Ordinary Portland Cement

with extraordinarily high CO_2 emissions. What can be done to reduce them?

"Global CO_2 emissions from the cement industry are now greater than the entire aviation industry"
(Pearce, F 1997 'The Concrete Jungle Overheats' New Scientist issue 2091)

Rob Scot McLeod examines the science behind cement and the alternatives that may be available to us...

Cement is a major industrial commodity that is manufactured commercially in over 120 countries[1]. Mixed with aggregates and water, cement forms the ubiquitous concrete which is used in the construction of buildings, roads, bridges and other structures. In countries, even where wood is in good supply, concrete also features heavily in the construction of residential buildings.

In fact twice as much concrete is used in construction around the world than the total of all other building materials[2]. Despite its relatively low embodied energy, this scale of cement use is alarming given that cement production is responsible for 7-10% of total CO_2 emissions worldwide[3,4]. This places cement as the third biggest Greenhouse Gas culprit after the transportation and energy generation sectors[4]. With the cement industry growing at a rate of about 5% per year,[5] increasingly severe CO_2 reduction measures will be required to keep cement emissions in line with levels set by the Kyoto Protocol[6].

There is no doubt that carbon taxes and other legislative measures to reduce carbon emission levels will provide the cement industry with an economic catalyst for change. But whilst such environmental weighting drives up the production costs for carbon emitters to the benefit of their non-emitting (or less emitting) competitors; there remains a practical need to find solutions to the problem.

With many industries it is obvious how we can make them greener or less polluting; buildings can be better designed or retro insulated and vehicle engines can be made to run more efficiently or on alternative fuels. Cement manufacture however is a well-established process and any improvements are likely to be incremental as old plant is upgraded.

So what CO_2 reduction options are available to the cement industry, and how can we establish whether these improvements are substantial enough to meet this sectors' share of the Kyoto CO_2 targets both now and in the future? Although there are several different types of cement, Portland Cement (PC) is the most widely used and for simplicity I will refer to PC and cement interchangeably.

> Cement consumption is increasing globally by 5% per year.

Cement production and CO_2 emission predictions

In 1994 Professor Joseph Davidovits of Caen University was the first to document the climate change implications associated with high levels of PC production. According to Davidovits a worldwide freeze of CO_2 emissions at 1990 levels, as agreed under the Kyoto Protocol, is not compatible with the high cement demands of developing countries[4]. China and Japan are increasing cement production by 5% per year and Korea and Thailand by approximately 16%. On average global cement production is rising by 5% per year.

At this rate world cement production would reach 3, 500 million tonnes by 2020, a figure which represents a 3-fold increase on 1990 levels[7]. Assuming this prediction is correct, then only by implementing replacements that emit one third or less of the CO_2 produced by current cement manufacturing can we keep to this target in fifteen years time. Redirecting the building industry away from its reliance on cement and steel will take time and in the interim there is an urgent need to promote lower CO_2 cement replacements.

Cement and CO_2 formation

Cement is a defined chemical entity formed from predetermined ratios of reactants at a fairly precise temperature. Ordinary Portland cement results from the calcination of limestone and silica in the following reaction.

Limestone + silica (1450°C) =
Portland cement + carbon dioxide

$$5CaCO_3 + 2SiO_2 \rightarrow (3CaO, SiO_2)\ (2CaO, SiO_2) + 5CO_2$$

The production of 1 tonne of cement produces 0.55 tonnes of chemical CO_2, in a reaction that takes place at 1450°C. An additional 0.4 tonnes of CO_2 is given off as a result of the burning of carbon fuel to provide this heat[7].

To put it simply, 1 tonne of cement produced = 1 tonne of CO_2 released. Without altering the chemistry of cement the reaction component of this CO_2 cannot change. The other 40% of CO_2 emissions resulting from the fossil fuels burnt in the cement kilns could be fractionally reduced if modern operating efficiency improvements could be made to existing kilns.

Cement CO_2 reduction options

Essentially there are three ways to reduce the CO_2 emissions from cement manufacture. Perhaps the most obvious is to scale down production immediately, but this concept would not be popular with cement manufacturers or developing nations currently expanding their infrastructure. Therefore we are left with two options: i) reduce emissions within the existing industry; and ii) replace cement with viable alternatives where possible.

Reducing emissions within the cement industries

There are a number of cement and concrete making initiatives that are tackling CO_2 emissions both in the manufacturing of the product; the end use; and via the waste stream.

Industrial wastes: the proportion of 'pure' cement in a cement based mixture can be reduced by replacing some of it with other pozzolanic material (i.e. material which has the ability to act as a cement like binder). Industrial wastes including fly ash slag, a by-product of the coal power industry, silica fume and rice husk ash all have the combined benefit of being pozzuolana that would otherwise be destined for landfill.

Whilst every tonne of pozzuolana effectively saves a tonne of cement there are often engineering constraints limiting the percentage of cement that can be replaced. In the past these limits have typically been in the range of 10 -15%[4] but more recently structures containing high volume fly ash at 50 - 60% replacement levels have been built[8].

Autoclaved aerated concrete (aircrete): quicklime is mixed with cement, sand (or pulverised fuel ash - PFA), water and aluminium powder to form a slurry which rises and sets to form lightweight structural blocks. These blocks are then heated in a pressurised autoclave to give them strength. AirCrete blocks have excellent thermal and acoustic properties, and are suitable for load bearing walls in low and medium rise buildings. Typically the cement component of an AirCrete block is approximately 20% by dry weight[9], which is comparable with a conventional aggregate block. Since AirCrete blocks are less than half the density of conventional medium density blocks, less than half the cement is required for an equivalent built volume. Autoclaves operate at relatively low temperatures and use far less energy than traditional brick kilns.

CaO- and MgO- waste stream carbon sequestration: This is a method of using waste products from the cement industry to reabsorb CO_2 directly from the ambient air. Waste stream sequestration is estimated to cost in the region of $8 US/tonne of CO_2 absorbed[10]. This figure represents a small fraction of the price that the Intergovernmental Panel on Climate Change places on the value of carbon credit, whose bottom estimate is $55 US/tonne of CO_2[11]. Given that mandatory carbon taxes may soon be on the agenda, waste stream sequestration could become a financially viable alternative for the cement industry.

Reducing CO_2 emissions by using alternatives to cement

There are a number of products with similar properties to cement, the most obvious of which is probably lime, which need to be re-evaluated in light of their potentially lower CO_2 emissions.

Lime and limecrete: before delving into the intricacies of lime it is important to remember that lime is essentially formed in the same way as cement.

Limestone (heat) =
Quicklime + Carbon Dioxide

$$CaCO_3 \rightarrow CaO + CO_2$$

By converting limestone to quicklime, the raw product from which all calcium based lime is made, carbon dioxide is released. Burning fossil fuels to provide the heat for this reaction also releases CO_2, although temperatures required by lime kilns are lower than cement kilns thereby producing less CO_2. Cement is in fact composed predominantly of lime, the lime content of Portland cement being around 63.5%[1].

There are two forms of lime commonly referred to. These are hydraulic and non hydraulic lime.

Hydraulic lime mortars are formed by burning and slaking chalky limestone which contains a high silica content allowing stronger bond formations than non hydraulic mortars. The more hydraulic a lime is the more cement like its properties are. However it is the traditional non-hydraulic lime putties, known for their permeable and flexible characteristics that have a greater ability to reabsorb CO_2 by carbonation during their prolonged setting process.

Fig 1. Comparison of relative energy consumption and Net CO_2 emissions for cement replacement materials, assuming Portland cement = 100

Cement type	Manufacturing temperature	% Energy consumption	% Net CO_2 emissions
Portland Cement	1450-1500° C	100	100
PC + PFA(15)†	1450-1500° C	85 (-15%)	85
Eco-cement (TecEco)	unknown	70 (-30%)	73*
PC + Termite(40)**	1450-1500° C	60 (-40%)	60
EcoSmart Concrete + PFA(50)	1450-1500° C	50 (-50%)	50
Non Hydraulic (Lime Putty)	1350° C	100	50
Hydraulic Lime (NHL2)	<1000° C	50 (-50%)	40
Carbunculus (TM)	750-800° C	40 (-60%)	20

NB Carbunculus is a brand of geopolymeric cement, * assumes maximum 12% carbon sequestration (Harrison, 2005) ** termite mounds at 40% PC replacement levels

† PFA (15) and PFA (50) refer to pulverised fuel ash at 15% and 50% PC replacement levels respectively.

Hardening by carbonation occurs when calcium hydroxide in an aqueous state breaks down to bond with dissolved carbon dioxide, forming calcium carbonate with water as a by product.

Aqueous calcium hydroxide (slaked lime)

$Ca(OH)_2 \rightarrow Ca^{++} + 2OH^-$

Calcium ion + hydroxide ion + carbon dioxide = calcium carbonate and water

$Ca^{++} + 2OH^- + CO_2 \rightarrow CaCO_3 + H_2O$

Some non hydraulic limes are capable of reabsorbing nearly all of the CO_2 released in their chemical formation, but this figure does not account for the CO_2 released by the kiln which can be on a par with PC[12]. In practice carbonation occurs gradually over a long period of time and is often only partially achieved. John Harrison (the founder of TecEco, see below) attributes this situation to the use of aggregates that are too fine to permit water and gas vapours to pass freely through the material[13].

Limecrete can be made by mixing lime with a suitable aggregate or for insulation purposes, e.g. Leca[16].

CeramiCrete: this American product combines magnesium oxide with a phosphate instead of Portland cement's calcium based chemistry. It still emits CO_2 in the same manner as PC but is significantly stronger so builders need less of it thereby reducing CO_2 emissions. Furthermore CeramiCrete is less dense than PC and this in turn reduces transport related CO_2 emissions. There are numerous other advantages to this product including its ability to bond to a variety of materials such as soil and straw[14]. However, it is likely to remain more expensive than PC to produce.

Eco-cement: produced by TecEco, a small Australian company, this product is undergoing considerable research and development. Their products combine reactive magnesia with fly ash and a small amount of Portland cement in variable proportions depending on the end use. According to TecEco an average PC block containing 1.4kg cement can sequester 0.1kg CO_2 over time (this is a net CO_2 reduction of 7%). An equivalent Eco-block is said to carbonate 50-75% more than this, giving net CO_2 reductions of 11- 12.5%[13]. Because Magnesium carbonates can be formed at lower temperatures than Calcium carbonate, TecEco have begun developing kiln technologies that will directly utilise waste heat (such as from power generation) and concentrated solar energy as the primary heat source[13].

Earthship Brighton UK - The world's first eco-cement home with eco-cement floors and mortars

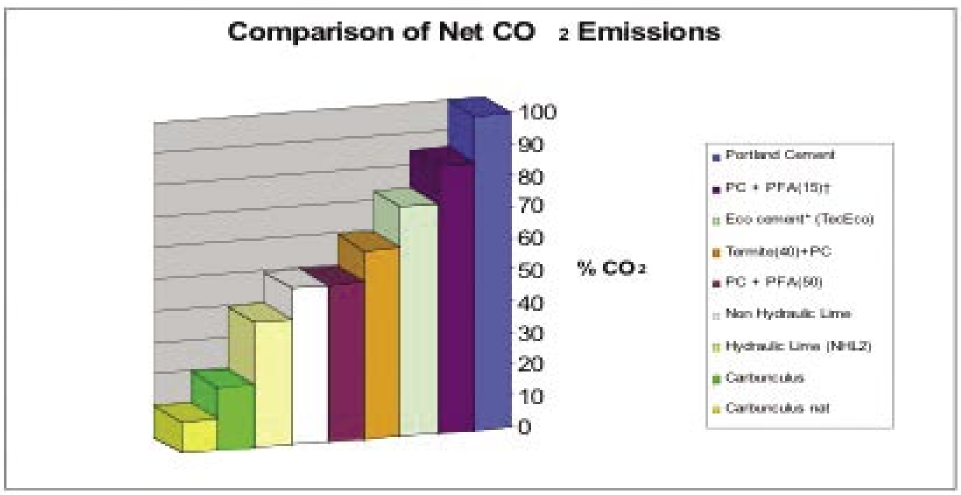

Fig 2 Comparative CO_2 emissions of cement replacement materials on a weight for weight basis, assuming Portland cement = 100 (1 tonne CO_2 per 1 tonne cement)

If shown to be feasible net CO_2 reductions of up to 50% could be achieved over conventional cement kilns. Other beneficial properties include high early tensile strength compared to lime, good acid resistance and a high tolerance to salts. Due to the relative abundance of the raw materials, it may also prove cheaper to produce than PC.

Geopolymeric cements: this type of cement has its origins in the original Roman cements first used over 2000 years ago. Geopolymeric cements are formed in a different manner to PC and lime and do not involve the release of bound CO_2. The raw materials for geopolymeric cements are aluminium and silicon rich materials that are activated by alkali compounds. This silicate based chemistry can be achieved at relatively low temperatures, with the added benefit of requiring far less capital investment in manufacturing plant and equipment. The net result is a product that sets in a matter of hours with CO_2 emissions that are 80% - 90% less than PC[4].

High quality earth bricks have been made by the addition of small quantities of geopolymeric cement to laterite soils, and then firing the bricks at low temperatures (85°C). The resulting bricks have excellent hygroscopic and breathable properties and contain less than 1/8th of a conventional bricks embodied energy[4]. Further research and development of geopolymeric cement products is currently underway prior to their commercial release.

Earth: locally sourced alternative materials have been in use all over the world since man first began building shelters. In the western world we, oddly, need to proove its capabilities once more to the regulating bodies. One fantastic example of proof is the work that Tom Morton and Arc Architects have been carrying out with earth bricks and mortars over the last couple of years see page 24 in this issue. Other earth building systems have been well documented in BFF over the last couple of years; cob; adobe and rammed earth will all have major parts to play in reducing cement/concrete use in the future.

Another localised example might be that of Termite mounds which are widespread throughout the African savannah and are often destroyed by farmers[15]. If an environmental impact assessment could establish that their use as a local cement substitute was relatively benign then significant financial and CO_2 savings could result. This low tech approach demonstrates that this global problem can be tackled locally and on many levels.

Conclusions

In summing up, we must remember that to prevent rapid climate change, it is necessary to reduce net anthropogenic CO_2 emissions drastically. Based on current consumption rates there will be a 3-fold increase in cement manufacturing CO_2 emissions between 1990 levels and 2020[7]. Using the Kyoto Protocol's 'first commitment period' CO_2 reduction target of 5.2% below 1990 levels as our initial base line target, we will need to cut our cement CO_2 outputs by two thirds plus 5.2%, i.e. 73% by 2020[7]. Subsequent Kyoto commitment periods set even greater reduction targets.

Geopolymeric cements and earth (for low rise buildings) are the only products/materials reviewed here that are clearly capable of achieving CO_2 reductions of this magnitude, whist still maintaining some of the beneficial characteristics of Portland cement. This is because all of the other products use either a large percentage of PC, or rely on a similar calcination process to cement, which releases large quantities of CO_2 by virtue of the chemical reaction and furnace heat required.

Eco-cement and other magnesium based cement alternatives are possible exceptions to this finding because they have the potential to be fired at much lower temperatures than PC (possibly utilising waste heat) and are potentially stronger and less dense than calcium based cements. Future developments may well see large CO_2 reductions achieved by these products particularly as they begin to incorporate higher proportions of waste pozzuolana.

Rather than awaiting the final stages of R&D that will see this new generation of eco cements on the market, we should turn our attention towards specifying the most environmentally benign products from those currently available. Products like Canadian EcoSmart concrete have already demonstrated that by using high volume fly ash, CO_2 emissions can be halved overnight whilst creating cement that is both structurally superior to PC and cheaper to produce. Carbon taxes, mandates, assessment ratings and other incentives that drive all cement manufacturers and building specifiers to adopt such practices are urgently needed.

Meanwhile, following suit with the cigarette industry, a large warning should be printed on all cement packets stating that the 'use of this product can seriously harm our planet's health.'

Rob Scot McLeod

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Response from the cement industry

In response to this article, Martin Casey, Director of External Affairs at the British Cement Association (BCA) pointed out that he disagrees with the figure of 7-10% as the global CO_2 contribution of the cement industry. The cement industry has always stated that the figure is 5%.

Casey also made the point that magnesium is not available in the UK, meaning that for the cement industry to use this technology it would need to be imported, increasing embodied energy. A fair comment.

Casey also says that the BCA represents the British cement industry, while the article is global and that he could not comment on what was beyond the boundaries of the BCA, other than to say that all the developing nations are using the most efficient methods possible to produce cement and have invested heavily in plant upgrades to this end.

His final point was that the BCA has an overt sustainability policy, and has recently published a performance report detailing how the industry is addressing corporate responsibility and sets out plans for delivering real environmental benefits. This can be found at **www.cementindustry.co.uk**