UNITED KINGDOM QUALITY ASH ASSOCIATION

Technical Datasheet

Sustainability using Fly Ash in Concrete

Overview of the issues

Concrete, while being an irreplaceable part in modern construction techniques, in recent years has attracted increasing scrutiny in respect of how sustainable the material is. This is primarily due to Portland cement being based on calcium carbonate as the main material in its manufacture. The carbon dioxide arises from two main sources:

1. The energy input as electricity in producing Portland cement (CEM I) is due to the drying and grinding of the ingredients;
    a. Cement is made by mixing calcium carbonate (limestone, chalk, etc) and silica (clay or sand).
    b. These are dried using the waste heat from the kiln.
    c. They are then inter-ground to a fine powder.
    d. This is heated in a kiln fired mainly by coal or gas to a high temperature (~1450C) for a long period of time, where the reactions take place and a clinker forms.
    e. This is then ground to a fine powder.
    f. The whole production process is energy intensive with a cement works requiring the electricity for a small town.
    g. The fuel and electricity amounts to additional CO_2 emissions of ~450kg/tonne of Portland cement.
2. The release of carbon dioxide from the dissociation of Calcium Carbonate to Calcium Oxide occurs in the cement kiln at about 850C. This is inevitable and simple chemistry and produces ~550kg of CO_2 per tonne of limestone/chalk.

It is from the processes as given above one arrives at the often quoted 1 tonne of CO_2 per tonne of cement.

The cement industry has responded in recent years to these issues by replacing the primary fuels (coal and gas) with waste and secondary fuels wherever possible and by considerable efficiencies in kiln/factory design. Additionally, they are producing cements that are blended in factory with secondary cementitious materials, such as fly ash, limestone, etc. Over recent years they have managed to reduce the Embodied CO_2 (ECO_2) in the Portland cement produced from ~980kg/tonne to ~860kg/tonne. Portland cement is sold to EN197-1 as CEM I, though the standard also describes a wide range of other cements containing fly ash, Ground Granulated Blast-furnace Slag (GGBS), natural pozzolanas, etc. There is increasing use of these other non CEM I cements as a way of reducing overall CO_2 emissions.

In addition to the above factory made cement options, the concrete producers are able to contribute to reducing CO_2 by the use of mixer additions. There are two main additions used within the UK, Fly Ash and GGBS. Both these materials are produced to harmonised EU standards and are third party accredited products. This is where the similarities disappear as the two products work in differing ways; GGBS is partially a cement, whereas Fly Ash is a true pozzolanic material.

Fly ash

Fly ash results from the burning of coal in power stations and is simply the mineral residue in the coal laid down with the coal measures many millions of years ago. These melt in the furnace producing a fine powder consisting of glassy spherical particles. The CO_2 emissions associated with power generation are not considered as being part of the environmental burden on the fly ash.

Fly ash differs from GGBS in that it contains little calcium and therefore is unable to react cementitiously unless there is lime (calcium oxide or calcium hydroxide) from another source present. This lime may be added as a separate ingredient or resulting from the hydration of CEM I, the latter in the case of concrete. As fly ash does not contain any significant lime, the ash addition rates are generally much lower than found with GGBS, e.g. up to a maximum 55% of fly ash within the total cementitious content will normally be used.

Figure 1 - A fish pass and slipway made using fly ash concrete

GGBS

GGBS is a by-product of the manufacture of iron, resulting from the addition of limestone to the blast furnace to remove mainly siliceous and other impurities from iron ore. As with the manufacture of cement, CO_2 is produced in the blast furnace, as part of this process. The resulting material rapidly cooled to ensure amorphous material is formed. This produces both a wet and a very hard clinker that has to be dried and then ground to a fine powder. Slag clinker is harder than cement clinker, so more energy is required to produce a sufficiently fine product, especially as GGBS is often ground much finer that CEM I. The environmental effects of the production of CO_2 in the blast furnace are normally associated with the production of iron rather than the by-product GGBS. GGBS has similar chemistry to cement except it is a much slower reacting material. The primary difference is a lower calcium and higher silica content than CEM I. Usually it is mixed with CEM I in concrete manufacture which acts as an activator, with up to 80% of the total cementitious material being GGBS. A significant quantity of the iron slag is imported from mainland Europe to the UK for the production of GGBS.

Comparing Differing Options

There are many sustainability comparisons between the two main secondary additions available from a number of sources. These range from carbon calculators through to direct comparisons. Because of the inherently higher proportions of GGBS that can be used in replacing CEM I in traditional concrete mixes, the immediate conclusion usually reached is GGBS is more sustainable than fly ash. However, there are a considerable number of factors other than the stark ECO_2 emissions values that need thought before arriving at a final conclusion. Some factors worthy of consideration are:

1. Fly ash produced and supplied to EN450-1:2005 Category N has very little environmental impact associated with its production. It is at the simplest level fly ash taken from a silo without further processing or conversely it can be processed to reduce carbon content and/or make finer to improve its performance and make a compliant material. These processes amount to a minimal impact relative to the manufacture, drying and grinding of other materials.

2. Fly ash uses the excess lime from the hydration of Portland cement (~66% CaO) to form the hydration products when used in concrete, see UKQAA Technical Datasheet 1. Therefore there is virtually no CO_2 associated with the chemical reduction of lime excepting that from the CEM I when using fly ash (~2% CaO) as an addition. However, GGBS contains significant amounts of lime (~42% CaO). Whether this lime results from the chemical reduction of limestone for GGBS in the blast-furnace or from the manufacture of Portland cement in the cement kiln, means these materials in the most basic chemical terms very similar. This is best shown by example:

   A concrete producer makes a RC30 70 mm W/C 0.65 MCC 260. The environmental mix composition for various cementitious types can be calculated is as follows:

	Content in kg/m^3 for equal 28 day strength concretes				
Type	**CEM I**	**Fly ash**	**GGBS**	**Total Cementitious Content kg/m^3**	**Total CaO kg/m^3 from the cementitious components**
RC30 with 100% CEM I	305	0	0	305	200
RC30 with 30% fly ash	242	103	0	345	161
RC30 with 50% GGBS	150		150	305	162
RC30 with 50% fly ash	225	225		450	153
RC30 with 70% GGBS	102		238	340	167

One can clearly see that proportions of CaO (quicklime) in the resulting concrete mixes containing either GGBS or fly ash are very similar; though both are markedly reduced from that of CEM I only mix. This CaO was produced from $CaCO_3$ in some process, somewhere - simply because CaO does not occur naturally. It follows that both the common additions used to produce concrete involve roughly an equal amount of CO_2 being emitted to the atmosphere.

3. GGBS does have to be ground to a fine powder and being somewhat harder to grind than Portland cement, this results in a fairly significant energy use and the associated emissions.

4. Fly ash is a true by-product in that if electricity production stops, so does the supply of fly ash. However, at the time of writing this, it is well known there is insufficient indigenous GGBS available in the UK and a considerable amount is imported from mainland Europe and farther a field to maintain supplies. If GGBS is used in preference to fly ash, of course this resulting ash is most likely to be used for a low grade application or disposed of in the UK.

5. If fly ash produced is compliant with EN450-1:2005 for use in concrete and yet is not sold for that purpose, the excess will either be used for lesser applications or become a waste and landfilled. Landfilling excess material will involve taking one of a number of possible routes:

   a. It will be mixed with water, known as conditioning, taken to a landfill site, compacted and ultimately grassed over and/or returned to farmland or building plots.

   b. Some ash may be pumped into lagoons as slurry and allowed to settle eventually forming stable land.

   c. In some cases conditioned ash may be transported many miles to suitable disposal sites.

   Inherent within each of the above, are considerable additional environmental and cost implications such as the energy for processing, transportation, etc and all adds to the overall environmental burden of disposal. This coupled with preparation of the disposal sites, when this material is displaced by an imported product. One could consider the production and use of fly ash in concrete as having an overall double positive environmental impact, firstly by reducing the overall emissions by partially replacing CEM I and secondly by avoiding the emissions associated with disposal.

6. Landfilled fly ash is not necessarily lost forever, as it can be recovered, dried and processed to produce an acceptable cementitious/pozzolanic material. This is still compliant with EN450-1:2005. However, such recovery does add to the overall ECO_2 burden and the preferred route is always by the sale of freshly produced fly ash.

The environmental impacts of different mix formulations

There are numerous ways of comparing differing cementitious types and the associated environmental impacts. This depends on the source data used and the level of complexity one uses. The BRE Environmental Profile scheme has produced numerous profiles for various products, some of which are made freely available. Some of these profiles are kept confidential by the supplying industry. However, both the secondary cementitious additions industries, e.g. fly ash and GGBS, have made public their Environmental Profile. Each profile has a value for Global Warming Potential over 100 years expressed as equivalent tonnes of CO_2, the GWP (100) figure.

Mix description	CO_2 kg/m^3 using GWP (100) values for CEM I	% reduction on CEM I mixes by using 30% fly ash	% reduction on CEM I by using 50% fly ash	% reduction on CEM I using 50% GGBS
Blinding, mass fill, strip footings, mass foundations	226	21%	47%	46%
Trench foundations	236	19%	47%	46%
Reinforced Foundations	314	19%	39%	43%
Ground floors	334	18%	40%	42%
Structural: in situ floors, superstructure, walls, basements	368	17%	36%	39%
Typical Precast Concrete Mix	426	20%	38%	40%
XC1, 40mm cover	250	27%	32%	42%
XC3/4, 40mm cover	314	39%	39%	43%
XS1, 40mm cover	368	26%	48%	43%
XD3, 40mm cover	514	37%	53%	48%
Note: The above figures are for typical concrete mix designs and based on available figures for GWP (100) from cradle to gate and estimates for materials where such data is not available. Cement, addition, aggregate and water have been included, but transport of the materials to the concrete producer and subsequently to the construction site excluded. The impacts for individual sites may vary considerably from the above figures.				

The previous table is a comparison between the total GWP (100) for a CEM I concrete and the possible reductions using additions at various rates. Traditional 30% fly ash and 50% GGBS concretes are given, plus the use of a 50% fly ash combination.

As will be seen from this table, comparable reductions in overall CO_2 emissions are possible by adopting the use of 50% fly ash contents. While this does need some care, there are many technical reasons as well as environmental reasons why this is a sensible approach. Higher fly ash contents are effective in thicker sections, where early strength is less critical, when exposed to potentially deleterious compounds, where higher than UK normal curing temperatures exist, etc. In the USA there is considerable interest in the use of High Volume Fly Ash Concrete, where even more than 50% fly ash is used.

Figure 2 - Heathrow Terminal 5 used fly ash concrete

High Volume Fly Ash concrete

As the production of Portland cement accounts for ~7% of the world's production of CO_2, it is not surprising that many researchers have looked at increasing the content of fly ash in concrete to reduce the Portland cement component and therefore, the overall environmental impact. In recent years this has become known as High Volume Fly Ash (HVFA) concrete. This contains in excess of 50% fly ash as a proportion of the total cementitious content, with up to 70% being possible and even 85% being proposed. However, do not think this is a new concept. In the UK in the early 1980's experiments with High Fly ash Content Concrete (HFCC) were carried out at Didcot power station using up to 56% fly ash, Mumbles slipway (52% fly ash) and Wincaton Sewage Works (54% fly ash). These structures were tested after 10 years using cores and considerable gains in strength were found, low depths of carbonation and low oxygen permeability values measured.

In the USA and India various contracts have been successfully carried out with HVFA. By the judicious use of suitable admixtures such as super plasticiser and air entraining agent, many of the perceived technical issues of setting times, strength gain, frost resistance, etc can be overcome. While strength at later ages, e.g. 91 days, would normally be specified for such concretes, reasonable 28 day strengths can be obtained. These HVFA mixes can be adjusted accordingly depending on the construction phasing, weather conditions, etc to optimise the environmental performance. Insitu strength has been found to be greater than would be expected, particularly in thick sections and warmer weather. One would expect parameters like carbonation to be relatively high with mixes containing so little Portland cement, but the low permeability of HVFA concrete ensures that CO_2 cannot permeate the concrete and corrode the reinforcing. Carbonation depths are found to be low in real concretes, whereas accelerated testing results in high result/apparent poor performance. The heat of hydration is reduced substantially, therefore thermal cracking is eliminated and high quality finishes can easily be achieved.

Estimating the reduction in GWP (100) or ECO_2 values may be harder with HVFA mixtures, but the benefits are considerable and can amount to ~60% reductions in comparison with traditional CEM I concrete.

Conclusions

The use of fly ash in concrete can significantly reduce the overall CO_2 emissions by substituting for some of or even the considerable majority of CEM I in a concrete. In general terms it is true to say that the greater the proportion of fly ash, the greater the environmental benefits. By using fly ash from UKQAA members you can be confident that you are using a UK sourced material, diverting material from landfill, reducing CO_2 emissions and yet gaining a considerable number of technical benefits ranging from low heat of hydration, improved resistance against sulfate attack and Alkali Silica Reaction (ASR), plus lower chloride, oxygen and water permeabilities, etc.

Using fly ash in your concrete is a win-win situation for you and the environment.

In general usage the term 'fly ash' is used for pulverized coal ash but it can also cover ash from burning other materials. Such 'fly ash' may have significantly differing properties and might not offer the same advantages as ash from burning pulverized coal. UKQAA datasheets only refer to PFA / fly ash produced from the burning of predominantly coal in power stations.

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