Low Carbon Concrete – Options for the Next Generation of Infrastructure

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Synopsis: Concrete production accounts for approximately 5% of worldwide greenhouse gas emissions. The majority of these emissions derive from the cement binder. Although developments in cement manufacture have led to a significant reduction in CO_2 emissions, further substantial reductions will require radical change. This paper summarises the findings of a study of options for 'low carbon concrete'. The study was commissioned in 2007 by UK Government's Environment Agency, through its Carbon Reduction Fund, with the aim of identifying low CO_2 alternatives to concrete for use on flood alleviation schemes.

An extensive desk study identified seven groups of technologies with potential to reduce the carbon footprint: secondary cementitious materials, modified Portland or non-Portland cements, low cement concrete, ultra high strength concrete changes in Portland cement (PC) manufacture, alternative binders and carbon capture. A short list was produced of three candidates with potential for high CO_2 reduction and suitability for construction: (i) Agent-C (a bituminous binder from the processing of heavy fuel oils); (ii) high slag binder comprising a blend of 20% Portland cement and 80% ground granulated blastfurnace slag; and (iii) geopolymer (an alumino-silicate material formed by the reaction of alumina and silicate rich materials with an alkali activator). These three candidates were studied in detail for engineering characteristics, availability, environmental impact and construction issues. The CO_2 emissions associated with manufacture and transport of the materials were calculated and recommendations made for their future development.

Keywords: carbon, emissions, binder, geopolymer, slag, bituminous.

1. Introduction

This paper summarises the results of the Low Carbon Concrete study conducted in 2007 on behalf of the UK Government Environment Agency (EA), Carbon Reduction Fund. The objective of the study was to identify low CO_2 alternatives to conventional concrete for use in EA infrastructure schemes, such as flood alleviation schemes.

The prompt for the study was a newspaper article discussing low carbon alternatives to concrete, including use of a bituminous binder from processing heavy fuel oils, which was claimed to have negative carbon emissions (1). At the outset, it was decided that the study should not focus on a single proprietary material but should review other alternatives to Portland cement binder. Concrete production accounts for approximately 5% of worldwide greenhouse gas emissions (1). Most of the embodied CO_2 emissions in concrete derive from the Portland cement (Figure 1) and the worldwide production of Portland cement accounts for approximately 3% of annual CO_2 emissions (2).

The study comprised three stages:

a) a desk study to review candidate materials and strategies being developed in different countries
b) screening the options to produce a maximum short-list of three candidate materials
c) a detailed appraisal of the shortlisted materials for engineering suitability and effectiveness in reducing CO_2 emissions.

Each of these stages is discussed in detail below.

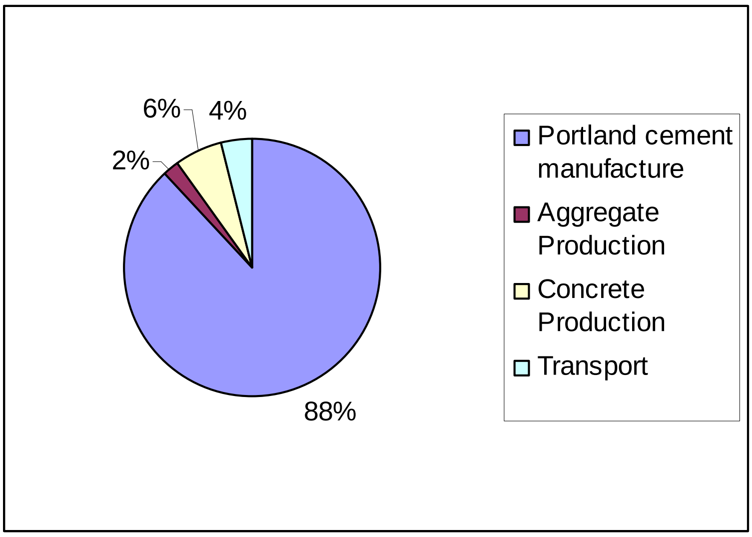

Figure 1. Summary of CO2 emissions derived from concrete (3).

2. Desk Study

2.1 Background

Each tonne of Portland cement produced generates approximately 1 tonne of CO_2; 42% derived from the fuel required in processing and burning the constituents and grinding the cement and 58% being a by-product of de-carbonation of the limestone within the kiln (4).

A number of factors have acted to mitigate the potential carbon emissions associated with Portland cement use in concrete:

- changes in the production process have increased cement strength development and allowed the content to be reduced by over 25% for the same concrete strength
- blending of Portland cement with secondary cementitious materials (such as slag and fly ash) resulting in an estimated annual UK reduction in greenhouse gas emissions equivalent to 1.2million tonnes CO_2
- use of water-reducing admixtures resulting in over a 10% reduction in cement content for the same concrete strength
- improvements in kiln efficiency and use of alternative waste fuels (such as scrap tyres, waste solvents and biofuels) have reduced fuel consumption by 50% since the 1970's (5).

Despite significant work in the cement and concrete industry to enhance and emphasise the sustainability of concrete, including its whole life benefits of thermal mass and longevity, further significant reductions in embodied CO_2 in concrete will require fuller application of these existing technologies across the industry, as well as more radical change (6). This is reflected in the results of the desk study.

2.2 Findings

An initial desk study of construction industry databases and web sites indicated that the strategies being adopted or developed in twelve countries around the world (America, Australia, Canada, China, Denmark, France, Holland, India, Ireland, Japan, Turkey, United Kingdom) can be divided into seven groups as shown in Table 1.

Table 1. Summary of low carbon concrete options.

Group	Example
Secondary cementitious materials	Fly ash Slag Silica fume Metakaolin Municipal solid waste incinerator ash (MSWIA)
Non-Portland cement binders (7)	Calcium sulfate based cement Calcium sulfoaluminate cements Magnesite based cement (8) Magnesium phosphate cement (8) Geopolymer
Low cement concrete	Lean mix concrete
Ultra high strength concrete	Fibre reinforced superplasticised silica fume concrete (FRSSFC)
Changes in Portland cement manufacture (7)	Oxygen enrichment of kiln atmosphere to enhance burning Belite cements Alinite and Fluoralinite cement Portland limestone cement
Alternative binder types	Bituminous based materials
Carbon capture (8)	Sequestering carbon from the kiln Capturing carbon in the concrete, eg hemp

3. Screening

In order to provide a short-list of three materials for detailed consideration, a coarse screening process was used which applied the following key questions to each of the seven groups of options:

- What potential impact would it have on CO_2 emissions?
- Is it suitable for use in construction and especially flood alleviation schemes?
- Where can it be sourced?

Long-term effects such as carbon capture by carbonation or extended service life were not considered in the screening process. A very approximate assessment of CO_2 emission was undertaken based on the potential reduction in the cement content or concrete volume or the embodied CO_2 of the binder relative to Portland cement. The CO_2 emissions for the options were categorised as shown in Table 2.

Table 2. Carbon categories.

Category	CO_2 emissions relative to Portland cement concrete (%)
Very high	>85
High	66-85
Medium	33-66
Low	0-33
Very Low	<0

CO_2 emissions less than 0% indicate that the material ‘captures’ CO_2 by incorporating a component that could release CO_2 into the atmosphere if used or disposed of in an alternative way.

The results of the coarse screening are summarised in Table 3.

The effect upon CO_2 emissions of changes in kiln technology, such as oxygen enrichment and carbon sequestration, are not known. Introduction of such technology across the industry will be a slow process and given the need for immediate measures, it has not been considered further

Table 3. Summary of coarse screening

Group	Example	CO_2 emissions	Applicability to flood alleviation schemes	Availability of technology in UK
Secondary cementitious materials	80% slag	Low	Proven	Widespread
	40%fly ash	Medium	Proven	Widespread
	10% Silica fume	Very high	Proven	Imported
	10% Metakaolin	Very high	Proven	Limited
	MSWIA	Medium	Unproven	Limited
Non-Portland cement binders	Geopolymer	Low	Unproven	Limited
	Calcium sulphate based	Low	Unproven	None
	Calcium sulfoaluminate	High	Unproven	Limited
	Magnesite based	High	Unproven	Imported
Low cement concrete	Lean concrete	Medium	Proven	Widespread
Ultra high strength concrete	FRSSFC	Medium	Proven	Imported
Changes in Portland cement manufacture	Alinite and Fluoralinite	Medium	Unproven	None
	Belite	Very High	Unproven	Limited
Alternative binder types	Agent-C	Very Low	Proven	Imported
Carbon capture	Lime based binder and hemp	Very Low	Unsuitable	Imported

Only five materials have low or very low CO_2 emissions and two of these are either unsuitable for flood alleviation schemes or unavailable in the UK. The remaining candidates are 80% slag (‘high slag’), geopolymer and Agent-C.

4. Detailed Appraisal

4.1 Introduction

The detailed appraisal of the materials considered:

- Engineering Properties (eg. strength, elastic modulus, creep, long-term performance)
- Environmental Impact
- Availability
- Construction Issues
- CO_2 Emissions.

The cost of the materials was also assessed, but meaningful comparison was difficult due to the economies of scale afforded to established materials and the lack of a reliable price for geopolymer.

A flood alleviation project in St Ives, Cornwall, UK, was used as a notional construction site in order to assess the potential uses of the different materials and calculate CO_2 emissions.

Table 4 summarises the composition of the candidate materials alongside a conventional C25/30 (cylinder strength/cube strength) concrete. A brief description of the materials and a summary of the findings of the appraisal are given below.

Table 4. Mass of constituents (kg/m^3) for candidate materials

Constituents	Conventional concrete	Agent-C	High Slag	Geopolymer
Binder	210 (PC) 140 (Slag)	150 (Agent-C)	70 (PC) 280 (Slag)	400 (Fly ash)
Fine Aggregate	650	830	650	500
Coarse aggregate	1200	1150	1200	1300
Water	175	0	175	22
Other		260 (limestone filler)		144 (silicate/hydroxide) 7 (superlasticiser)
Voids	0-2%	0-5%	0-2%	0-2%

4.2 Agent-C

Agent-C is a bituminous binder produced by the processing of Vacuum Flashed Cracked Residue (VFCR), a heavy fuel oil from the distillation of crude oil. It has a density of 1090kg/m^3 and a high proportion of asphaltenes and long chain carbon molecules giving it a high viscosity and reduced temperature susceptibility (9). The material is mixed with aggregates to give a bituminous material, which is laid at a temperature of around 200°C using standard asphalt plant.

Agent-C is currently sold for use in bituminous surfacing materials, such as porous asphalt, and for the production of low carbon alternatives to concrete in precast products such as pavers. It was also been used in the form of a dense macadam to cast six, 45 tonne, armour blocks for coastal protection at Ijmuiden, Netherlands in 2005. These are reported to be currently performing better than the equivalent concrete blocks.

4.3 High Slag

Slag is a by-product of the production of iron. The material is drawn off from the blastfurnace and rapidly cooled using water to produce a glassy granulate, similar in appearance to sand. The granulate is allowed to drain and then dried in a rotary drier. The dry granulate is fed into high pressure roller crushers and subsequently into a ball mill and ground to give a powder slightly finer than Portland cement. The material has latent hydraulic properties, requiring an alkaline activator. This is usually achieved by blending it with Portland cement. Slag has been beneficially used in concrete since the 1960s to reduce the risk of early-age thermal cracking and alkali-aggregate reaction and increase the sulphate and chloride resistance of concrete.

The early strength development reduces with the proportion of slag as indicated in Figure 2. Therefore, although up to 80% slag by mass of total cement could be used, the typical proportion is around 50% to avoid delays to the construction process.

In the UK, approximately two-thirds of available slag is already used in construction and this limits the future capacity to introduce more slag to reduce CO_2 emissions.

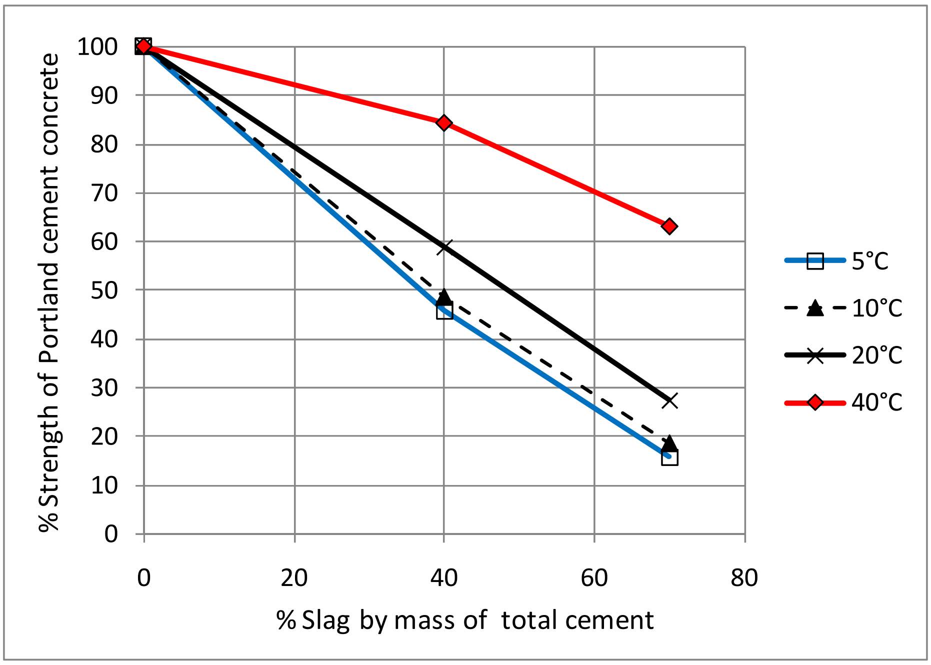

Figure 2. Effect of % slag and temperature on 3-day compressive strength (10).

4.4 Geopolymer

Geopolymer is a term used to describe a family of alumino-silicate materials formed by the reaction of alumina and silicate rich materials with a metal alkali activator. A key parameter in determining the characteristics and use of the geopolymer is the silica:alumina ratio, as indicated in Table 5. For civil engineering a silica:alumina ratio of approximately 2 is required.

Table 5. Influence of silica : alumina ratio.

Silica:alumina Ratio	Characteristics	Potential Use
1	Rigid crystalline structure	Bricks, ceramics and fire protection
2		Low CO_2 cement and concrete Waste encapsulation
3	Ductile polymeric structure	Foundry equipment Heat resistant composite (200-1000°C)
>3		Sealants
20-35		Fire and heat resistant fibre composites

The alumino-silicate component of geopolymer can be derived from materials such as metakaolin, slag or fly ash. The accelerator would typically be a potassium or sodium hydroxide or silicate. The calcium and carbon content of the binder have to be controlled to avoid variable properties. Fly ash should have a loss on ignition less than 7% and derive from a sub-bituminous coal with a calcium content less than 10%.

The Commonwealth Scientific and Industrial Research Organization (CSIRO) has investigated the use of the material in construction, including marine structures, fluid containment and conduits, although it admits that the transition from a well-established, material such as cement to a novel one is difficult. Trials undertaken by Curtin University of Technology, Perth, Australia on reinforced beams and columns have proved promising (11) and concrete is being produced commercially using geopolymer binder (12). However, no published examples have been obtained of the material being used in reinforced structural elements in the field.

By virtue of their stable alumino-silicate structure, it would be expected that geopolymers would have good durability and they have been considered for stabilisation and encapsulation of the nuclear waste. Fire resistance should be superior to conventional concrete because of the negligible water in the mix and the sulfate and acid resistance should be enhanced because of the lack of calcium bearing material in the binder. The alkalinity of the constituents should provide a sufficiently high pH to passivate steel reinforcement to corrosion.

The short setting time of these materials and the need with some combinations for heat treatment is a major drawback, which is likely to restrict its use in the first instance to precast items, specialist fast-setting repair materials and sprayed concrete.

There are no standards and codes covering the use of geopolymer in construction and this would most likely be facilitated by testing against a performance specification.

4.5 Engineering Characteristics

Table 6 (appended) summarises the engineering properties of the materials and practical aspects of their use, largely based on published information.

The higher creep of Agent-C and greater sensitivity to temperature together with the limited corrosion protection to embedded steel makes the material unsuitable for structural applications. Concrete containing geopolymer is expected to have better durability than conventional concrete, but many of its engineering characteristics are unknown and this lack of information hampers its adoption,

4.6 CO_2 Emissions

CO_2 emissions were calculated for conventional concrete and the candidate materials allowing for production of the primary materials, secondary processing and transport (Table 7). These calculations include the energy for heating Agent-C, heated mix water for high slag and steam-curing the geopolymer. The EA carbon converter was used, which prescribes the CO_2 emissions arising from different fuel types, eg 2.63 kg of CO_2 for 1 litre of diesel. The conventional concrete was assumed to have a 350kg/m^3 binder content comprising 40% slag. The notional use was at a construction site in St Ives, Cornwall, UK.

Table 7. Summary of CO_2 calculation.

Concrete Type	kg CO_2 per cubic metre of concrete			
	Primary processing and Constituents	Secondary processing	Transport	Total
Conventional	202.4	29.9	16.2	248
Agent-C (best)	-501.3	58.3	21.2	-422
Agent-C (realistic)	-18.3	58.3	21.2	61
High slag	99.2	29.9	14.8	144
Geopolymer	23.2	34.4	20.9	78

The assumptions made in the calculation are extremely important. For example, it can be observed that the CO_2 reduction of the Agent-C differs significantly between the ‘best case’, where the VFCR is replaced by a zero carbon fuel, and the ‘realistic case’, where it is replaced by a light fuel oil.

The potential CO_2 reduction associated with the three materials has been calculated based on the availability of the binder constituents in the UK and for the potential for use in place of conventional concrete based on the notional site and three other infrastructure schemes in the same locality (Table 8). The average amount of concrete used at the three schemes was approximately 970m^3 representing 237 tonnes of CO_2 when using conventional concrete.

It can be observed that high slag has the greatest availability and potential for CO_2 reduction (40%). The limited opportunity to use Agent-C to replace concrete in infrastructure schemes restricts its impact to a 2% reduction in CO_2. This value would be expected to be higher for schemes requiring armour blocks. Geopolymer is unlikely to be widely available in the next 10 years, until there is confidence in the material and sources of supply are established. Its potential use in the table is conservatively restricted to precast items and acid-resistant sewer linings, giving a modest 7% CO_2 reduction.

Table 8. Potential CO_2 reduction for candidate materials.

Material	Estimated CO_2 reduction per annum			
	CO_2 reduction (thousand tonnes) in UK Based on availability of constituents			CO_2 reduction (tonnes) for typical infrastructure scheme
	Now	5 years	10 years	
Agent-C	0	187	Future availability may limit use	4
High slag	315	315		96
Geopolymer	0	0	850	17

5. Conclusions

A study has been undertaken to identify Low Carbon Concrete candidate materials for use on infrastructure schemes. The focus of the study has been on the Portland cement binder as this represents approximately 80% of the embodied CO_2 within concrete and its production contributes approximately 3% of worldwide CO_2 emissions.

Despite the substantial progress made within the cement and concrete industry to improve production efficiency and enhance the sustainability of concrete, further significant reductions in carbon emissions will require radical action. Seven groups of technologies being adopted or developed around the world were identified by a desk study: secondary cementitious materials, modified Portland or non-Portland cements, low cement concrete, ultra high strength concrete, changes in Portland cement manufacture, alternative binders and carbon capture.

These seven groups were reduced to the following short list of candidates, by coarse screening them on the basis of likely CO_2 emissions, suitability for flood alleviation schemes and availability:

- Agent-C (a bituminous based binder utilising heavy fuel oil residue)
- high slag binder concrete (incorporating 80% slag)
- geopolymer (an alkali-activated alumino-silicate material).

A detailed appraisal of the engineering properties, environmental impact, availability, CO_2 emissions and construction issues has been carried out using a typical flood alleviation scheme as the notional application.

Conventional concrete containing 40% slag was estimated to embody 244kg/m^3 CO_2 emissions. The equivalent values for the candidate materials are 61kg/m^3 for Agent-C, 78kg/m^3 for geopolymer and 144kg/m^3 for high slag concrete.

The true impact of the materials is dependent on their availability and potential for use as a substitute for concrete in typical infrastructure schemes. When this is taken into consideration high slag concrete is ranked the best low carbon candidate in the short-term because of its widespread availability and established use in the concrete industry (Table 9). Specification changes could promote higher levels of slag in the short-term, leading to a 40% reduction in CO_2 emission for a typical scheme, but lower early strength development and limitations in supply in the long-term will restrict its use.

The bituminous based binder, Agent-C, has the potential to produce a concrete substitute with low or negative carbon emissions. The latter outcome assumes that the heavy fuel oil from which it is made will be replaced by a clean fuel thereby eliminating the carbon emissions generated when it is burned. However, engineering properties limit use to non-structural applications.

Geopolymer appears to be a good candidate binder for low carbon concrete, because of its potential durability and ability to use a range of constituent materials. However, substantial work is needed to overcome practical issues, develop confidence in the material and establish sources of supply.

Table 9. Summary of ranking of candidate materials

Material	CO_2 emissions			Availability Ranking	Opportunity Ranking	Combined Ranking
	(kg/m^3)	% reduction relative to conventional concrete	Ranking			
Agent-C	61	75	1	2	3	6 (2)
High slag	144	42	3	1	1	5 (1)
Geopolymer	78	70	2	3	2	7 (3)

6. Acknowledgement

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Table 6. Summary of the engineering characteristics.

Characteristic	Conventional concrete	Agent-C	High slag	Geopolymer
Health &Safety	Highly alkaline cement powder	High temperature Risk of burns/fire	As conventional concrete	Highly alkaline liquid accelerators
Environmental impact	Leaching of calcium hydroxide	Limited leaching of polycyclic aromatic hydrocarbons	Reduced leaching once hardened	Alkaline spillages
Handling time (hours)	2-3	0-1	3-4	0-1
Handling	Pump, skip	Asphalt plant pouring, pressing, extrusion	As conventional concrete	Very viscous skip, spray
Compressive strength (MPa)				
1-day	5-10	15-25	1-5	Lower
28-day	30-40	15-25	20-30	Higher
Flexural strength (MPa)	4-5	4-11	As conventional concrete	Higher
Tensile strength (MPa)	2-3	3-5	As conventional concrete	Higher
Density (kg/m^3)	2400	As conventional concrete	As conventional concrete	Unknown
Water absorption (%)	3-4	<0.25	2	Unknown
Water permeability coefficient (m^2/s)	10x10^{-13}	Lower	3x10^{-13}	Unknown
Elastic modulus (GPa)	25-35	17-20	As conventional concrete	Unknown
Max service temperature (°C)	300	70	Slightly higher	Higher
Thermal expansion Coefficient (microstrain/°C)	8-13	25	As conventional concrete	Unknown
Dimensional stability	Movement depends on service conditions	Higher early contraction due to cooling and long-term creep	As conventional concrete	Unknown
Durability	Protects embedded metal but vulnerable to chloride and carbonation induced corrosion and acid and sulphate attack.	Performance in armour blocks reported to better than conventional concrete. Limited protection to embedded steel	Higher resistance to sulphates and chlorides. Lower resistance to carbonation	Expected to have good resistance to sulphates and acids and provide passive protection to embedded steel