fe₂O₃, Fe₃O₄) Bentz, 2011. Such ash types are common in Europe but in many parts of the world, lime-rich ashes are available.

Because of its pozzolanic properties, fly ash is often used to replace typically 30% of the mass of Portland cement in a concrete mix, for example to lower permeability and reduce initial heat evolution. The fly ash type used is limited to a Class-C and Class-F types. The classification as C (calcium rich) or F (aluminosilicate rich) types has been abandoned by ASTM, although the terms are still widely used. Even these two classes have wide range specification limits that are dependent on variability of source. Ensuring consistency is therefore a major concern among cement suppliers and standards typically require that each batch of cement uses SCMs from the same source. Fly ash will contribute to the strength of concrete after seven days of curing. Strength development of fly ash in concrete is due to a chemical reaction between the fly ash and calcium hydroxides produced by hydration of OPC (Mahasenan et al., 2003).

The main documents controlling the use of PFA are the Manual of Contract Documents For Highway Works, Volume 1, Specification For Highway Works, Series 1700 Structural Concrete (Highway Agency, Department for Transport), BS 3892: 1993 Pulverized-fuel ash. Specification for pulverized-fuel ash for use with Portland cement, ASTM C618-01 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete and BS EN450-1: 2012 Fly ash for concrete. Definition, specifications and conformity criteria.

3.2.3. Ground granulated blast furnace slag (GGBS)

This is a by-product of the iron and steel industry; while pig iron is extracted from melted raw iron ore, the left-over material (which floats to the top) is referred to as slag. It consists of calcium, magnesium aluminosilicates and also has pozzolanic properties depending on quenching history. Also depending on the cooling method used, there are three main types of blast furnace slag: air cooled, granulated and expanded slag. Granulated slag is formed by quickly quenching molten slag with water. The result is glassy sand-like material that, when ground to a fine powder and contacted with alkali such as lime or Portland cement, develops strong hydraulic cementation properties (van Oss Hendrick, 2012).

Expanded slag and air cooled slag are primarily used as an aggregate in concrete and bitumen applications but when ground into a fine powder, can also be used as supplementary cementitious materials similar to GGBS (provided a high proportion of the glass is preserved). However all slag, including some steel furnace slag (SFS), can be used as raw feed material for cement clinker manu-

facture in a kiln. Reductions in CO₂ are significant due to the process being less energy intensive and involving less heat to perform the calcinations process.

The main documents that control the use of GGBS in cement are the Manual of Contract Documents For Highway Works, Volume 1, Specification For Highway Works, Series 1700 Structural Concrete (Highway Agency, Department for Transport), BS 6610:1991 Specification for Pozzolanic pulverized-fuel ash cement, ASTM C595-02a Standard Specification for Blended Hydraulic Cements, BS EN 197-4: 2004 Cement. Composition, specifications and conformity criteria for low early strength blast furnace cements, and BS EN 197-1 Cement. Composition, specifications and conformity criteria for common cements.

3.2.4. Silica fume

Silica fume, also known as microsilica, is a by-product of the production of silicon and silicon alloys in electric arc furnaces. It is added to cement to produce high performance concretes that are much stronger and more durable than other concretes made using blended cements; it is also very useful for reducing the permeability of concrete and therefore able to better protect steel reinforcement. A problem with silica fume is that it greatly increases water demand so many codes limit addition to ~6% unless the mix is heavily superplasticized. Unfortunately, where silica fume was once a cheap waste product, it is now an expensive high performance cement supplement primarily used in bridges and other exposed structures that require high weathering performance.

Using silica fume will contribute incrementally to reducing CO₂ emissions but it is not as easy to obtain as other recovered mineral components (RMCs) such as GGBS and fly ash. The production process is very energy intensive but these values attribute zero CO₂ to the fume as it is a by-product of another manufacturing process. According to the U.S. Environmental Protection Agency 1 lb of CO₂ is avoided for every 2.2 lbs of SCM substituted in a cement, or 0.432 kg of CO₂ per kg of SCM (Norchem, 2011).

The standards documents that control the use of silica fume in cement are ASTM C1240-12 Standard Specification for Silica Fume Used in Cementitious Mixtures and BS EN 13,263 – 1:2005 + A1:2009 Silica fume for concrete. Definitions, requirements and conformity criteria.

3.3. Novel, resource efficient cements

{Limestone-based novel cements}.

3.3.1. Calcium sulfoaluminate cement ($4CaO \cdot 3Al_2O_3 \cdot SO_3 \cdot Ca_2SiO_4$, C₂(A,F))

Calcium Sulfoaluminate (C₂A) cements are manufactured and have been used on an industrial scale in China since the late 1970's. The cement powder is formulated to contain ye'elemite, Ca₄Al₆[O₁₂SO₄]. Belite-calcium sulfoaluminate ferrite C₂A clinkers can produce cements with similar performance to Portland cements while in principle

being manufactured in conventional Portland cement plants to deliver significantly less CO₂ emissions during calcination. They also require less heat compared to Portland cements, further reducing CO₂ emissions. C₂A clinker can be readily synthesized with a high content of ye'elemite, ranging from 35% to 70% mass and substantial amounts of belite and ferrite phases, when limestone reacts along with other materials or waste products. C₂A cements are manufactured in a process similar to that of Portland cement in a dry process rotary kiln at temperatures between 1250 and 1350 °C. C₂A cement compositions are in structural grades with phase contents of 35–70% ye'elemite, 30% belite and 10–30% ferrite (Calcium Ferro Aluminate) (Mineral Products Association, 2012).

As with Portland cement, gypsum is added in a controlled process in optimized amounts and ground with clinker to form different types of C₂A cements. The properties of C₂A cement change from rapid hardening cement to a shrinkage compensated cement when increasing amounts of gypsum are added and it will eventually become expansive and hence self-stressing at sufficiently high sulfate (Sharp et al., 1999). C₂A cement as supplied provides acceptable setting times and good strength development. This is achieved by a process based on the rapid formation of ettringite and variable quantities of amorphous gel phase. C₂A cements have a strength development similar to if not greater than Portland cement, with an early strength of between 35 to 55 MPa after one day, and 55 to 70 MPa after 28 days. These strength characteristics demonstrate equal performance to Portland cement. Anecdotally, there is evidence that C₂A cements have the ability to protect steel reinforcement against corrosion.

In comparison to Portland cement, C₂A cement can achieve energy savings as high as 25% and provide environmental benefits by reducing CO₂ emissions by around 20%. The use of C₂A cement as a construction material in countries other than China is entirely feasible, even initially as a niche market product. With greater use the benefits of this cement will eventually become evident to the market and its appeal as a high quality alternative to OPC/CEM1 will grow. Lafarge has patented a class of cement clinkers based on Belite, C₂A and Calcium Aluminoferrite phases (BCSAF) Gartner, 2012. These Belite-Calcium Sulfoaluminate Ferrite (BCSAF) clinkers can be used to make cement in the usual way by being mixed with gypsum and other materials, and are considered to be an intermediate between Portland cements and C₂A cements. BCSAF's have the potential to be manufactured in much larger volumes than slag based cements as they do not require a source of slag but show high content similar to that of Portland cements. Due to the reactivity of the C₂A phase, BCSAF cements can have greater strength in the early stages of development compared to Portland-slag cements – see Fig. 7. The above data was obtained from a pilot test set up by Lafarge Central Research (LCR) and tested by BRE which showed that cements based on C₂A are promising alternatives to Portland cement; especially as such

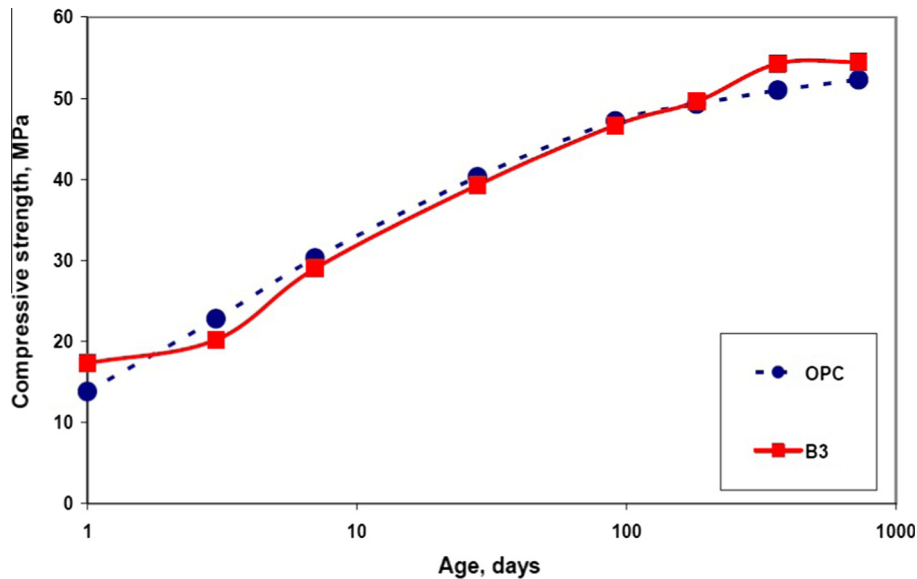


Figure 7. Compressive strength of BCSAF compared to Portland cement, BRE concrete data at $w/c = 0.55$, 300 kg/m^3 for pilot batch of BCSAF (B3) compared to OPC (CEM1 425) (at 20°C).

clinkers can be formed in existing ordinary Portland cement plants. However, the cost of raw materials is greater than that of Portland cement, although according to Gartner this may not be an economic factor once the projected CO_2 emissions costs (taxes) have been factored in. The development and testing of CSA cements thus show promise and could in time lead to the establishment of new codes and standards.

3.3.2. Calcium aluminate (CaAl_2O_4) and calcium alumina-silicate cements

These cements are made in a rotary kiln by using bauxite (an aluminum ore) instead of the typical calcium silicates found in clays. The limestone and bauxite mix is fused into a cement clinker in the same way as Portland cement. The result is a special type of cement used for its ability to reach high strength at a very early stage as well as its very good heat and chemical resistance properties.

Although using this cement reduces the amount of CO_2 produced during calcination, it is more expensive and less readily available than Portland cement. In use, calcium aluminosilicate cements are often blended with high concentrations of GGBS, except in refractory applications where they are used without slag.

3.3.3. Super-sulfated cements

Super sulfate cement is made by grinding a mixture of 80–85% selected GBFS with 10–15% calcium sulfate and about 5% of Portland cement clinker. It is generally used where high sulfate, acid and organic oil attacks on a structure are expected. Again the cost of this type of cement is high, due to the limited availability of materials.

{Non-limestone based novel cements}

3.3.4. Magnesium-oxide based cement as a 'carbon negative cement'

Water-activated-magnesium-oxide based cement was commonly used well before OPC ever came into existence. It requires around 30% less energy to produce, and has some significant advantages over OPC. For example, when hardened, the cement is permeable, making it useful in terms of heat regulation and control in the design of dwellings, particularly for warm climates. It can breathe, unlike OPC, and so it has been referred to as living cement. Magnesium based cements also have greater strength. Although it is an ancient cement similar to what was at one time thought to have been used by the Chinese to build the Great Wall, major cement producers are today using this cement in modern applications, for example US Gypsum's 'Grancrete', a spray-on structural cement and in wallboard imported from China. This type of cement is already used for housing in developing countries. Argonne National Laboratories have tested similar MgO -based 'Ceramicrete' cements with a view of developing them into more commercial products.

TecEco, a small Australian research and development company, is one of the earliest players in this field. They have developed and been granted international patents for TecEco cements in which reactive magnesia, also known as caustic calcined magnesia, caustic magnesia or CCM, is substituted for Portland cement. The reactive magnesia hydrates to brucite, $\text{Mg}(\text{OH})_2$, and in Eco-Cement exposed to the atmosphere, carbonates to magnesite, MgCO_3 . Various cement formulations have been developed by TecEco based on this fundamental concept including Tec-Cements, Eco-Cements and Enviro-Cements (TecEco Pty Ltd, 2013).

New research is underway to develop a magnesium-based cement that absorbs more CO_2 than it produces

during the manufacturing process (Biello, 2008). A working formulation of ‘carbon-negative cement’ derived from magnesium silicates was devised by Nikolaos Vlasopoulos, chief scientist at London-based Novacem Ltd., an Imperial College start-up, working in collaboration with Lafarge and Laing O’Rourke. The aim was to license the process by 2015. According to the inventors, magnesium silicates are globally available but not uniformly distributed.

The precursor material, olivine ($\text{Mg, Fe}_2\text{SiO}_4$), is carbonated in an autoclave process at a temperature of 180 °C and pressure of 150 bars (Mineral Products Association, 2012; Vlasopoulos, 2010). The process produces magnesium carbonate which is further heated in air at 700 °C to produce magnesium oxide. The final Novacem cement composition is a blend of magnesium oxide and hydrated magnesium carbonates, which influence the mechanical properties of the cement. It can be further improved by reducing the water/cement ratio (Velandia et al., 2011). As Novacem requires a much lower temperature to produce the cement precursor, it can use biomass fuels to further reduce its CO_2 emissions. The cement is referred to as a carbon negative product not just because of the fuel it uses but also because the CO_2 it produces in the manufacturing process is recycled back into the process.

The production of 1 tonne of Novacem hydrated magnesium carbonate cement supposedly absorbs up to 100 kg more CO_2 than it emits. In 2011 concrete trials were undertaken with Laing O’Rourke and it was reported that the concrete had achieved strengths of 40–60 MPa, similar to those of Portland cement.

However, on the 16th of October 2012 it was announced that the “Novacem Liquidator had sold the company’s Technology and Intellectual Property to Calix Limited” (Novacem announces company now closed and in liquidation, 2012). Despite the fact that MIT’s Technology Review had ranked Novacem’s magnesium-based cement to be among the 2010 top ten emerging technologies, the company was unable to raise the necessary capital to continue the development of the technology. A further disadvantage of the product is that magnesium oxide is not as abundant on land as calcium sourced from limestone.

3.3.5. Alkali-activated cements/geopolymers

Alkali-activated cements (AACs) are competitive with ordinary Portland cement (OPC) in performance and cost, and their production emits 95% less CO_2 than OPC (if the NaOH and KOH required are assumed to be carbon free); they have longer life, better durability, and they recycle millions of tons of industrial waste – i.e., Recovered Mineral Components (RMCs).

AACs are not a limestone or calcium silicate based cements, instead the chemistry is based on an aluminum–silicon system. The composition is simply made up of sand, water, natural or synthetic pozzolans and another ingredient which is the alkali activator. The activator is usually

mixed into the water to make a solution before further mixing. The alkaline solution decomposes the precursors into silicate and aluminum units which then re-combine to produce ‘geopolymers’. These aluminum and silicate polymers grow to high molecular weights, creating a strong binder. Although the first geopolymers were based on metakaolin, AAC’s are now generally separated into two groups, alkali-activated fly ash cement and alkali-activated slag cement. But a mixture of the two, with or without OPC is also in use (Bondar, 2007).

3.3.6. Sequestered carbon cement

The Calera Corporation have a process that essentially mimics marine cement, similar to what is found in the coral reef, taking the calcium and magnesium in seawater and captured carbon dioxide from effluent gases to form carbonates. The idea is that CO_2 rich gases are filtered through sea water. The calcium and magnesium are stripped from the sea water and react with CO_2 to produce high quality cement, which is snow white, air permeable and stronger than regular OPC. Many other laboratories and scientific institutes are looking into the same idea, however Calera seem to be at the most advanced stages of development. The Calera process is described in Fig. 8 (Calera, 2013).

Calera are at the moment testing concrete made from a blended cement of OPC and Calera cement. There is an expressed interest from the California Department of Transport and Moss Land Power plant to utilize this cement making process.

4. Current and projected economics of cement production

The cement industry has to cope with many economic factors including energy prices, green taxes, production costs and market forces that ultimately affect how much a tonne of cement will cost. UK cement manufacturers rarely publish absolute values but give percentage changes; together with cement price indices published by the government, this allows an evaluation of trends in the industry to be made. This section looks at the UK, US and 2 Middle-Eastern cement markets, to illustrate some of the economic trends in cement production.

4.1. UK production and price indices

The latest UK cement industry statistics (2005–2011) are plotted in Fig. 9 for the indexed cost of electricity and coal used in production against the indexed cost of cement (Department for Business Innovation and Skills, 2012; Department of Energy and Climate Change, 2012). From these plots it can be seen that electricity and coal have risen by approximately 63% and 75%, respectively since 2006, but the corresponding rise in the price of cement is around 35%. CEMEX has confirmed that the price rise was due to higher kiln fuel and electricity costs that had to be recovered through price increases (Global Cement, 2012). The

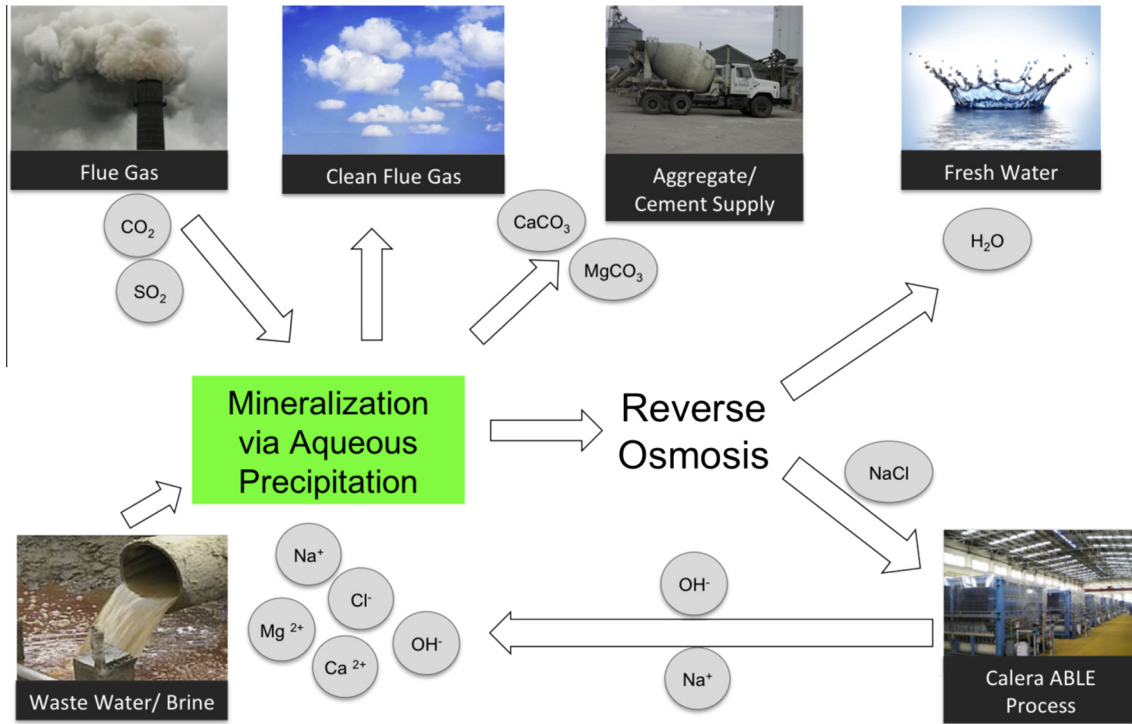


Figure 8. Carbonation formation according to Calera.

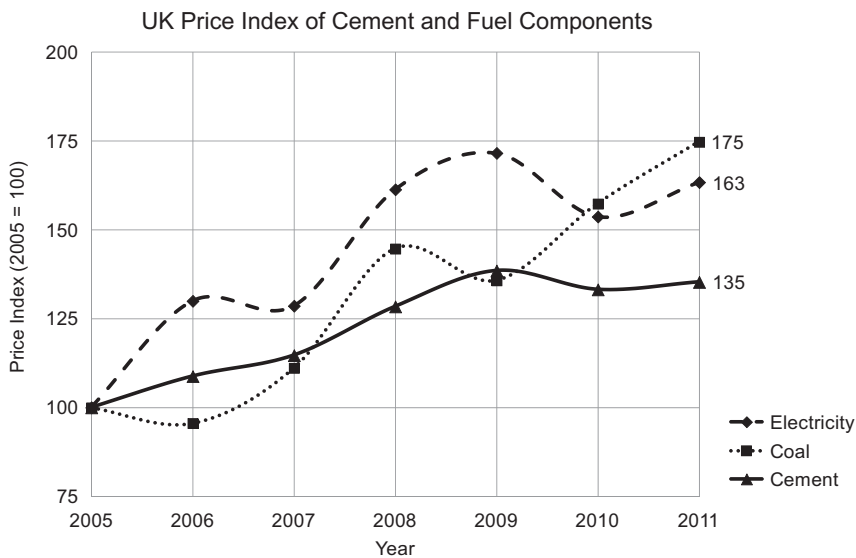


Figure 9. UK cement and fuel component price trends.

data shows that electricity prices started to increase from 2005, with coal prices following a similar trend from 2007. The price of cement followed accordingly, rising steadily between 2005 and 2008; by the end of 2007 cement producers were expected to introduce budget-busting price hikes, with an expected price increase of around 20% (equivalent at the time to GBP £15 per tonne of cement on top of the already set price of GBP £70 per tonne at the start of 2008. However, the drop in demand for cement,

attributed to the ‘credit crunch’, was effective (thus far) in mitigating further price increases.

Although coal prices are on the increase and electricity prices show a steady trend, the price of cement is starting to see a decrease with a price index, reaching 135 – higher than that of previous years but still below the peak in 2009, due to reduced demand. Since 2011 cement production increased in the UK by about 8% compared to 2010, perhaps signaling the start of a recovery in the cement market.

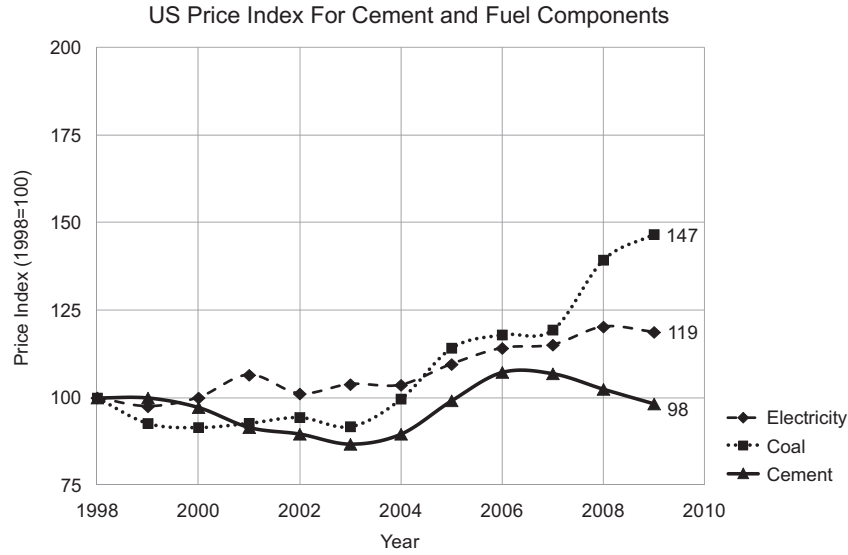


Figure 10. US cement and fuel component price trends.

4.2. US production and price indices

Beyond the UK, cement industry statistics from the US have also been evaluated and the results are plotted in Fig. 10 (U.S. geological Survey, 2012; USGS, 2010; U.S. Energy Information Administration, 2011). The plots show cement price indices from 1998 to 2009, together with coal and electricity price indices. A base index of 1998 = 100 was used. US cement prices have decreased by approximately 13% between 1998 and 2003. Coal prices also fell during the same period (despite a small rise in 2002) but electricity prices have either remained unchanged or increased slightly. Cement prices started to rise from 2003, reaching a peak of index price of 107 in 2006. This could be due to the sharp increase in the price of coal at this time

(about 26%) as well as a continuing increase in electricity prices.

From 2006 the cement industry faced a decrease in cement prices, dropping by about 9% even when coal and electricity prices were on the rise; this is similar to the effect of the credit crunch on the UK price of cement, but it happened 2–3 years before that. The startling fact is that in 2009 the price of cement was effectively lower, albeit only slightly, than what it was in 1998. The availability of low cost Mexican cement has also not helped indigenous producers. So, not only has the US cement industry had to suffer a weak market and low demand, it has had to put a squeeze on cement prices to compensate for increasing kiln fuel and electricity prices over a good number of years. Cement production has recently increased in the US and

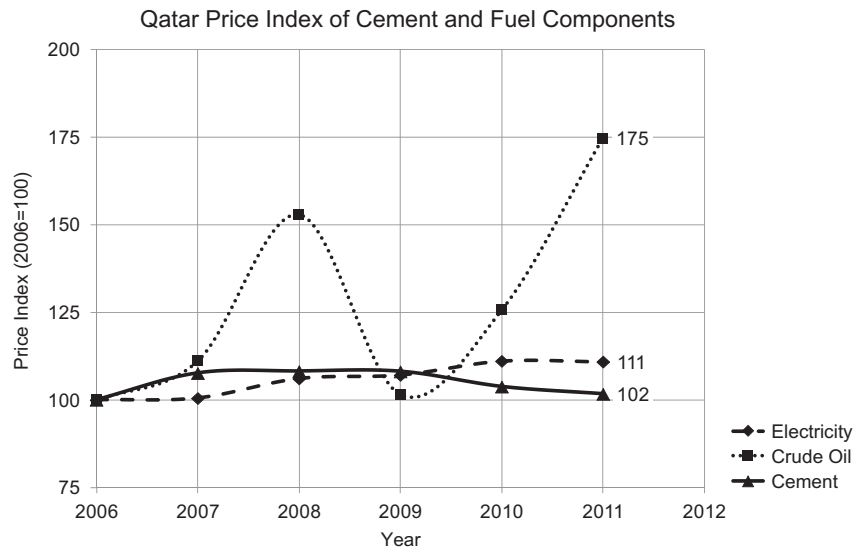


Figure 11. Qatar cement and fuel component price trends.

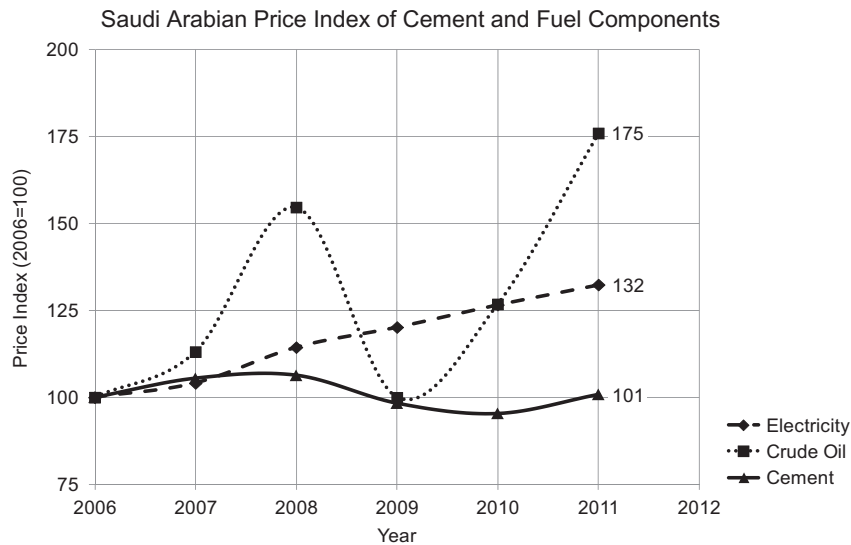


Figure 12. Saudi Arabian cement and fuel component price trends.

there is an expectation that cement market prices will also recover.

4.3. Qatar production and price indices

In Qatar, the first of two Gulf Cooperation Council (GCC) countries examined in this paper, the trends governing cement price are somewhat different. Qatar is notable for having 4.24 tonnes of cement consumption per capita, the highest in the world (Al Jazira Capital, 2011). Oil and natural gas are the dominant fuels used in cement production. Qatar's cement industry statistics (2006–2011) are plotted in Fig. 11 for the indexed cost of electricity and crude oil used in production against the indexed cost of cement (Qatar Statistics Authority, 2013; NBK Capital, 2010). Qatar, as a major producer of natural gas, has stable fuel costs for electricity generation. The Qatari government has also set a maximum price for the sale price of cement. All of these factors ensure stability at times of instability, such as the crude oil price peak of 2008 attributed to 'Peak Oil' (Financial Times Lexicon, 2012); this enabled the cement industry to weather the slowdown in construction triggered by the global financial crisis.

Yadullah Ijtehadi identified eight emerging trends that are expected to dominate cement production in the GCC (Ijtehadi, 2011). Trend (8) suggests that the future focus of Qatar, as hosts of the 2022 FIFA World Cup, is sports development. Plans in the pipeline for the intervening decade include the construction of sports stadia, new hotel accommodation, airports, ports and numerous leisure and recreational developments; cost ~US\$ 230 billion. As a consequence, Qatar will face a cement shortfall from 2013 that could, according to some sources, exceed 3 million tonnes per annum by 2015. This will drive up the cost of cement due to a combination of construction material

and labor shortages. The other trends are (1) Gulf cement profits rising, (2) UAE construction sector rebound, (3) UAE companies facing difficulties as a consequence, (4) Saudi clinker capacity rising, (5) Saudi fuel shortages, (6) Saudi export bans and price manipulation, and (7) Kuwait cement prices declining.

4.4. Saudi Arabian production and price indices

The biggest cement producer in the GCC is the Kingdom of Saudi Arabia (KSA). Their cement industry pricing statistics (2006–2011) are plotted in Fig. 12 for electricity, crude oil and cement (Al Jazira Capital, 2011). KSA has suffered dropping cement prices since 2008, but the trend was reversed with an increase in cement prices by 5.4% in the 3rd quarter of 2011. This is mainly attributed to increased demand as reflected by higher volumes of cement sold.

KSA construction activity witnessed an increase as government tendered and implemented more government contracts; In March 2011, the King decreed the construction of half a million new housing units, building of new hospitals and the injection of capital into specialist credit institutions to facilitate debt write-offs and increase mortgage lending. This has boosted the demand for cement and the trend is expected to continue.

4.5. Comparison of price trends

The UK, US, Qatari and Saudi Arabian cement price data in Sections 4.1–4.4 has been presented for different base index years. Simultaneous comparisons of price are, in any case, not possible without knowledge of the monetary price of a tonne of cement in each country, local energy prices, wage structures, taxes, currency exchange

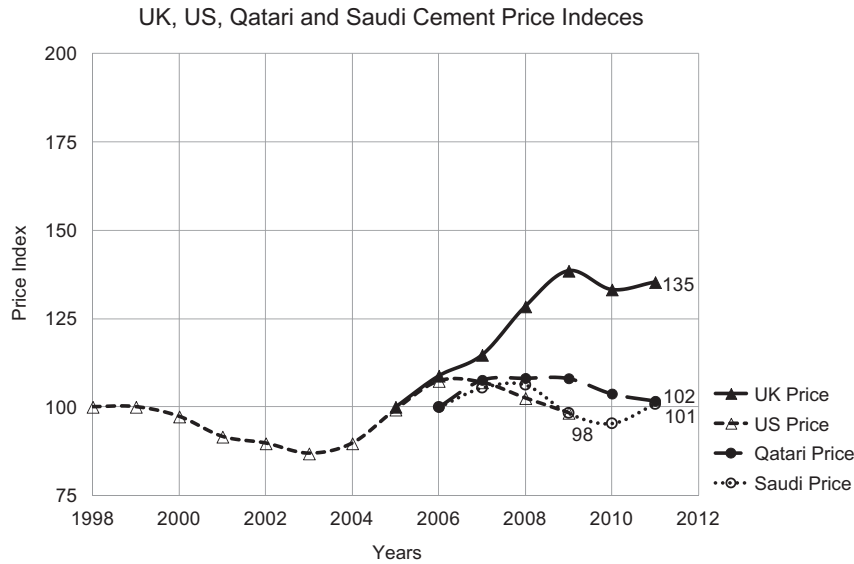


Figure 13. UK, US, Qatari and Saudi Arabian cement price index trends.

rates, supply and demand trends, etc. Indexed prices can, however, be compared directly to gain insight on overall market trends. Fig. 13 shows the change in cement price indices for the UK (2005 base) against the US (1998 base), Saudi Arabia (2006 base) and Qatar (2006 base). From 2005/6 onwards we see a parting of the way between the UK, where prices have continued to rise sharply, and the others where the general trend has been one of steady or declining prices.

At the end of 2005 one of the deadliest and most destructive hurricanes, Katrina, hit the Gulf States in the US. This was expected to result in a greater demand for cement but in reality it constrained demand and delayed cement deliveries (U.S. geological Survey, 2012). From 2006 to 2008 there were delays in new projects due to problems attributed to 2005 and to the drop in new home construction, both of which contributed to the decline in cement production. By 2007 the US was already seeing the start of tighter credit supply and decline in the housing market and mortgage rates. By 2008 in the private sector the pressure of a depressed market and the economic crisis (the credit crunch) were in full swing; the lack of State funding to reduce property tax revenues made matters worse. During this time the US cement industry saw the closure of three old production plants and the construction of two new ones. The price of cement in the US fell to compensate for delays in projects and the recession; by lowering the price of cement a smaller but sufficient profit was made, effectively compensating for the decrease in production and cement sales. In 2009 a further 14 cement production plants were closed in the US and cement production reached its lowest level in 12 years.

In contrast, the massive construction booms in KSA, and Qatar over the same period, have helped the cement sector to consolidate, expand and increase its profitability

– while at the same time keeping cement prices in check. In Qatar, cement prices have remained steady due to the government cap, with prices averaging US \$68.7 per tonne. KSA, on the other hand, achieved the same objective while continuing to have the edge over other GCC countries due to the favorable cost structures that benefit its cement producers; specifically, access to fuel at artificially low prices from the government, the ready availability of raw materials (limestone, primarily) and strong domestic demand. Energy and raw material account for around 32% and 29%, respectively of the total production cost of cement in KSA. At the end of 2011, the cost of cement in KSA was US \$64.6 per tonne, with Saudi cement manufacturers maintaining and enjoying gross profit margins above 50% compared to the GCC average of 30%.

The difference is in part due to the dampening effect of the economic crisis. In the UAE in 2010 roughly 50% of building projects were put on hold. The result was stagnation of the cement market in the UAE and flooding of other GCC markets with cheap (at cost) cement as excess supply from UAE producers effectively depressed cement prices in small, neighboring countries. The decline in sales, demand and profits continues today to put pressure on cement producers in the UAE, where the gross profit margin averages only 15.5%. Lafarge and Holcim, two of the world's largest cement producers, operate at a gross profit margin of 26.7% and 42.8%, respectively. (Al Jazira Capital, 2011).

The story in the UK, which over the same period has seen a 35% increase in cement prices, is different. UK prices are also significantly higher than in the US and GCC region. The cost of cement in the UK in 2008 was approximately GBP £70 per tonne. In the US Qatar and KSA the corresponding costs were approximately US \$85 (GB £46), Qatari Riyals, QAR 262 (GB £36) and Saudi Riyals, SAR

234 (GB £34) per tonne, respectively at the prevailing exchange rates. Cement was thus 34%, 48% and 51% cheaper in these countries (Taken, 2013).

The escalation in price of UK cement from 2005 onwards (Trout, 2011) is now summarized:

2005: Prices in 2005 were pushed up by a combination of fuel costs and regulatory factors; cement prices in January 2006 rose by GB £5–6 per tonne. CEMEX explicitly stated that higher kiln fuel and electricity costs were being recovered through higher pricing.

2006: Prices of building materials generally rose by 2.9% in the first half of 2006, but bricks were up by 6% and cement was up by 8%. The upward trend continued when, in September 2006, Lafarge announced a 15% rise in the price of bulk cement from January 2007.

2007: In 2007, escalating prices led to the British Aggregates Association (BAA) commissioning Cartel Damage Claims to investigate cement makers for giving preferential treatment to their associated concrete businesses. The UK Office of Fair Trading investigated reports of discriminatory pricing in March 2007 that were rejected by the cement manufacturers. It had become increasingly clear that higher costs were in general being recouped from customers. The price increase of cement products during 2007 was 6–7%.

2008: At the start of 2008 the rising cement price trend was all too obvious. A calculation by EC Harris suggested cement-based building materials had experienced inflation of 7.9% during the 12 months to February 2008. A 10% rise since January was reported in August 2008. In October 2008 the annual figure had risen to 14.5% according to the Department for Business, Enterprise and Regulatory Reform (now the BIS), but that masked a slow-down to 4.7% in the latter six months as the recession started to bite.

In May 2008 an appeal by cement producers against a cartel lawsuit was rejected in Germany. In November 2008, a European Commission investigation into a suspected price cartel allegedly maintained by the multinationals: Lafarge, Holcim, Heidelberg Cement, CEMEX and Dyckerhoff was given a great deal of publicity. No case was brought against cement producers in the UK, however.

2009: Prices continued to rise into 2009 but unevenly; attempts to inflate prices to compensate for falling volumes could not last. Lafarge reported price rises of 8.6% raising the index figure from 130.6 in December 2008 to 143.3 in February 2009. Monthly levels declined steadily thereafter as a reflection of market weakness.

2010: During 2010 the annual cement price average showed a decline for the first time in years. The decline was modest and in fact the price of cement remained remarkably steady throughout the year compared to the index of 134.6 in November and December 2009. Lafarge reported ‘pressure on pricing’ in 2010 and looking ahead, at the turn of 2011, Hanson foresaw ‘downward pressure on prices’ in Europe. Holcim’s chief executive also warned that cement prices would be kept under pressure by the market.

2011: UK cement prices proved to be relatively flat in the UK in 2011 according to the government index. In May 2011 the price was informally said to be around GB £90 per tonne, rising to GB £96 per tonne of Ordinary Portland compared to GB £102 per tonne in May 2010 (David Langdon, 2012). The cost of UK cement is 2–3 times higher than US, Qatari and Saudi Arabian cement.

2012: Indicatively, in March 2012 the Competition Commission in Johannesburg reached a settlement with Lafarge Industries South Africa in which the latter admitted to taking part in a price-fixing and market division cartel involving the main cement producers in South Africa. Lafarge agreed to pay a penalty of Rand 148,724,400 (GB £10.41 Million), or around 6% of its 2010 annual turnover (fin24, 2012). Similar practices and outcomes have been reported in connection with other cement manufacturers operating in India, Ghana, Trinidad and elsewhere.

4.6. Projections of future economic factors governing cement production

The UK is the first country with “legally binding targets for greenhouse gas emissions beyond 2020” (Trout, 2012). A carbon price floor of GB £16 per tonne of CO₂ was introduced from April 2013 and this is expected to rise to GB £30 per tonne in 2020. The introduction of the carbon price floor was immediately opposed by industry as the costs were so high and compensation was requested. In November 2011 it was announced that a package for energy intensive industries, such as cement, to the value of UK £250 Million would be available to help with high energy costs and the carbon price floor plan. The package would also help to raise the green taxes that were announced in 2012. It is estimated that the UK will pay an extra €36 Euros per megawatt hour (MWh) of electricity by 2020 with the introduction of climate change policies. This compares with €22 Euros in Germany, €20 Euros in Denmark, €19.3 Euros in France and the equivalent of €12.7 Euros in China. (Global Cement, 2012). The differences raise one of the core problems of any green or carbon tax in a global economy – i.e., if your neighbors do not have the same tax as you they can undercut you. Similar arguments exist in Australia and the US.

According to the Mineral Products Association (MPA), the cement industry does not meet the requirements for the first €140 Million Euros of this package because support for the sector is not permitted under the EU emissions trading scheme. What is also of concern is that the UK, had production levels not been low due to the recession, would have missed its own emissions targets. Since 1990 emissions in the UK have dropped by 25%, but the UK will undoubtedly miss the targets that have been set for the next twenty years. It is clear that some dramatic changes are needed to make the cement industry, both in the UK and globally,

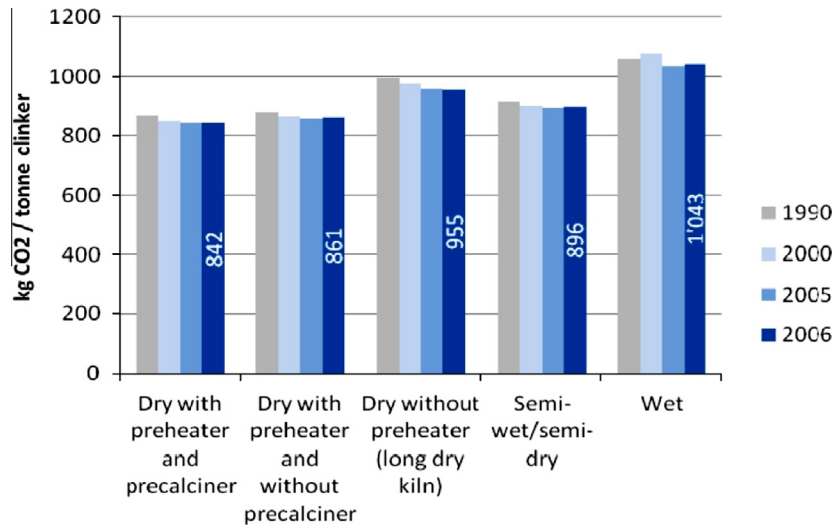


Figure 14. Global gross CO₂ emissions per tonne of clinker per kiln type.

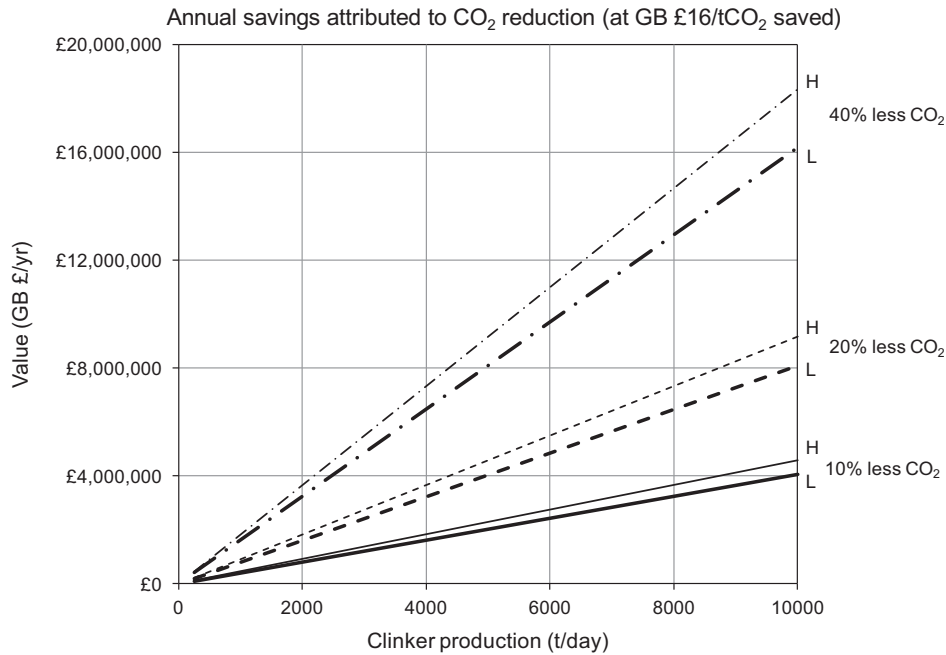


Figure 15. The value of carbon emission reduction in gross cement production.

less energy intensive and more sustainable. The proposal is that, through investment in alternative fuels and novel cement technologies such as those that have been outlined in Sections 3.1–3.3 of the present paper, the cement industry can achieve lower CO₂ emissions, reduced costs and increased profitability, and at the same time pay less in green taxes. Progress to date in stemming carbon emissions from cement production are summarized in Fig. 14 (World Business Council for Sustainable Development, 2009).

Given that the majority of kilns are of the dry type (with or without preheater and/or precalciner), the range of CO₂ emissions (*E*, in tonnes of CO₂ per tonne of clinker) lies somewhere between 0.842 (*L*) and 0.995 (*H*) tonnes of CO₂ per tonne of clinker produced. Using the UK carbon

price floor (*CPF*, GB £16 per tonne of CO₂ from 1st April 2013, rising to £30 in 2020), percentage carbon emission reduction (*R*, %), plant size (*T*, tonnes of clinker per day) and the number of days (*D*, days) of plant operation per year, it is possible, to determine the annual monetary saving (*S*, GB £ per year) that can be achieved. The required linear expression, which can be used to inform early investment decisions, is of the form:

$$S = CPF \times D \times E \times R \times T \tag{1}$$

The range of savings (*S*) from 10%, 20% and 40% CO₂ emission reductions (*R*) as a function of plant size (*T*), assuming *D* = 300 days per year, is conveniently presented in Fig. 15. These recurrent, annual savings can be

amortized by the plant owner over a period of years to determine either the total savings that would go toward funding the improvements needed to deliver the savings, or alternatively the length of time needed to pay back the investment.

Thus, a 6,000 tonnes of clinker per day cement plant owner aiming to reduce emissions by 40% would save approximately GB £10 million per annum to invest. This sum could be amortized over 5 years to cover the cost of GB £50 million of investment in plant upgrade, or pay back GB £100 million pounds in 10 years. Beyond these periods, all long-term savings can be used to boost the bottom line and improve profitability without increasing product cost. The capital cost of the aforementioned plant, built to modern standards and assuming a unit cost of US \$230 per tonne of clinker production per annum (Ingenieros, 2013), would be around US \$180 million. In this context, savings of US \$50 or \$100 million are substantial. It should be noted that in this analysis, bank interest and service charges (which are historically very low) and potential tax incentives (which vary from country to country) have not been considered, but that is easily remedied before a commitment to invest is made.

5. Conclusions

It is clear that cement, in all its different types and forms, is a vital product that, combined with other ingredients in the correct ratio, makes it a key construction material. Concrete is a prime example of a cement-based construction material. The demand for concrete is high, increasing and recognizes no borders. This will continue to be the case for the foreseeable future.

In order to ensure sustainable, cost-effective but still profitable cement production in the second decade of the 21st century, the industry needs to change. The two most important challenges facing the industry are a pressing need to reduce CO₂ emissions and improve energy efficiency. Some of the remedies have been outlined in this paper, but more research is needed. The most effective methods of producing green, environmentally and economically sustainable cements of the highest quality are (a) the use of alternative, low carbon fuels and (b) development of novel cement formulations and production methods.

Alternative fuels derived from waste are currently being used in some parts of the world, helping to reduce energy costs, generate income and reduce landfill, but not all alternative fuels reduce CO₂ emissions. The use of other fossil fuels such as biomass, on the other hand, can be an effective fuel substitute, producing CO₂ emissions that are about 20–25% less than those of coal. However, the IEA's predictions suggest that it will only be economically viable for the cement industry to use biomass sourced alternative fuels until 2030; it remains to be seen if other alternative low carbon fuels can be found or developed before then.

A large fraction of the CO₂ that is released in the production of Portland cement is from the calcination process itself; it is a byproduct of the firing of calcium carbonate

and silica in a rotary kiln to produce calcium silicate (clinker) and carbon dioxide. It is therefore conceivable that a more permanent solution to achieving carbon reduction is to use different raw materials and/or different manufacturing processes. These are subjects of major research initiatives worldwide, most of which generally remain shrouded in secrecy, but there should be no doubt that the race to develop the next generation of cements is underway.

C\$A cements use limestone as one of the raw materials in their production but offer a 20% reduction in CO₂ emissions by requiring a lower kiln firing temperature and therefore burning less fossil and fossil-derived fuels. The production of C\$A cements in operational plants is possible as the manufacturing process is the same – its use in China dating back to the 1970s is testament to this. There are fewer costs associated with plant conversion. However, some of the raw materials used in the production of C\$A cements have been identified as being more expensive, but this downside is potentially outweighed by savings on carbon taxes. This makes C\$A the most viable alternative to Portland cement at this time; although the development of robust internationally recognized regulatory standards for these cements are required.

Novacem's carbon-reducing cement, still in the early stages of development, perhaps held the greatest promise for entirely eliminating CO₂ emissions from cement production. However, given the uncertainties of availability of the right type of magnesium silicates, the large capital investment required to obtain magnesium oxide, unanswered questions relating to long term strength and durability and the fact that Novacem Ltd recently went out of business, the barriers to further development of the Novacem process continue to be significant if not insurmountable.

With new ownership development may resume and further progress may be made. However, the problems of integration with operational cement plants and substantial start-up costs are likely to be significant, so this novel cement could eventually be overlooked. Other carbon negative cements and processes, such as the one developed by Calera Corporation, are also early stage.

As discussed in Section 4 of this paper, there are many economic factors that can adversely impact growth of the cement industry. In recent years, decreases in cement production combined with sharp rises in energy costs have caused the price of cement to fall in some cases and rise in others, the common thread a desire by cement producers to stay in business. Focusing on the latter, since 2009 the UK has experienced a recession that saw a reduction in construction projects which in turn contributed to a decline in cement production, with the cost of this presumably passed onto consumers. In 2012 it was evident that the UK economy had not fully recovered and that a "double-dip" recession was the likely outcome. As a consequence of this, cement production has not reverted to its previous highs although it is expected to gradually restructure and grow in 2013.

An important pre-requisite for investment in new, low carbon cement technologies, is price stability. This is the silver lining that manufacturers in Qatar and Saudi Arabia can benefit from as a consequence of government subsidies and in the US as a consequence of a combination of a Hurricane Katrina and the economic crisis.

One very important development that will affect the cement industry's future in the UK is the introduction of a carbon tax on emissions and introduction of a carbon price floor in April 2013. It is likely that other countries in Europe and worldwide will introduce similar measures aimed at carbon emission reduction. This is a double-edged sword, bad in both cases if cement producers do nothing to change, but potentially a great opportunity and win-win situation if all of the changes required to deliver deep cuts in carbon emissions are made, improving the long term sustainability and profitability of cement production in this and other countries.

In the do nothing scenario the cost of production will increase significantly as cement production continues to emit large volumes of greenhouse gases into Earth's atmosphere. There is still a huge demand for cement and the industry contributes greatly to the economy and employment prospects of its host nations. But without change, the cement industry will decline.

On April 16th of this year, the Saudi government, in response to a severe shortage of locally produced cement, ended the ban on cement imports and announced its intention of allowing 10 million tonnes of clinker to be imported in the next 12 months (*Global Cement Weekly*, 2013). The source of this cement is not known although it may be significant that on the same day, Iran announced that it had exported ~13 m tonnes of cement over the past 12 months. Clearly, Iran has surplus production. This is an excellent example of local demand temporarily exceeding local supply, and the benefits that flexible cross-border trade in cement can help to fill the gap.

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