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SUSTAINABLE CONCRETE: HOW CAN ADDITIONS CONTRIBUTE?

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ABSTRACT: This paper reviews the additions available in the UK. It provides indicative data for the extent of their use and their environmental burdens relative to Portland cement. It concludes that. additions are currently making a significant contribution towards reducing the environmental burdens of concrete, particularly in relation to greenhouse gas emissions.

Keywords: Sustainability, carbon dioxide, environmental burdens, Portland cement, ground granulated blastfurnace slag, fly ash, silica fume

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INTRODUCTION

The European Standard for concrete BS EN 206-1[1] defines an addition as "a finely divided material used in concrete in order to improve certain properties or to achieve special properties." and the Standard deals specifically with two types of inorganic additions:

- nearly inert additions (type I);
- pozzolanic or latent hydraulic additions (type II).

Type II additions are cementitious and actively contribute towards the strength development of concrete. As such they are permitted to count as part of the 'cement content' and replace a proportion of the normal cement. Because Portland cement is the major contributor to many of the environmental burdens of concrete, there can be significant 'sustainability' benefits in replacing it as far as possible, with alternative materials. Additions will not necessarily replace Portland cement on a one-for-one basis and it is possible to include similar inorganic materials as part of the composition of factory-produced, blended cements to the European Cement standard BS EN 197-1[2].

Type II additions are generally by-products from high-temperature processes:

- Ground granulated blastfurnace slag from Iron Blast-furnaces
- Fly ash from Coal Power Stations
- Silica fume from Ferrosilicon Arc-furnaces
- Natural pozzolanas from volcanic eruptions

It is their high temperature history that makes them chemically reactive with water or alkali.

Limestone fines can also be used as an addition in concrete. Limestone is chemically, relatively inert but limestone fines, because of their fine particle size, can contribute towards strength by a physical, void-filling mechanism. Views differ on whether they should be considered as Type I or Type II additions.

Table 1 indicates the extent to which these additions are used in the UK (tonnes per annum).

	As 'addition'	As a component of blended cement
Portland cement	n/a	12,500,000 tonnes
ground granulated blastfurnace slag	2,000,000 tonnes	minimal
Fly ash	500,000 tonnes	~ 100,000 tonnes?
Silica fume	3,000 tonnes	minimal
Natural pozzolanas	minimal	minimal
Limestone fines	< 10,000 tonnes?	~50,000 tonnes?

Table 1: Extent of use of additions in the UK

PRODUCTION AND PROPERTIES OF ADDITIONS

Ground Granulated Blastfurnace Slag (ggbs) is a by-product from the blast-furnaces used to make iron. These operate at a temperature of about 1500^{o}C and are fed with a carefully controlled mixture of iron-ore, coke and limestone. The iron ore is reduced to iron and the remaining materials form a slag that floats on top of the iron. This slag is periodically tapped off as a molten liquid and if it is to be used for the manufacture of ggbs it has to be rapidly quenched in large volumes of water. The quenching optimises the cementitious properties and produces granules similar to a coarse sand. This 'granulated' slag is then dried and ground to a fine powder.

Fly Ash is a general term for the fine ash carried over in the gases from a furnace and can refer to the ash from any furnace. However, the fly ash used as an addition in concrete is specifically ‘pulverised fuel ash’ (pfa), which is produced when pulverised coal is burned in a coal fired power station. The ash is carried out with the flue gases and these pass through electrostatic precipitators that remove the fine ash from the flue gases. In the UK this ash has historically been known as ‘pfa’, but the term ‘fly ash’ is used in European Standards. Fly ash particles are very fine (typically <0.5mm) and are normally used in concrete without any further processing. However if too coarse, they can be passed through an air-classifier to remove the coarser particles.

Silica Fume is produced during the manufacture of silicon or ferrosilicon. This process involves the reduction of high purity quartz in electric arc furnaces at temperatures of over 2,000^{o}C. SiO gas given off as the quartz reduces, mixes with oxygen in the upper parts of the furnace and oxidises to SiO_2, condensing into the pure spherical particles of micro-silica that form the major part of the smoke or fume from the furnace. The fume is collected in specially designed baghouse filters.

Properties: Typically, the fineness of Portland cement is about 350m^2/kg, ggbs is about 450 m^2/kg and fly ash and limestone fines are about 500 m^2/kg. By contrast, silica fume is very much finer at around 18,000 m^2/kg.

Table 2 shows typical ranges of chemical compositions for the major oxides present in UK cementitious materials.

	Portland cement	GGBS	Fly ash	Silica fume
CaO	60 to 70%	35 to 45%	< 10%	< 1%
SiO_2	20 to 22%	33 to 40%	35 to 50%	85 to 95%
Al_2O_3	4 to 7%	8 to 16%	20 to 40%	< 1%
MgO	1 to 3%	7 to 15%	< 5%	< 4%

Table 2: Chemical composition

The major factor that determines the cementitious activity of an addition is its chemical composition. A secondary factor is the fineness, with finer materials being more reactive. Ggbs is closest to Portland cement in chemical composition and is actually a slow-setting cement in its own right. However in practice, it needs to be blended with Portland cement to give an adequate rate of strength development. Fly ash and silica fume on their own, do not have any cementitious properties but they do have pozzolanic properties, i.e. they react with the calcium hydroxide liberated when Portland cement hydrates, to form cementing compounds. As mentioned previously, limestone fines make a physical rather than a chemical contribution

The cementitious activity determines the extent to which it is possible to use an addition to replace Portland cement and indicative replacement proportions are shown in Table 3.

	Permitted by BS 8500 [3] (BS EN 206-1 [1])	Typical proportion
GGBS	6 to 85%	50%
Fly ash	6 to 55%	30%
Silica fume	(up to 12.5%)	10%
Limestone fines	6 to 20%	15%

Table 3: Replacement proportions for additions

ENVIRONMENTAL IMPACTS

Measured by tonnage, Portland cement is easily the world's major manufactured chemical. Unfortunately its manufacture is highly energy intensive and the energy used by the Cement Industry constitutes about 2% of global primary energy consumption. In addition, its primary raw material is limestone (calcium carbonate) and large quantities of carbon dioxide are released as this is decomposed in cement kilns. As a result of fuel burnt and the chemical decomposition of limestone, the Cement Industry is responsible for about 5% of total global carbon dioxide emissions. The major environmental burdens resulting from the production of a tonne of Portland cement are

- emission of one tonne of carbon dioxide
- use of 1,700 kWh of primary energy
- extraction of 1.5 tonnes of minerals

Carbon dioxide emission is the major sustainability issue associated with Portland cement. Historically, the manufacture of each tonne of Portland cement has resulted in the emission of well over 1 tonne of carbon dioxide. As a result of increased efficiency in operation, modern Cement Works emit somewhat less than this. Table 4 details the sources of carbon dioxide emissions associated with a Cement Works. It should be noted that some environmental accounting protocols do not include emissions associated with the production of electricity and/or allow emissions from the use of waste fuels to be ignored where the waste would otherwise have been burnt in municipal incinerators.

Source	Indicative CO_2 emitted	Comment
Chemical decomposition (breakdown of limestone)	500 kg	The major source of CO_2 and intrinsically unavoidable
Fuel	350 kg	Use of waste as fuel can benefit 'sustainability'
Electricity	80 kg	The CO_2 is normally emitted off-site, at a Power Station
TOTAL	930 kg	

Table 4: Indicative CO_2 emissions associated with the production of 1 tonne of Portland cement

A major obstacle to reduction in carbon dioxide emission is the inherent emission of 0.5 tonne of carbon dioxide due to chemical breakdown of the limestone [4]. Improvements in design and efficiency are unlikely to be able to reduce the total emissions much below 0.9 tonne of carbon dioxide and the only identifiable opportunity for further large-scale reduction is 'sequestration', i.e. to collect the carbon dioxide and prevent its emission into the atmosphere.

Additions are generally the by-products of other industries, which arise, irrespective of whether or not they are usefully used. As such, there are obvious environmental benefits in using them as replacements for Portland cement. If these by-products require further processing prior to use in concrete, there will be environmental burdens associated with the processing. Fly ash and silica fume are normally used without further processing and their environmental burdens are relatively small. The production of ggbs from blastfurnace slag involves processing (drying and grinding), which needs to be taken into account. Table 5 shows the environmental profile for the production of 1 tonne of ggbs, compared with typical values for Portland cement.

Environmental Issue	Measured as	Impact	
		Manufacture of one tonne of ggbs [1]	Typical manufacture of one tonne of PC
Climate change	CO_2 equivalent	0.05 tonne	0.95 tonnes
Energy use	primary energy [2]	1,300 MJ	5,000 MJ
Mineral extraction	weight quarried	0	1.5 tonnes
Waste disposal	weight to tip	1 tonne saved [3]	0.02 tonne

Notes:
1. the profile for ggbs is the impacts involved in processing granulated blastfurnace slag to produce ggbs. No account has been taken of the impacts of Iron-making because the slag evolves, irrespective of whether or not it can be used.
2. includes energy involved in the generation and distribution of electricity.
3. The use of slag for the manufacture of ggbs potentially saves it from having to be disposed of to tip.

Table 5: Environmental burdens associated with the manufacture of ggbs

Limestone fines will also have some environmental burdens, arising from the quarrying, drying and grinding of limestone.

At first sight, it might appear that the best addition for increasing the sustainability of concrete would be the one with the lowest environmental burden. However there are several factors that need to be taken into account:

- the environmental impacts required to produce the addition,
- the replacement level
- any need for an increase in cementitious content to achieve specified 28-day strength
- transport distances

In practice, the replacement level and the need for extra cementitious are the most important factors Ggbs is particularly effective because it is highly cementitious and can be used at high replacement levels, (typically 50% or more) and can usually replace Portland cement on a 1:1 basis.

A UK Concrete Industry Alliance project studied the relative environmental benefits of using ggbs and pfa in concrete. The calculated environmental impacts per tonne of concrete, relative to a reference Portland cement concrete are shown in Table 6, for concretes of the same 28-day strength ('C30')

Impact	100% PC	50 % ggbs	30% fly ash
Greenhouse gas (CO_2)	142 kg (100%)	85.4 kg (60%)	118 kg (83%)
Primary energy use	1,070 MJ (100%)	760 MJ (71%)	925 MJ (86%)
Mineral extraction	1,048kg (100%)	965 kg (92%)	1007 kg (96%)

Table 6: Calculated environmental impacts for 1 tonne of concrete [5]

From this table it can be seen that replacing 50% of the Portland cement with ggbs has resulted in a 40% reduction in the carbon dioxide emissions associated with the concrete. Use of fly ash has also resulted in a significant reduction. By contrast, replacing 50% of the Portland cement with ggbs has only reduced mineral extraction by 8%. The environmental issue where additions have most to offer for concrete is carbon dioxide emission. By contrast, they have little effect on mineral extraction where the major burden for concrete comes from the aggregate.

Availability and transport are two further issues that are relevant to the use of additions. Ggbs and fly ash are widely available, and transport distances from the point of production to the point of use are generally comparable to that for Portland cement. In practice, transport of cement and additions are relatively insignificant factors for the carbon dioxide burden of concrete because the carbon dioxide emission associated with moving a tonne of cement 100 miles by road is only about 10kg, i.e. about 1% of the carbon dioxide associated with producing it.

CONCLUSIONS

Additions are currently making significant contributions to reducing the environmental burden of concrete, particularly in relation to carbon dioxide emission (greenhouse gas). In 2005, the use of ggbs and fly ash saved the UK:

- 2.5 million tonnes of carbon dioxide emission
- 2 million megawatt hours of energy
- 4 million tonnes of mineral extraction
- potentially, 2.5 million tonnes of material sent to landfill

There still remains considerable potential for their increased use.

REFERENCES

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