Lindon K. A. Sear, BSc, PhD, FICT - Technical Director
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Concrete: Constructions Sustainable Option

Fly ash in Concrete - Enhanced Durability For Sustainable Construction

ABSTRACT. Fly ash has been used for many years in concrete because it is able to offer many technical advantages such as enhanced durability and performance. For example its ability to improve the sulfate resistance, reduce chloride diffusion, prevent alkali silica reaction, give long term strength gain properties and reduce heat generation in cementitious applications is well known.

These benefits have been researched by many people with published papers totalling several thousands. However, it is only in recent years it is increasingly recognised that using fly ash in concrete also results in significant environmental and sustainability benefits, simply by replacing virgin aggregates. For example in foamed concrete it acts as a cementitious binder as used in road sub-base hydraulically bound mixtures, by enhancing a structure durability extending its working life, etc. In this way it is able to significantly reduce overall environmental impact and greenhouse gas emissions.

This paper will consider the sustainability and environmental benefits of greater utilisation of the material in cementitious applications. It will review how industry has moved towards reducing environmental impacts using fly ash, the standards and new specifications that have enabled recent changes and look at the future for this important and readily available material.

Keywords: Fly ash, Pulverised Fuel Ash, PFA, durability, sustainability

Dr L K A Sear is the Technical Director of the United Kingdom Quality Ash Association representing the interests of the UK coal fired power station operators. He represents the members of the UKQAA on a number of British and European Standard Committees. He is involved in the steering committees of many research projects ranging from the environmental aspects of PFA/fly ash through to the thaumasite form of sulfate attack. In addition, Lindon gives many presentations and attends exhibitions and conferences relating to the applications of fly ash. Consequently he has a broad knowledge of the use of fly ash in concrete, fill applications, grouting etc.

INTRODUCTION

Fly ash, whether it is coal fired power station ash or volcanic ash, has been used for many years to produce hydraulic cement. In general concrete structures properly made with these pozzolanic materials have proven to be durable without the need for continual remediation and/or replacement. In addition pozzolanic materials reduce the overall environmental impacts of making concrete by reducing the amount of Portland cement required with a given concrete mix. Fly ash from coal fired power stations is a readily available pozzolanic binder, which is not subject to any environmentally expensive processing. But as well as acting as a binder, it is quite possible to use fly ash as an aggregate, replacing natural materials. In whatever way fly ash is added to concrete, in most circumstances as well as environmental and sustainability benefits, there are often significant technical benefits, for example reduced chloride permeability, resistance to alkali silica reaction, enhanced sulfate resistance, etc. In this manner the use of fly ash in concrete and cementitious systems is more sustainable. However, in the future ash quality issues will have to be fully addressed and the introduction of beneficiation processes will become increasingly necessary.

THE PRODUCTION OF FLY ASH

Fly ash is a by-product of the combustion of coal in a power station. Coal contains minerals that were laid down when the coal measures were deposited, many millions of years ago. It is these minerals when burned that form the fly ash. The coal is ground to a fine powder, similar to talcum powder, and burned in the power station furnace at in excess of 1250ºC within 2 to 4 seconds. The high temperature coupled with the ash being in a gas stream results in rounded particles of glassy material being formed. These fly ash particles are extracted from the gas stream using electrostatic precipitators as shown in figure 1 and may be used in a number of ways, primarily within the construction industry.

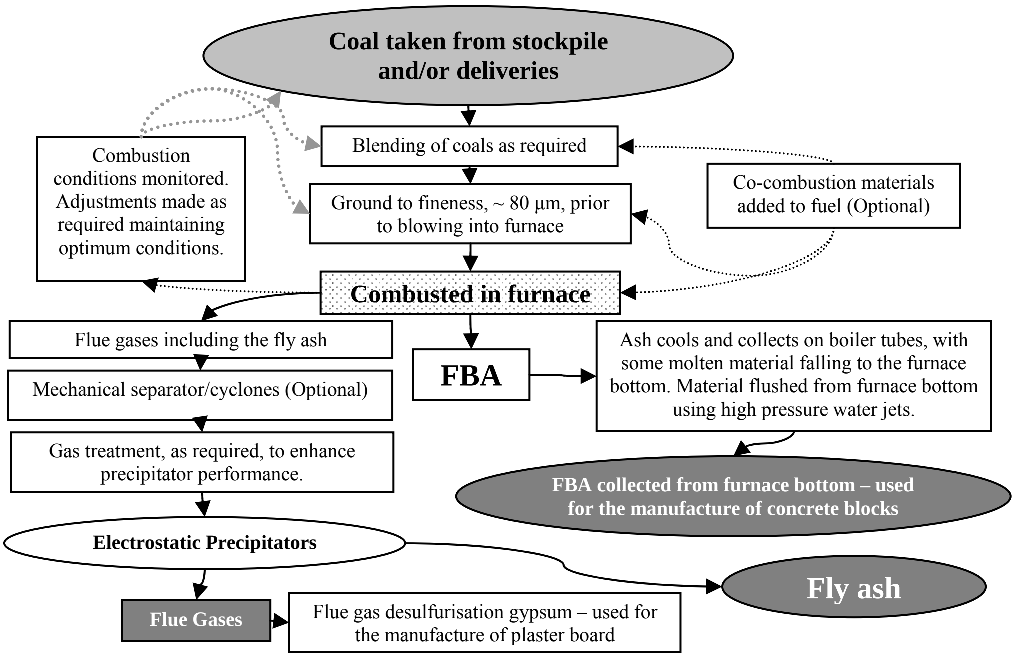
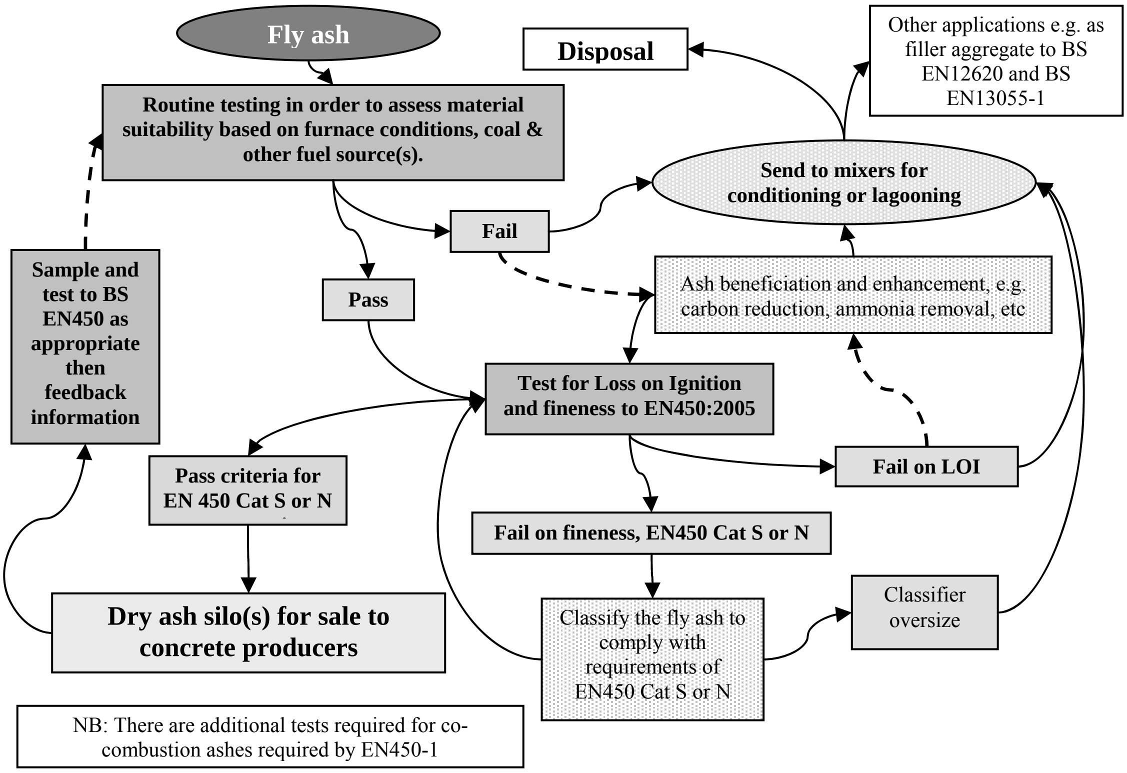


Figure 1 - Flow chart for Fly Ash and Furnace Bottom Ash (FBA) Production at a coal fired power station

The resulting dry ash will be tested for compliance with the appropriate standard. For example fly ash production to EN450-1:2005, when it is used as a Type II addition is shown in figure 2. Fineness and Loss On Ignition (LOI) are the common parameters used for control purposes, though some selection based on other criteria such as colour may be used at some power stations. Depending on the requirements of the fly ash, the material may be tested and either accepted for direct sale to the customer, processed to bring the material within the specification or rejected, where it will be sent to the mono fill disposal site found at or near to most power stations. Normally for use in concrete the fly ash would be supplied dry, though conditioned ash may be supplied as filler aggregate to cement, precast concrete and grouting companies.

The use of fly ash in concrete, in whatever form it is supplied, is beneficial to the environment as it reduces the amount of Portland cement and/or replaces virgin aggregates. Fly ash will continue to be produced as pulverised coal fired electricity generation will continue for the foreseeable future [1], though this is felt by many to be dependant on development of clean coal technologies and carbon capture [2]. Coal fired power generation, irrespective of the CO_2 issues, forms the predominate backbone of UK power generation as shown in figure 3. Even though the stock of coal fired power stations is rather old, modernisation and retrofitting of equipment has kept them operational in many cases well beyond their original design life. With an ever expanding UK population and the apparent lack of an energy policy for a number of years, coal fired generation has proven to be reliable, cost effective and readily available. For this reason ash production has risen in recent years to ~6,000,000 tonnes per annum. However, there are ash quality issues to consider.



NB: There are additional tests required for co-combustion ashes required by EN450-1

Figure 2- Flow chart for production of Fly ash for use in concrete as a Type II addition complying with BS EN450:2005

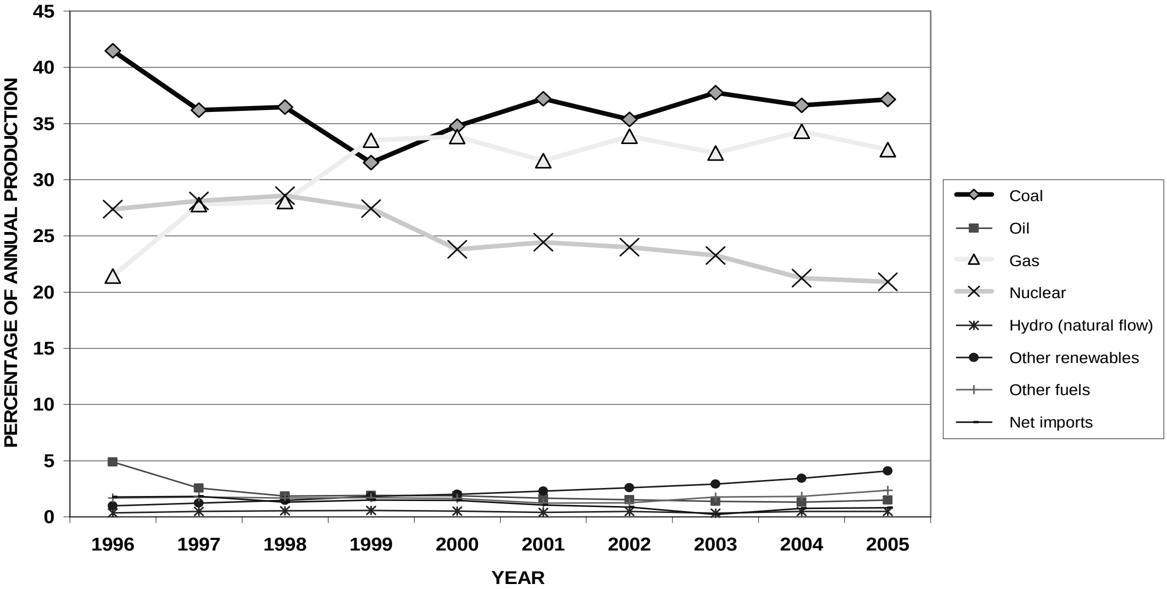


Figure 3 - Proportion of Electricity per Annum by Energy Source
Source: DTI Energy Statistics [3] (Dukes 5.4)

Ash Quality Issues

Ash quality is seen by some to have declined in recent years. Loss On Ignition (LOI) of <5% was common place 10 years ago, but in recent years a mean of 6% is more common. For use in concrete, loss on ignition (LOI) is seen as a major issue particularly when air entrainment is required. The UK standard for concrete, BS8500 [4], limits LOI of fly ash as an addition to a maximum of 7%. However, in order to reduce the emissions of nitrous oxides from power stations, the industry has been fitting so called low NOx burners. This has resulted in an increase in loss on ignition within fly ash in recent years [5]. Eventually all coal fired stations will have to fit these burners and this trend has resulted in carbon reduction systems being fitted to some power stations. Within the UK the STI electrostatic system [6] has been fitted to three power stations, which is capable of producing ash with LOI's as low as 2.5% from 10% or higher LOI ash. Other stations are investing in the Rocktron [7] approach for full ash beneficiation.

The injection of ammonia into the furnace gas stream has been another issue in recent years. This is designed to increase precipitator efficiency when using low sulfur coals. Though the amounts of ammonia are extremely small, there have been incidents where concrete made with ammoniated ash has released noticeable amounts of ammonia [8]. The alkali environment in cementitious systems releases ammonia gas and as ammonia levels above 10ppm are easily detectable by man, the issues are one of smell and health and safety rather than having a detrimental effect on the concrete. This problem is not insurmountable and the ammonia can be removed efficiently with the appropriate equipment. One power station in the UK is fitting this equipment to overcome this problem.

It is envisaged in the future that such beneficiation equipment will become more prevalent in order that the fly ash industry can continue to supply the cementitious and concrete markets for years to come.

Where does all the ash go to?

Products from coal fired power stations are used in a variety of construction applications. Many of these applications are cementitious; the largest proportion of the UK fly ash produced going towards making aerated concrete blocks, with concrete, cement manufacture, fill and grouting being the others. In all these applications ash is used because it acts both as inert filler and as a pozzolanic material, enhancing strength and durability.

The market breakdown [9] for 2005 is shown in figure 4, but note that it excludes the material that is landfilled. Some ~50% of the fly ash produced within the UK is currently being landfilled, which should be considered a wasted resource rather than a waste. Of the fly ash that is disposed most is conditioned, which is where it is mixed with water, typically ~15% and disposed of in mono landfill site, being transported as an aggregate would be. Some is lagooned, i.e. mixed with copious amounts of water and pumped as slurry to settlement lagoons. In either case the fly ash could be recovered and used in concrete, though there is an apparent reduction in ash reactivity with time.

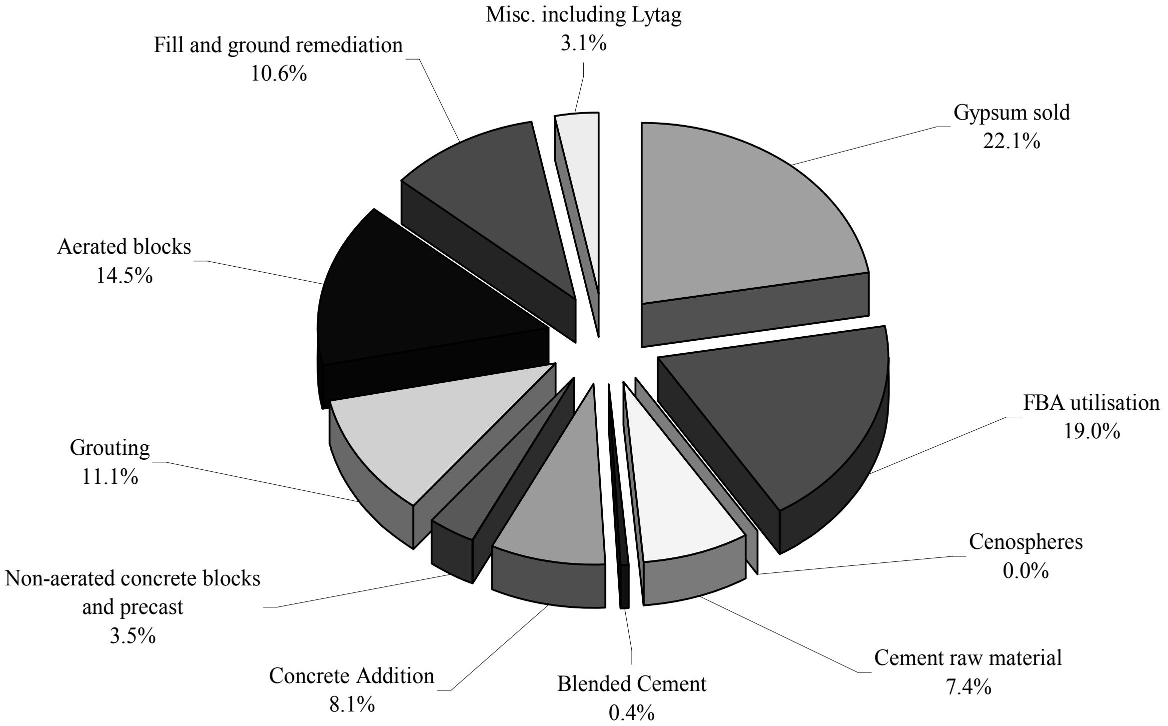


Figure 4 – The markets for coal fired power station products.
The proportions of sold material by application – Jan to Dec 2005

Why do concrete producers take fly ash?

There are many reasons why fly ash is used within the cement and concrete industry. While we will mainly consider the environmental and sustainability aspects in this paper, there are numerous technical benefits imparted to concrete containing fly ash, it is economical, it is available in larger quantities, etc. These benefits have been well documented over the years and the current standards for concrete reflect the technical performance of fly ash concrete.

ENVIRONMENTAL ASPECTS OF FLY ASH IN CONCRETE

Let us consider that fly ash collected from the electrostatic precipitators can either be used or disposed of. Disposal involves the ash being sent to large mixers, similar to concrete pan mixers, where water is added. This is known as conditioning. The resulting earth dry/conditioned ash is loaded on trucks or conveyors to be taken to the disposal site. Mixing the ash with water and transporting it to the landfill site in itself requires energy and has an environmental impact. However, if ash is to be used in concrete it is normally supplied as a dry material in a cement tanker. As there is no energy and water use involved for dry ash the overall environmental impacts are reduced.

The cement industry has become a big user of fly ash both as a kiln feed and for blending into cement. The ash may be added as a minor addition constituent, which can be up to 5% of cement, or within blended cements. These additions comply with BS EN197-1 ‘Common Cements’ and are an effective way for a cement supplier to reduce the overall emissions associated with Portland cement manufacture.

Fly ash for use as a concrete addition at the mixer is normally supplied complying with EN450:2005, where it can be counted as being part of the cement content of the concrete, see BS8500. EN450 describes two basic types of fly ash, Category N and Category S. The differences are described below.

EN450:2005 Category N fly ash

Category N, which we shall call ‘normal’ fly ash, is fly ash that is taken dry direct from the power station. EN450 imposes a series of quality control requirements on the ash, such as fineness, chemical properties, etc but this material would normally be controlled by a process of selection and rejection based on the various control parameters. As a result Category N fly ash is generally sourced straight from the power station silos without any processing. This could be considered as zero environmental impact at the factory gate from production and even possibly a negative impact if the energy for disposal is taken into account.

EN450:2005 Category S fly ash

Category S, which we shall call ‘special’ fly ash, is again dry ash from the station. In the majority of cases this is processed to remove the coarser ash particles within the material. Typically this is done with air swept classifiers and the process reduces the water demand and increases the strength of the resulting concrete by removing the misshapen and generally coarser fraction. This requires energy, typically 9.75 kW/h per tonne of Category S fly ash, which equates to ~4.2 kg of CO_2 per tonne of product. However, in relation to the improvements in reactivity and water demand of the resulting concretes, classification is a positive environmental benefit.

What are the relative impacts of using fly ash?

As we have established, the environmental impacts of producing fly ash are minimal at the factory gate with little or no processing being required. Some users take fly ash as conditioned material for use within concrete. Conditioning is the addition of typically ~15% water to the ash to prevent dust problems. This is carried out in large mixers similar to those for mixing concrete. The resulting damp ash is either sold for other applications or disposed of in mono landfills. It could be said that the act of conditioning the ash adds to the environmental costs of disposal whereas using dry ash to EN450 Category N fly ash in concrete further reduces the overall impact.

Table 1 shows the calculations inherent in comparing a 40 MPa CEM I concrete with mixes containing both 30% and 50% EN450 fly ash additions. A figure of 960 kg/tonne of CO_2 was used for CEM I within these computations. The calculations would be similar if CEM II/B-V (30%) or a CEM IV/B (50%) blended cements as opposed to mixer additions were to be specified. No admixtures are used and a typical UK average figure of 0.43 kg of CO_2 is produced to generate 1 kWh of electricity. It is clear that the classification of fly ash has no significant effect on the overall reduction in CO_2 emissions, as the power consumption is relatively minimal. It is clear the use of fly ash results in significant reductions in overall CO_2 emissions.

Table 1 – The impacts of producing a 40 MPa design strength @ 28 days concrete;

ENVIRONMENTAL IMPACT	CEM I ONLY	CAT N	CAT S	CAT N	CAT S
Normal replacement level	0%	30% fly ash		50% fly ash	
Total Cementitious 40 MPa concrete kg/m^3	280	320	310	410	395
Normal extra over of total cementitious required to maintain strength @ 28 days	0%	+15%	+10%	+45%	+40%
Typical CEM I reduction in kg/m^3 for 40 MPa concrete @ 28 days	N/A	-56 kg/m^3	-63 kg/m^3	-75 kg/m^3	-83 kg/m^3
CO_2 reduction achieved	N/A	- 53.76 kg/m^3	- 60.5 kg/m^3	- 72.0 kg/m^3	-79.7 kg/m^3
Electrical energy – CO_2 produced to process material @ 0.430 kg per kW/h	N/A	NIL	9.75/1000 x 93 x 0.43 = 0.39 kg/m^3	NIL	9.75/1000 x 197.5 x 0.43 = 0.83 kg/m^3
Overall reduction in CO_2 emissions per m^3 of concrete produced	N/A	- 54 kg/m^3	- 60 kg/m^3	- 72 kg/m^3	- 79 kg/m^3
Percentage reduction in comparison with CEM I only concrete	0%	-20%	-22%	-27%	-29%

As fly ash is pozzolanic, the reactions are relatively slow in comparison with modern CEM I. There are benefits in specifying strength at 56 days, by which time the pozzolanic reaction will have had some significant contribution to the measured strength. Table 2 repeats the 40 MPa concrete calculation, but based on a 56 day concrete strength.

Table 2 – The impacts of producing a 40MPa design strength @ 56 days concrete;

ENVIRONMENTAL IMPACT	CEM I ONLY	CAT N	CAT S	CAT N	CAT S
Normal replacement level	0%	30% fly ash		50% fly ash	
Total Cementitious 40 MPa concrete kg/m^3	265	280	270	375	360
Normal extra over of total cementitious required to maintain strength @ 56 days	0%	+6%	+2%	+40%	+36%
Typical CEM I reduction in kg/m^3 for 40 MPa concrete @ 56 days	N/A	-69 kg/m^3	-76 kg/m^3	-78 kg/m^3	-85 kg/m^3
Overall reduction in CO_2 emissions per m^3 of concrete produced	N/A	- 66 kg/m^3	- 73 kg/m^3	- 75 kg/m^3	- 81 kg/m^3
Percentage reduction in comparison with CEM I only concrete	0%	-26%	-29%	-29%	-32%

Are these the only environmental benefits are there others?

In addition to the obvious benefits of reducing overall CO_2 emissions when replacing Portland cement, fly ash can act as an aggregate, the so called inert filler. To produce 1 tonne of virgin aggregate takes ~21 kg of CO_2, whereas fly ash is CO_2 neutral. Fly ash can comply with both BS EN12620 Aggregates for Concrete [10] and BS EN13055-1 Lightweight Aggregates for Concrete, Mortar and Grout [11] as filler aggregate and therefore it may be used within concrete and grouts to replace virgin aggregate. In concrete mixes this only becomes practicable when either very coarsely graded fine aggregates and/or very low cement contents are being used. For example it is quite possible to design a 10 MPa concrete mix for pumping with a low cementitious content, by adding fly ash as filler aggregate. With such an application it is important to remember that the particle density of fly ash is typically ~2.3 where naturally aggregate is higher ~2.6, i.e. a 13% increase in volume per unit mass. The increased volume has to be allowed for in the mix design.

In grouting, fly ash has proven to be far superior to virgin aggregates for most applications. The inherent round particle shape of fly ash in comparison with many virgin materials reduces the required water content for a given workability and makes the grout easy to pump. The pozzolanic reaction, coupled with the lower water content, gives better strengths with fly ash than the virgin aggregate equivalent. This leads to a reduction in Portland cement content and, due to the reduced particle density of fly ash, less material being required. These differences can be very substantial, with one grouting contract [12] reporting that using fly ash grouts reduces vehicle movements by 40% and material cost by ~50% in comparison with those for Portland cement and virgin sand grout.

Other factors

The above calculations do not take into account transportation of the material to the user. Many environmental profiles use simple assumptions for transport using average travel distances, often ignoring the impacts of shipping, handling etc for imported materials. In the real world transport is a major environmental impact and whether it is fly ash, cement, aggregates, etc a comprehensive environmental assessment has to take transport into account. For example Parrott [13] concluded that transporting the raw materials from the source to the concrete plant and the concrete to the site accounted for ~10% of the environmental impacts of producing the concrete on average. If imported materials are used the additional transport and handling would increase the environmental impacts significantly.

What is clear is that the overall environmental impacts are different depending on circumstances. Issues such as transport distances, imported materials, methods of transportation, application for the product, exposure conditions, etc all have to be assessed on a case by case basis in order to draw sensible and accurate conclusions.

ENHANCED DURABILITY

Fly ash imparts many technical benefits to concrete. These include resistance to the penetration of chlorides reducing corrosion of reinforcing, preventing alkali silica reaction, reducing the heat of hydration and reducing the risk of cracking, etc. These benefits, when fly ash concrete is used in the appropriate applications, can extend the working life of a structure.

Chloride Ingress

The ability of fly ash concrete to reduce the permeability in respect of chlorides is well known with in excess of 480 papers published on the properties of fly ash concretes. The improved performance of fly ash concrete is reflected within BS8500, the UK National specification for concrete. Table 3 is a small extract of the 100 year design life tables for XD3 exposure. This shows the technical benefits of using fly ash, which are cement and combination types IIB-V and IVB-V, and are reflected within the specification as significantly lower strengths, minimum cement contents and maximum water/cement ratios are required when using fly ash in comparison with CEM I.

Table 3 – Extract of BS8500 UK National Specification for Concrete

NOMINAL COVER mm	55 + ΔC	60 + ΔC	65 + ΔC	CEMENT/COMBINATION TYPES
XD3 for 100 year design life	C45/55$^{E)}$ 0.35$^{F)}$ 380	C40/50$^{E)}$ 0.40 380	C35/45$^{E)}$ 0.45 360	CEM I, IIA, IIB-S, SRPC
	C32/40$^{E)}$ 0.45 360	C28/35 0.50 340	C25/30 0.50 340	IIB-V, IIIA
	C25/30 0.50 340	C25/30 0.55 320	C25/30 0.55 320	IIIB, IVB-V

The reduction in cementitious content when using fly ash can result in very significant additional reductions in environment impact in some exposure classifications. For example using table 3 with 60 mm nominal cover using the IIB-V mixes results in a reduction of CO_2 of ~39% and for IVB-V a reduction of 45% in comparison with CEM I.

Alkali Silica Reaction

Similarly with Alkali Silica Reaction (ASR), the addition of fly ash to the concrete significantly reduces the risks of this deleterious reaction occurring. This is recognised within BRE Digest 330 [14] and BS8500, with no distinction being drawn between Category S or N material. At least 25% fly ash is required to enhance the resistance to ASR and higher proportions are required for the most reactive aggregate/cement combinations.

Sulfate Resistance

Fly ash concrete gives increasing sulfate resistance with increasing ash content. In respect of the formation of ettringite, a minimum of 25% fly ash of the total cementitious content is required to give sulfate resistance to concrete as per BRE Special Digest 1 [15] and BS8500. However, for the thaumasite form of attack, recent research shows there are considerable advantages in using 50% fly ash of the total cementitious content with the higher classes of sulfate exposure.

Carbonation

It is continually levelled against PFA concrete that carbonation is greater than for Portland cement, especially with higher proportions of ash, e.g. >30% - 55%. In most research organisations it is normal to assess the carbonation of concrete using accelerated testing regimes, by increasing the proportion of CO_2 to which the concrete samples are exposed. While this accelerates the ingress of CO_2, it doesn’t reflect the true performance of materials such as pozzolanas as it fails to accelerate the hydration characteristics and the pore blocking of PFA that lower permeability and reduce the accessibility of CO_2 to the concrete.

It is generally accepted that concrete of equal 28 day strength has similar carbonation performance irrespective of cementitious type, including fly ash based concrete. It is this premise that is used within BS8500 in respect of the carbonation exposure classes, XC 1 to 3.

REDUCING THE CARBON FOOTPRINT OF CONCRETE FURTHER

The substitution of Portland cement with fly ash reduces overall CO_2 emissions. However, if a structure could be designed and constructed to last for a longer period of time and/or use fewer materials for the same performance criteria, this would automatically reduce the carbon footprint. As well as the above obvious comparisons, fly ash can be used to significantly reduce the carbon footprint of a concrete construction by taking advantage of the durability enhancement possible using such pozzolanic materials. As just one example of best environmental practice, Heathrow Terminal 5 required a 7MPa Tensile Strength concrete for runway construction [16]. They used fly ash to reduce the overall carbon footprint and by judicious design and modern admixtures managed to increase the flexural strength sufficiently to reduce the runway thickness. They have also experimented with 40% fly ash contents, to further reduce environmental impacts. The result is a more durable structure using less material, producing less overall emissions and a reduced carbon footprint.

SUSTAINABILITY

The UK power industry has produced fly ash since the 1950's and a considerable amount of fly ash has been produced over the years. Many hundreds of millions of tonnes of fly ash are no longer accessible as the number of stations has reduced from in excess of 100 to only 18 coal fired stations. The closed power station sites being developed and the ash disposal sites have been reclaimed or developed, usually for industrial purposes and occasionally for housing. However, on the remaining coal fired power station there is some 55,000,000 tonnes of fly ash readily available and a further 60,000,000 tonnes may be accessible if required. Barlow Mound [17], see figure 5, is an example of a large fly ash stockpile. In addition the combustion of pulverised coal is unlikely to cease in the foreseeable future, for even with carbon sequestration, fly ash will still be produced. The stockpiles of fly ash form a readily available mineral resource for future generations. They would need extracting, screening, drying and possibly grinding or classification for use in concrete, but they could be put to beneficial use. All these technologies already exist and unlike some other secondary materials, there is no need to import fly ash as supply outstrips demand and large quantities of material are available on stock.

Figure 5 – Barlow Mound, Drax Power Station

CONCLUSIONS

Using fly ash in concrete and other cementitious applications can significantly reduce the overall environmental impact by substituting for Portland cement and virgin aggregates. Depending on the application and the exposure conditions, very significant reductions are possible and the enhanced durability and extended lifetime of the resulting structures can lead a further reduced overall environmental impact.

Fly ash is sustainable for the foreseeable future as there are significant amounts of both freshly produced and stockpile fly ash available within the UK that could be beneficially used. There is no need to resort to imported fly ash with appropriate beneficiation.

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