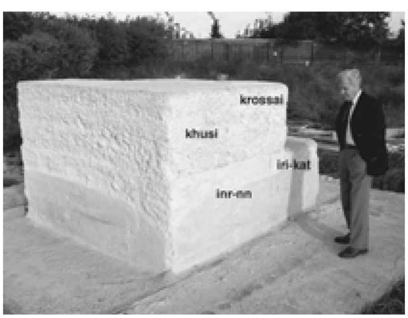
20 Cement

Cement is the second of our five key materials emitting almost as much CO_2 as steel—in fact steel and cement drive nearly half of all industrial emissions. Cement is the ubiquitous building material of the world, with most demand in the most rapidly developing countries. What fraction of these emissions can we save by energy and process efficiencies, and what else could we do?

We haven't managed a really good conspiracy theory yet, so now's the time: they may have been trying to deceive us about how the Great Pyramid of Giza in Egypt was made … Of course we all know that in fact it was made around 2560 BC by slaves carving blocks out of rock, rolling them on wooden poles under the watchful eye of Elizabeth Taylor, and heaving them up with hemp ropes while singing the chorus of the Hebrew slaves from Verdi's Nabucco … but maybe that's just a cover-up—because actually it could have been much easier than that. For at least some of the blocks, all they needed were moulds and buckets because they're not rocks at all—they're just blocks of concrete poured into moulds to look like rock.

The Great Pyramid of Giza: carved or poured?



Dr. Davidovits standing before four blocks of 'pyramid' limestone concrete, totalling 12 metric tonnes[25]

This very interesting theory was proposed in the 1980's by Dr Joseph Davidovits, a materials scientist working in France, and has not been widely accepted by Egyptologists, but the debate is still very much alive. In 2006, an academic paper by Professor Michel Barsoum at Drexel University in Philadelphia, and two colleagues, provided detailed analysis of samples of material from the pyramid[1]. The pyramid samples contained a high density of very small grains of material with high silicon constituents, none of which were found in the limestone found in the area. Professor Barsoum and colleagues deduced that this would occur if the pyramid material had at some point been a solution (in water) and the small grains had formed as part of the chemical reactions during solidification of what must have been an early cement. Professor Barsoum and co. are very careful not to overstate their results, and other authors have subsequently argued against them. But, if they're right then, as they conclude, they have found that the Egyptians had discovered how to make a very sophisticated lime based cement that has survived for nearly 5,000 years.

3,000 years later, and we know for sure that the Romans were using cement: the dome of the Pantheon in Rome, originally designed for Marcus Agrippa in about

The Pantheon Dome

Roman ruins in front of Mount Vesuvius

The Great Wall of China

AD 31, but rebuilt by Hadrian around AD 126, was made with about four and a half thousand tonnes of Roman concrete. The strength of this concrete has been tested to be not less than half that of modern concrete made with Portland cement. We know about the production of Roman concrete through the writings of Marcus Vitruvius Pollio, whose "De Architectura" from about 25AD, gives details of lime mortars and the ratios in which they should be mixed with small stones to form concrete for different applications. The word 'concrete' itself comes from the Latin 'concretus', meaning 'compounded'.

The basis of both the postulated early Egyptian cement and the definite Roman material is limestone (largely $CaCO_3$): when it is heated to 1000°C in a kiln, carbon dioxide is released to leave behind 'lime' (CaO). This is then mixed with water and sand in certain proportions to make mortars which harden when exposed to the atmosphere as carbon dioxide is reabsorbed. Mortars made in this way are called 'non-hydraulic' as they must be exposed to air to set, i.e. they cannot set underwater.

Around 100 BC the Romans discovered that they could make a much stronger mortar if they used sand from the slopes of Mount Vesuvius, and what's more, it would set underwater. This was because this 'sand' was in fact fine volcanic ash, which contained silica and alumina that combine chemically with the lime to give a 'hydraulic' mortar which, when mixed with water, sets in a chemical reaction called 'curing'. Though the Romans did not understand the exact chemistry of the new material, they used it for over half a millennium, even trying (unsuccessfully) to reinforce it using bronze bars. Most of their knowledge was lost with the fall of the empire, and we reverted to using predominantly non-hydraulic lime cement for the next thousand years. Most of Europe's royal palaces, Cambridge's colleges, the fabulous 12th Century rush of French cathedrals and the Great Wall of China are held together with lime cement (though apparently the ancient Chinese added in sticky-rice to improve strength)[2], and it was not until the mid-18th Century that serious efforts were made to improve upon the traditional formula. In particular, the search for better cement was motivated by the limited strength and slow setting time of non-hydraulic cement, and the fact that it couldn't set underwater.

John Smeaton, who was commissioned to build the third Eddystone lighthouse, conducted a survey of available options to find a strong cement that would harden sufficiently between tides that it would not be washed away. He concluded that limestone containing clay (which has the important silicas and aluminas in it) gave the desired results and achieved a cement comparable to what the Romans had used, so that the foundations of 'Smeaton's Tower', completed in 1759, remain

A masonry footbridge

Smeaton's tower

to this day (the tower itself was dismantled and moved in 1876). Smeaton did not develop his findings further, so no progress was made for 30 years until Rev. James Parker noticed that certain stones found in clay, once burnt, could be ground up to make a 'natural cement' that was strong and hydraulic, but set quickly (within 15 minutes). This setting time was too rapid to allow accurate block placement, and the natural cement had such low initial strength that it required support for many weeks. It was therefore mainly used for external plaster, to give a stone appearance to brick walls. Natural cements became popular, but were of variable quality and this triggered experiments by Louis Vicat in France, aiming to emulate its composition artificially. This was what Joseph Aspdin had in mind when, in 1824, he took out a patent for 'Portland Cement' (so called because it looked like the prestigious Portland stone used on building façades). Around twenty years later, amidst much secrecy, his son William found that by increasing the temperature and limestone content of his father's process he could produce a cement that overcame the problems of rapid setting and low initial strength and 'Ordinary Portland Cement' as we know it was born[3].

In masonry construction (building from blocks, such as stone or bricks), we bond the blocks with mortar—cement mixed with sand and water. An alternative, and the starting point for this chapter in Egypt, is to mix small blocks or stones into the mortar, to create a sludgy liquid that can be poured into a mould: concrete.

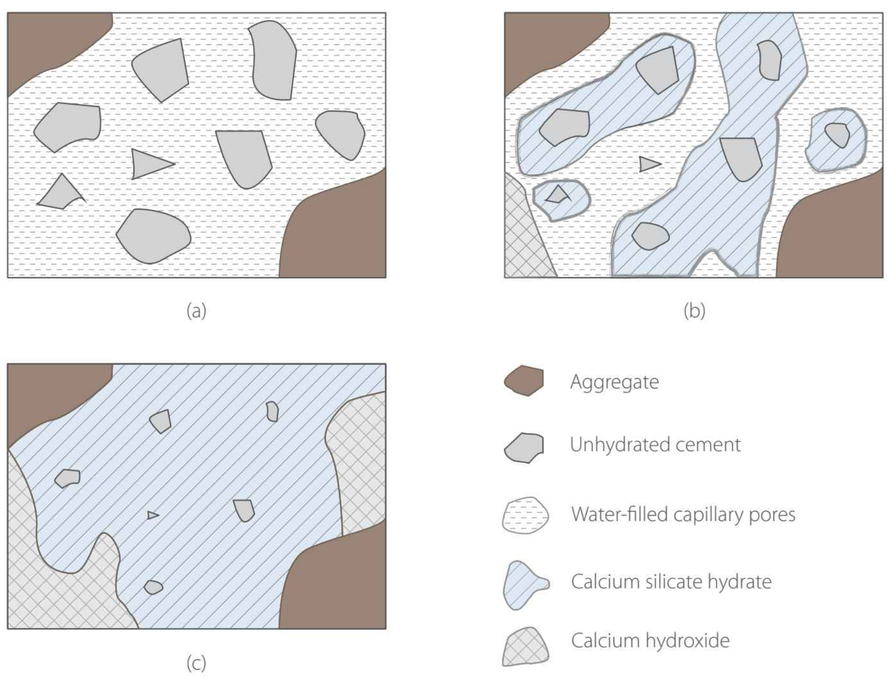


Figure 20.1—**The Portland cement reacts with water to form calcium silicate hydrate (C-S-H) gel which 'grows' out in spike shapes to link in with other particles and aggregate**

Concrete must be mixed in precise proportions, as Vitruvius knew: some of the proportions specified in his books are similar to those used today. The small stones (either gravel or crushed stone) and sand should have an even range of sizes so they nest without large gaps and the required chemical reactions can form the microstructure shown in Figure 20.1. The aggregates (small stones and sand) make up 70–85 % of the concrete by mass. They have low embodied emissions (the energy required is for mining, crushing and transportation only), so the figure for embodied emissions in a kilogram of concrete, typically 0.13 kg, is much lower than that for cement, and just over half that of a clay brick[4].

Pouring reinforced concrete

Cement, mortar and concrete are ceramics, so the atoms within their structure are bonded in a different way to those in metals. We discussed in chapter 3 how metals deform by the movement of dislocations, which can move because the atom to one side of the dislocation can form a new bond with atoms to the other side. However in ceramics this shifting is not possible: to use a rather violent variant of our analogy of the Chinese Dragon being pulled up the steps, the shoes of the ceramic dragon are glued to the steps so powerfully that as the force builds up on the man behind the empty step, he can't step forwards and eventually his legs break! Thereafter he can't make any further contribution to the Dragon's pulling power, so the force on the man behind increases and his legs break too, as do all remaining legs, and the Dragon has no remaining strength. This is called 'fast fracture' in the world of ceramics as a result of which all mortars and concretes are strong in compression but weak in tension. Early structures built from masonry bonded by cement were therefore designed to experience compression only, and this led to classic stone arched bridges, and the wonderful design of King's College Chapel. Compression is assured in the Chapel because loads are resisted by a 'line of thrust' in the form of an inverted catenary (the shape that a necklace of beads will adopt if hung loosely between two horizontally separated points) which is entirely encapsulated within the buttresses and roof supports.

King's College Chapel experiencing compression

However, the advent of Bessemer's steel making process opened up a new opportunity for creating structures with concrete that could withstand both compression and tension—and therefore require less material overall. Steel is strong in both compression and tension, so if a concrete beam will experience bending (as happens in virtually all buildings) thin strong bars of steel (reinforcing bars) can be placed on the lower side of the beam to withstand tension forces, while concrete elsewhere supports the compressive loading. That these two common materials are so compatible is remarkable: they stretch similar amounts when heated (this was where bronze failed the Romans), bond well together and while the steel gives concrete tensile strength, the concrete protects the steel from its main weakness,

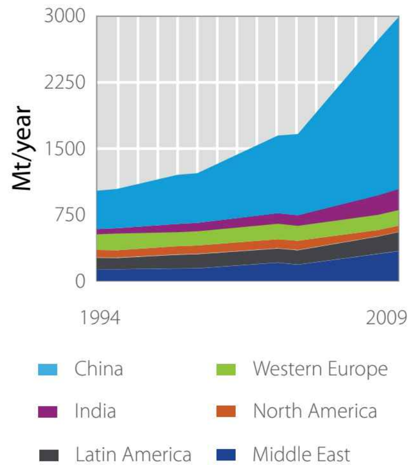


Figure 20.2—**Global cement production over time by region**[6]

corrosion. This composite (mixture of two materials) form of construction is now universal and today nearly all concrete is used in conjunction with steel reinforcing bars. No wonder that with global cement production around 2,800 Mt per year, equivalent to about 23,000 Mt of concrete[5], we found that steel reinforcing bars, with 271 Mt per year, are the largest single application of steel.

In this opening section, we started from the ancient Egyptians and have followed the evolution of cement, from lime based compositions to contemporary Portland cement. We've seen how cement is mainly used to make concrete which in turn is used with reinforcing steel as the world's primary building material. So now we're ready to begin our exploration of the present and future emissions associated with cement. In the next three sections we'll first examine demand for cement, then we'll look at the energy and emissions associated with its production to see whether it can be made more efficiently, and then we'll review opportunities to use less cement in future construction.

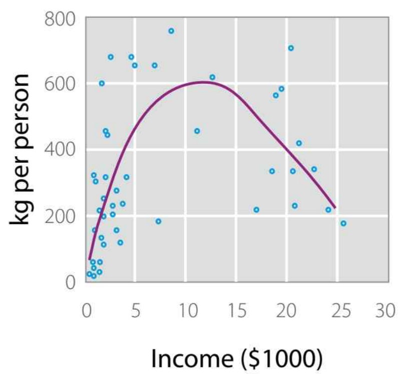


Figure 20.3—**Cement consumption per capita vs. GNP per person**[7]

Patterns of demand for cement

After Aspdin developed Portland cement in the mid-19th Century it was used in buildings around the UK, despite the initial high cost of the material (due to the cost of energy required to initiate the high temperature reaction). However once William Wilkinson, a builder from Newcastle, patented reinforced concrete in the second half of the century, concrete rapidly overtook other materials, particularly for construction of infrastructure and larger buildings: compared to building with bricks and stones, concrete which can be poured, is relatively cheap, easy to handle, and allows rapid construction. As a result, Figure 20.2 shows that recent global demand for cement has shot up. It was 10 Mt in 1910 and reached 600 Mt by 1970 and is over 2800 Mt today. The colours of Figure 20.2 showing demand by region demonstrate how cement-use relates to economic development: North American and European demand stagnated from the 1970's to 1995, while Chinese demand in particular has expanded at a phenomenal rate. For most countries, the largest end-use of cement is for infrastructure, with domestic housing next and the rest split evenly between other building types.

When we forecast future demand for steel and aluminium in Chapter 4, we noticed that developed countries appear to reach a plateau of stocks per person, after which demand is mainly for replacement goods, and old goods are recycled. There is no recycling route for cement, so no motivation to analyse stocks, however there is a connection between national demand for cement and average national incomes.

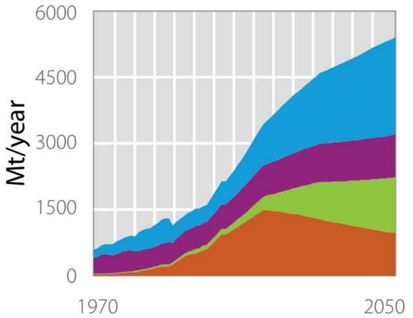


Figure 20.4—**Forecast growth in demand for cement by 2050**[8]

Company	Global share (2003 %)
Lafarge (France)	5.5
Holcim (Switzerland)	5.0
Cemex (Mexico)	4.3
Heidelberg Cement (Germany)	2.5
Italcementi (Italy)	2.1
Taiheiyo (Japan)	1.6

Table 20.1—**World market share of leading cement companies**[9]

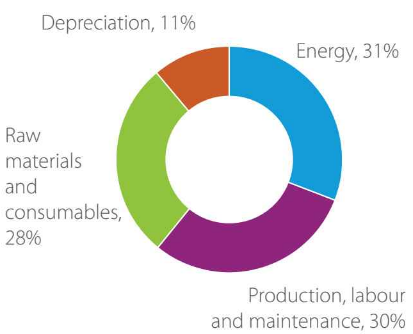


Figure 20.5—**Breakdown of costs in cement production**[10]

Figure 20.3 demonstrates that demand grows as national income grows to around $10–15,000 per person, but then declines, when demand for new buildings and infrastructure has been satisfied. This insight has been used with estimates of regional economic growth rates, income levels and population growth to forecast future demand. It is no surprise that cement use in China and India is expected to drive global demand between now and 2050. Most predictions agree that global cement demand will be between 4,500 Mt and 5,500 Mt by 2050 but it is unclear whether we will have reached 'peak cement' by then, as estimates for the latter half of the century vary substantially.

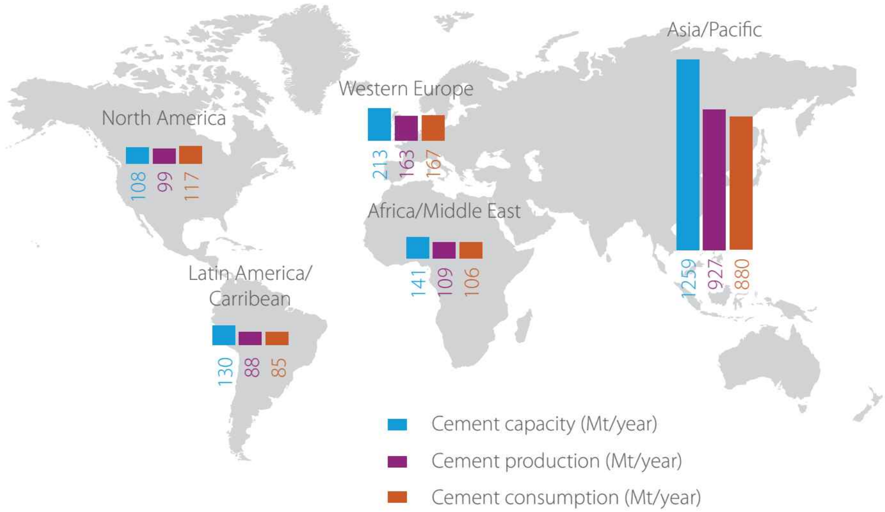
The raw materials required to make cement are well distributed across the planet, and because it has a low value by weight, relatively little cement is traded internationally: Figure 20.6 shows that the major continents produce most of their own cement. As a result, the industry is quite fragmented: Table 20.1 shows that the largest six cement companies supply only one fifth of global demand.

Figure 20.5 shows a typical breakdown of the costs of cement production. The industry has a high output per person, and has become significantly more productive in the past 30 years, as seen in Figure 20.7. Globally around 800,000 people are employed in making cement. Two thirds of them are in China, although they produce only 40% of the world's cement because small factories using older technology remain common.

Cement with one eye open: energy and emissions now and in the future

The production process for Portland cement has changed little since Aspdin invented it, and is shown in Figure 20.8. Limestone, clay and sand are collected and ground up, then mixed heaed to 1450°C in a kiln which causes chemical reactions that form pellets of clinker. Together with a small amount of gypsum, this is then ground finely to make cement. The hot stage of this process is the source of most emissions, both because energy is required to raise the temperature, and because the chemical reaction which converts limestone to lime releases carbon dioxide. In fact, half of the emissions from cement production are released in this reaction, with a further 40% from burning fuel for heating, and the remaining 10% is split evenly between grinding and transportation[12].

Figure 20.6—**Global cement capacity, production and consumption**[11]



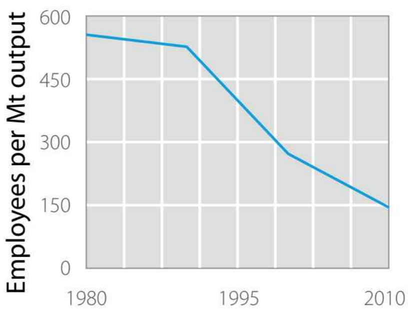


Figure 20.7—**Historical improvements in productivity in cement production**[11]

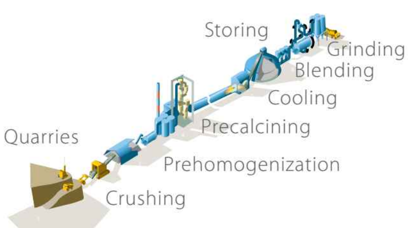


Figure 20.8—**Cement production process**[26]

As with steel and aluminium, we can start our search for future energy efficiency in cement making by calculating the minimum energy for the chemical reaction. The decomposition of calcium carbonate (limestone) into lime and carbon dioxide is the largest of a series of reactions. In total we can predict a minimum theoretical energy requirement of 1.8 GJ/tonne[13] and best practice is already remarkably close to this at 2.9 GJ/tonne, so we cannot expect much further improvement. Cement is so close to its theoretical limits because, in comparison with steel and aluminium, producing cement requires fewer, simpler inputs and demands less purity.

Although best practice in cement production is only 50% over the theoretical limit, the global average is around 4.7–5.5 GJ/tonne, almost double best practice. This wide range is because of extensive use of older, less efficient equipment, especially at cement factories in China and India. Many of these factories use the 'wet' process in which, during preparation, the raw materials are mixed with water which must later be evaporated at high energy cost. Also, older plants do not have the sophisticated heat recovery systems of modern ones in which exhaust gases heat incoming material. Global average energy use should improve quickly as older plants are replaced, and this is occurring rapidly in China[14].

The cement industry is pursuing two other opportunities for efficiency, both based on substitution—of fuel and of clinker. Cement kilns can burn waste as a substitute for fossil fuel because they operate at a high temperature and the presence of limestone helps to clean the exhaust gases. Substituting waste for fuels reduces emissions, although the magnitude of the reduction depends on the precise exchange. This approach is popular in Europe, and some cement producers claim to have substituted all of their fuel with waste.

Portland cement itself can also be substituted, at least partially, with other materials[15]:

- Ground granulated blast furnace slag (GGBS), a by-product of the blast furnace, adds long-term strength and durability to cement at the expense of lower initial strength and slower curing. Current production of GGBS is approximately 200 Mt per year and will increase in line with steel production.

- Pulverised fly ash (PFA) is a waste product from coal power stations that improves concrete workability and long-term strength but decreases initial strength. Current production is around 500 Mt per year.

- Pozzolans arise naturally (for example as volcanic ash) or artificially (for instance in calcinated clay) and can substitute up to half of cement requirements in some applications. During curing they react with water to improve durability and workability, again at the cost of reduced initial strength. At present 150 Mt per year of natural pozzolans are used in cement production. Artificial pozzolans are energy intensive so not widely used and do not provide the same environmental benefits as the other substitutions.

- Limestone can be ground up finely and used as a replacement for Portland cement. This improves workability but reduces strength and durability. Limestone is widely available in large quantities.

Limestone rocks

We've seen that four forms of substitution can offer improved performance and cost reductions, so occur already: on average 10-20 % of cement is replaced this way at present, and this is likely to increase. However with global cement production already greater than 2,850 Mt per year and with annual supplies of GGBS, PFA and pozzolans totalling just 850 Mt, substitution cannot be applied without limit.

For steel and aluminium, recycling is a key energy efficiency strategy, because secondary production requires so much less energy than primary production from ore. However, to reverse the reactions that make cement, the theoretical minimum required energy is around 1GJ/t, so a practical cement recycling process would give little if any energy benefit and, as a result, cement is not recycled at all at present[16]. Instead, concrete is 'recycled' by crushing to make a type of aggregate, which could be used to make new concrete if mixed with new cement. This is not

Crushed concrete

recycling, but is instead 'down-cycling' old concrete as a substitute for aggregate. However the embodied emissions in aggregate are around 25 times less than those of the old concrete and extra cement may be required to bind the wider range of particle sizes in crushed concrete. Crushed old concrete is commonly used for the bases of roads or other infrastructure, and while this is a better destination than landfill sites, it is a waste of such a carbon-intensive product.

We explored carbon capture and storage (CCS) in chapter 10. Not surprisingly, for cement producers CCS is even more attractive than for steel-makers, because of the high and unavoidable process emissions in cement making. Many developments to allow separation of a pure stream of CO_2 from kiln flue gases are underway[17] however, all the concerns we raised in chapter 10 apply equally to sequestering CO_2 from cement production.

If Dr. Davidovits is correct then not only did the Eygptians discover an advanced cement much earlier than previously thought, they also discovered one with low embodied emissions. We don't know what the Pharaohs called their cement but Dr. Davidovits in the 1970s called it a 'geopolymer'. Geopolymers are made from compounds of aluminium and silicon (commonly found in the earth's crust—for example, kaolin clay was found in Eygpt). The compounds harden when mixed with an alkaline solution (such as lime mixed with natron, a salt that doubled as an early form of toothpaste) and strengthen at room temperature. Apart from (possibly) building pyramids, geopolymers have been commercialised on a small-scale but they are expensive and have not yet been tested in large-scale applications where strength is critical[18]. Several other novel cement technologies are in early stages of development with some developers making extravagant claims that their cement absorbs more emissions during its life than emitted during production. However there has yet been little if any independent validation of these claims, and the new cements have not been tested in service or shown to meet standards required in construction[19].

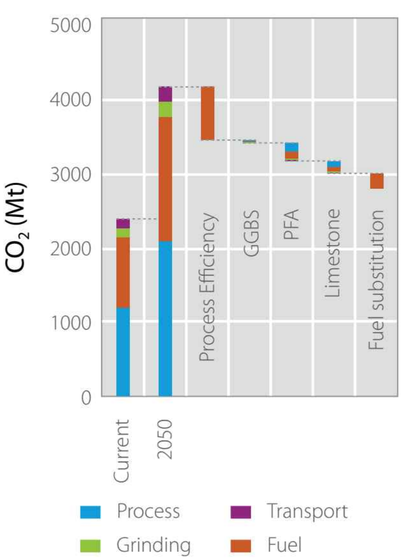


Figure 20.9—**Forecast for emissions reductions in the cement industry**

We've anticipated that demand for cement will grow by 75% by 2050, and looked at five options to reduce emissions associated with conventional cement production. Figure 20.9 shows the build-up of our prediction of how emissions will evolve to 2050. Given the economic advantages of upgrading to the best available technology, coupled with China's ambitious plans, we will bravely assume that global average energy per tonne falls to the level of current best practice, 2.9 GJ/tonne, by 2050. Similarly the economic advantages of substituting GGBS, PFA and pozzolans should drive a steady increase in their uptake to a maximum of 850 Mt/year, and we'll assume that limestone will replace 5% of the remaining cement (the level beyond which final performance suffers). We assume that the worldwide fraction of fuel substitution will increase to 17%, the current rate in Europe, and that this will reduce emissions from fuel combustion by the same amount..

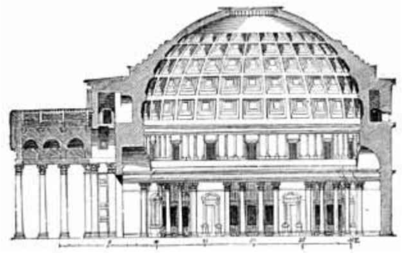
In summary, Figure 20.9 shows that if demand grows as anticipated, we can at best hope that absolute emissions from cement production will have grown by only 18% by 2050. This would be an impressive achievement, but our target remains a 50% cut by 2050, so we need to look at cement with both eyes open.

Cement with both eyes open: opportunities to use less cement to provide the same service

Our main work in preparing this book has been to look with both eyes open at the use of steel and aluminium—there has been so little attention given to material efficiency anywhere that we have invested most of our effort in gathering primary evidence about living well with less liquid metal production. So in this section, we'll take inspiration from what we learnt about the two metals, to identify parallel opportunities for using less powdered cement. We've found that this might be possible through using less cement when making concrete, designing structures that require less concrete, substituting other materials, delaying the end of life of concrete structures, and re-using concrete components after their first life.

We can use less cement by improving control of the amount used when mixing concrete. Strength is proportional to the amount of cement in the mix, so lower strength concrete should use less cement. Currently some control is applied, for example to give a lower strength mix for foundations and higher strength for the superstructure, but the concrete equivalent of steel rationalisation tends to favour use of fewer concrete mixes on a site, and hence over-use of cement.

Using less concrete through design has significant potential, and for inspiration we can return to the Pantheon in Rome which has the world's largest unreinforced concrete dome. To build it, the Roman engineers knew they had to minimise weight, so the dome thickness decreases from 6.4 m at the base to 1.2 m at the top, and they even left a 4.1 m radius 'oculus' (opening) at the very top of the dome. A great advantage of concrete is that we can pour into almost any shape, however for simplicity we usually use recto-linear moulds rounded up to the nearest 25mm. If we made optimised moulds we could use up to 40% less concrete in places[20].


A cross-section of the Pantheon dome

As concrete is only strong in compression, we should really only use it to resist compressive loads. Two strategies can be employed:

- In 'pre-stressing', a tensioned steel cable is used to compress the concrete. By eliminating tension, the full strength of the concrete can be used.
- We can remove concrete from areas in tension either with more advanced moulds, or by introducing pockets of air (or polystyrene) into a standard mould. This is another trick used by the Romans in the Pantheon dome.

Apart from purely structural functions, concrete also serves to protect steel reinforcement from corrosion, indeed a special 'cover' layer of 20–40 mm is specified outside the rebar purely for this purpose. We can reduce this layer either by guaranteeing more accurate placement of bars on site so that designers can cut their assumed margin of error[21], or by using stainless steel or plastic-coated rebar which requires even less cover—however as production of stainless steel leads to greater emissions than production of normal steel, this substitution will only be effective in particular cases.

It's possible to substitute other materials for concrete. The discussion in Chapter 3 showed that masonry, steel and timber are the main contenders:

- Masonry is a good alternative to concrete, being as strong and with lower embodied emissions. However, masonry must be bonded with mortar (made from cement), and cannot be reinforced or moulded into shape.
- Steel is an alternative to concrete in most applications (columns, beams, foundation piles), and unlike concrete it can be recycled. However it is more expensive and more emissions intensive per unit mass or per unit stiffness and must be protected against corrosion.
- Timber gives higher strength and stiffness per unit of embodied energy, however it is not as durable as concrete, so must be shielded against fire and rot. Commercial timber is surprisingly energy intensive because it is dried in kilns.


A few old masonry walls at Machu Picchu

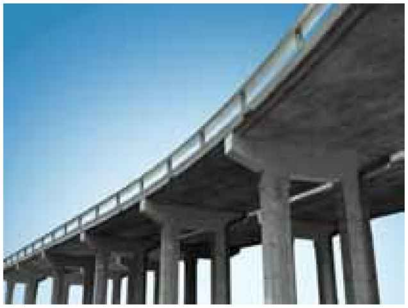
Properly designed and built concrete fails only under exceptional circumstances, for example when it is adjacent to corrosive chemicals in soil or water[22]. Therefore extending the life of concrete structures is an excellent strategy, and as we saw in chapter 16, we inevitably use the same approaches to extend the life of both reinforcing bars and cement.

St Peter's Basilica in Rome was built using reclaimed blocks from the Colosseum

Reusing concrete components is currently rare but would be easier were they to be made in standardised units that could be taken apart and reconfigured—like Lego blocks, Meccano and the Cambridge white bricks we saw in Chapter 15. The key challenge to enabling concrete re-use is to design connections that are strong in use, but can then be released to free the component blocks at the end of life. We have two options to achieve this:

- Chemical connectors, like the lime mortar in Cambridge houses, provide sufficient cohesion but can still be broken. Some work in Japan aims to develop advanced concretes that could be weakened to facilitate easier deconstruction[23].
- Mechanical connections create a physical interface between parts. In the US construction blocks, rather like Lego, are available with this type of connection. Further developments might create composite cement and steel blocks with steel-to-steel interfaces to permit dismantling and reuse.

These options to use less cement have significant future potential and we can also explore reductions in final demand for the services provided by cement. This would raise the same opportunities and issues as we found in chapter 17—but our impression is that the major opportunities for demand reduction will occur in buildings, as infrastructure such as bridges, are already in many cases used more intensely than anticipated in their original design, and are already built for long life.



A concrete highway bridge: has it been made well enough to last?

Outlook

Our exploration of cement in this chapter began with a remarkable theory about building Pyramids, and has taken us on a tour including the Pantheon in Rome and a lighthouse in Devon. We've found that although it will be difficult to improve on current best practice, there are many opportunities for energy efficiency in cement production, due to the wide gap between current best technology and average practice. However, because of the large contribution of process emissions which occur regardless of energy efficiency, we were unable to find sufficient options to meet our target emissions reduction with anticipated demand growth. Instead, we have found a plethora of opportunities for us to live well with less cement.

Cement production is strongly correlated with economic development, and almost half of global production is currently in China. However, this rapid expansion of use is apparently not sufficiently controlled to guarantee long-lasting buildings: we have found evidence that Chinese buildings may only last 20–30 years due to poor quality construction and insufficient maintenance[24]. While we evaluate the opportunities for global reductions in cement requirements for each application, the most urgent priority for future emissions associated with cement is to promote longevity in construction with cement today—to ensure that construction during today's rapid expansion lasts 150 years rather than 30.

Notes

1. Barsoum et al. (2006) describes their analysis of Davidovits' thesis.
2. Yang et al. (2010) describe their research into the use of sticky rice in ancient Chinese construction.
3. This history is based on Stanley (1979) with additions from Francis (1977) and van Oss (2011). The exact discoverer of Portland Cement is somewhat contentious, as several individuals lay claim to it, but the version presented is one generally accepted.
4. From the Hammond and Jones (2008) which is composed of average absolute values for embodied carbon with explanations of the factors considered in them.
5. Estimates concrete produced per tonne of cement varies from 7–9 tonnes as quoted in van Oss and Padovani (2003) so 8 tonnes was assumed.

Cement with one eye open: energy emissions now and in the future

6. Data on historic cement consumption is from Worrell et al. (2001) and from several USGS publications such as USGS (2010)
7. Aïtcin (2000) describes the correlation between cement consumption and development.
8. Forecast taken from Taylor et al. (2006) with different forecasts from Humphreys & Mahasenan (2002) using a range of assumptions.
9. Taken from Baumert et al. (2005)
10. Taken from Lafarge (2007)
11. These numbers are for 1999, from Batelle (2002)
12. Based on sources both from inside and outside the industry such as World Business Council for Sustainable Development (WBCSD, 2005) and Bosoaga et al. (2009). Van Oss (2005) provides further information including a more detailed description of the chemistry of cement.
13. From page 64, 'Cement Chemistry', Taylor, H., 1990
14. Taken from IEA (2007) and similar breakdowns repeated in other sources.
15. Allocation of carbon between products (e.g. steel) and by-products (e.g. slag) leads to splendid arguments because the by-product is made in a carbon-intensive process which operates in order to make something else (steel). Using such by-products as substitutes gives an overall benefit, so who should claim credit? More on this in WBCSD (2009). We could use more substitutes in cement if concrete was supported for longer after pouring, so the lower initial strength which is a consequence of many substitutes would not be a limitation. More on this in van Oss (2005).
16. Page 5 of the WellMet2050 report 'Taking our metal temperature' (Allwood et al., 2011) explains that average global exergy efficiency is about 10%. Therefore the required 30% efficiency to make recovering cement from concrete would be difficult to achieve.
17. Carbon sequestration can be done by either pre- or post-combustion processes, or by introducing an oxy-combustion system, each of which have various levels of capture, and different set-up and running costs. More information can be found in Naranjo et al. (2011) and Barker et al. (2009).
18. Based on information in WBCSD (2009), supported by van Oss (2011).
19. Taken from WBCSD (2009).

Cement with both eyes open: opportunities to use less cement to provide the same service

20. Orr et al. (2010) - This research team have made many exciting and efficient shapes from concrete cast in fabric.
21. Concrete creates an alkaline environment which inhibits corrosion of steel. However this useful effect declines near the surface due to a reaction between the concrete and CO_2 in the air. In order to ensure protection of the reinforcing steel, an additional 'cover layer' of concrete is therefore used. Most modern structural codes of practice allow this cover to be reduced, without affecting performance, provided certain conditions are met. For example, BS EN 1992-1-1:2004 (Eurocode 2) Clause 4.4.1.3 [3] specifies that cover can be reduced by up to 10mm if 'very accurate measurement' is used to verify correct placement of bars.
22. Chlorides, sulphates and silicates can all react adversely with reinforced concrete, but if known during design then appropriate mitigation measures can be taken.
23. Noguchi et al. (2011)

Outlook

24. Hu et al. (2010), states that residential units built in the 1960s and 70s were of such low quality that they only lasted 15 years. In later decades the standard of construction and maintenance has improved bringing the life expectancy up, however current building life is only 30 years in China (Hatayama et al. 2010).

Images

25. Joseph Davidovits, Geopolymer Chemistry and Applications 3rd ed. (2008-2011), Institut Géopolymère, ISBN978 -2-95114820-50
26. IEA and The World Business Council for Sustainable Development, Cement Technology Roadmap 2009