The use of fly ash for enhancing durability and sustainability

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ABSTRACT: Fly ash has been used for many years in a wide range of applications because it is able to offer many technical advantages such as enhanced durability and performance. For example it is able to improve the sulfate resistance, reduce chloride diffusion, prevent alkali silica reaction, and reduce heat generation, etc in cementitious applications.

These benefits have been researched by many people with published papers totalling many thousands. However, it is only in recent years it is increasingly recognised that using fly ash also results in significant environmental and sustainability benefits, simply by replacing virgin aggregates, acting as a cementitious binder reducing overall greenhouse gas emissions, enhancing durability, extending a structures work life, etc. While considering these technical and environmental benefits, it is of a surprise that still a considerable proportion of fly ash produced is landfilled every year.

This paper will take an overview of the use of coal fired power station ash. It will review the wide range of applications for fly ash, looking at more recent developments in research, standards, specifications, ash processing, etc and the new ideas that have emerged for possible applications. The paper will consider the sustainability and environmental benefits of greater utilisation of the material. Also, those applications where little progress seems to being made will be considered and reasons examined.

1 THE USE OF COAL FIRED POWER STATION PRODUCTS

Coal fired power stations produce a range of products which have been used in a wide variety of construction applications for many years. Typical usage patterns are shown in Figure 1, where 64% of the produced products are being used beneficially, either substituting for cement or virgin aggregate/material.

One of the most obvious has been the use of furnace bottom ash (FBA) that has established a role in the manufacture of lightweight concrete blocks for many years. As all UK coal fired power stations are ‘wet bottomed’, the FBA has proven to be a reliable coarse and fine aggregate in lightweight concrete block making, taking 100% of FBA production. In recent years, due to the contraction in the number of coal burning power stations and changes in burner technologies to reduce emissions, there is reduced production and a shortage of FBA. Block manufacturers are having to source similar materials, ranging from recovered bottom ash, incinerator bottom ash and even imported pumice from a variety of sources, including imports. Unfortunately, many of these options involve greater transport distances, processing or depletion of virgin aggregates adding to the environmental impact.

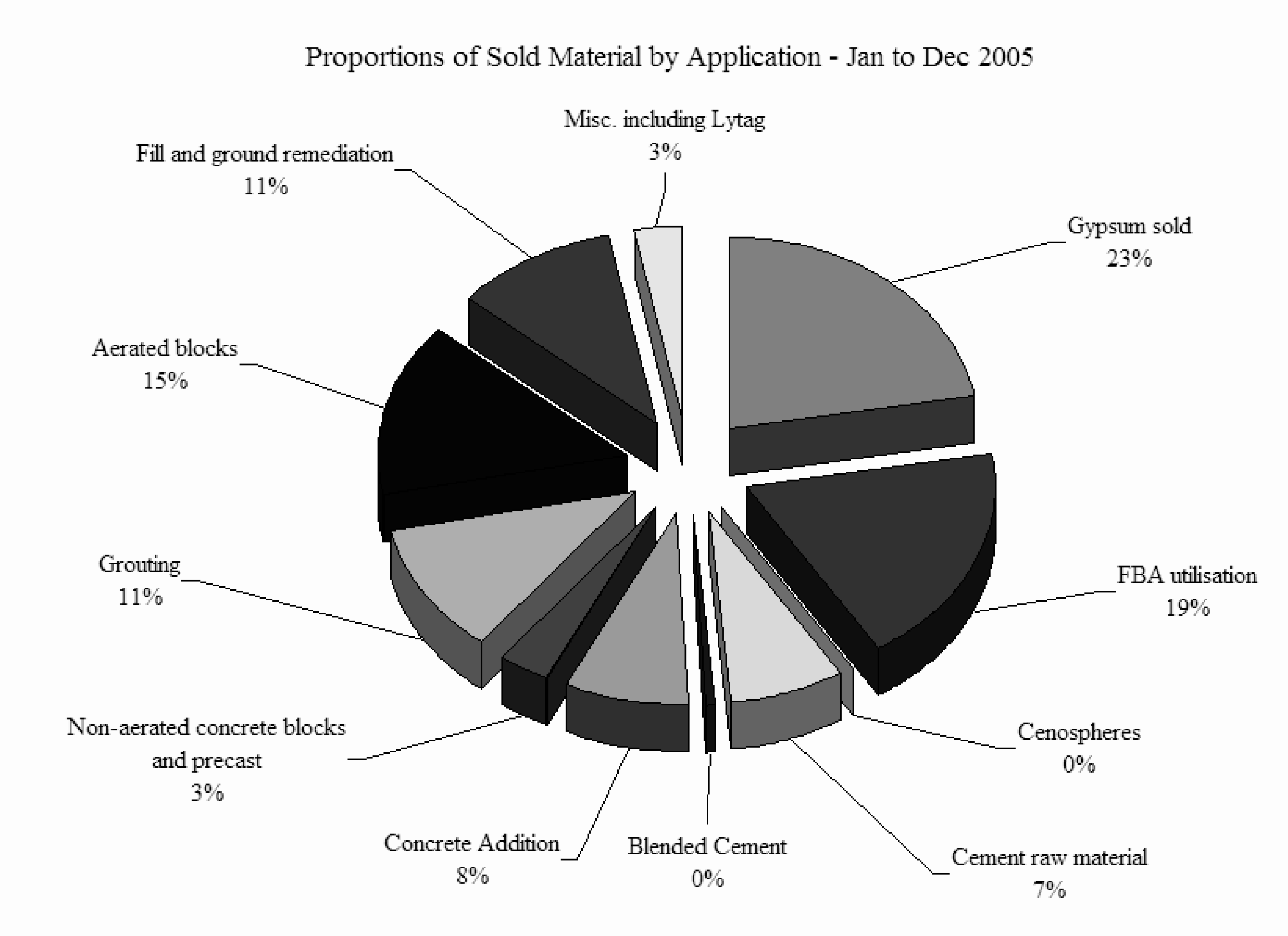

Figure 1. Applications for coal fired power station products.

Many modern power stations now operate Flue Gas Desulfurisation plants, to reduce SOx emissions to air. The majority of these systems use limestone to chemically react with the flue gases producing gypsum. This is very high quality gypsum which has found a ready market in the manufacture of gypsum plasterboard, again taking 100% of production.

The remaining material produced in a coal fired power station is fly ash that is the material which is carried with the flue gases and extracted using electrostatic precipitators. All references to fly ash in this paper refer to pulverised coal fired power station ash; widely know as Pulverised Fuel Ash (PFA) in the UK. This should not be confused with fly ashes produced from other furnaces that will have differing properties and environmental impacts.

Approximately 50% of fly ash produced currently is being used in construction products [UKQAAa 2006]. Many of these are cementitious applications covering cement manufacture as both kiln feed and blended cement, additions to concrete, grouting of mines and caverns, and aerated block manufacture. The other major applications are for fill and ground remediation.

The balance of the fly ash is disposed of in mono landfill. The ash is mixed with water (~15% by weight) so that it can be used in many applications or transferred and disposed of in the landfill without causing dust problems, this process if called ‘conditioning’. As large mixers are required to mix the ash with water and transport distances can be fairly significant, there is an environmental impact associated with preparing for disposal, as well as the obvious impact of disposing of the ash. Some stations use a lagooning system to dispose of their ash. The ash is mixed with copious amounts of water and the resulting slurry being pumped for disposal in lagoons. These are eventually drained and the ash may then be used.

These landfill sites are eventually landscaped and returned to agriculture or for industrial and housing use. However, there is approximately some 55,000,000 tonnes of fly ash readily accessible from these disposal sites, with a further 60,000,000 tonnes of material that could be recovered with greater difficulty.

All recovered material from landfill sites would require some form of processing, at least screening to remove agglomerated and lumpy material. For some applications, for example for use in concrete, drying and classifying may be required to produce a sufficiently reactive product.

2 RESEARCH

Research in to PFA/fly ash has been extensive over the years. The United Kingdom Quality Ash Association (UKQAA) bibliography contains 11,200 papers produced mainly since 1982 that all refer to fly ash. The considerable majority of these relate to the cementitious applications and in the main to concrete.

The properties of concrete using fly ash are well known. Fly ash is pozzolanic producing additional hydration products when in the presence of water and lime. It is these additional hydration products that enhance Portland cement concretes, reducing the permeability. As a result, the addition of fly ash to concrete improves resistance to alkali silica reaction, significantly reduces the permeability to chlorides, improves sulfate resistance, reduces the heat of hydration and the risk of thermal cracking, etc. Some of the very recent and more interesting research projects are summarised as follows.

2.1 *Heat of hydration and thermal cracking*

Two recent projects have been looking at heat of hydration and thermal cracking issues.

The University of Dundee [Dhir et al. 2006] has been testing the heat of hydration of modern cements, including those containing both Ground Granulated Blastfurnace Slag (GGBS) and PFA. The research has suggested that the fly ash is in effect having no effect on the maximum rate of heat production, irrespective of fly ash source, at normal curing temperatures. At higher temperatures the heat production due to the fly ash rises only marginally. These results are consistent with the normal understanding of the pozzolanic reaction.

The second project was to review CIRIA report 91 [CIRIA 1992], which was originally published in 1992. This revised report is due for publication in spring 2007. This report, authored by Bamforth, gives guidance on when thermal cracking is likely to occur and is based on the temperature differential of the concrete's core to the exposed surface. The models have been refined, based on both Bamforth's own work and Dundee University's research and contains more information about critical steel contents, restraint, and compliance with Euro Code 2 (EC2).

It is clear that fly ash is a very effective material in reducing the risks of thermal cracking, see Figure 2, particularly when higher proportions (>30%) are used.

Figure 2. Channel Tunnel Rail Link used PFA to reduce thermal cracking and enhance durability.

2.2 *Resistance to sulfate attack*

The ability of fly ash concrete to enhance the sulfate resistance of concrete has been recognised for many years within the UK. However, the discovery of the thaumasite form of sulfate attack some years ago in the M5 bridge foundations has led to a comprehensive review and more research.

Though much work has been done on PFA complying with BS3892 Part 1 on sulfate resistance, little had been done within the UK on unprocessed fly ash. This was increasingly more popular with the publication of EN450. During the research programme investigating the thaumasite form of attack carried out by both BRE [BRE 2003] and the University of Sheffield [Hill et al. 2003], unprocessed fly ash and greater proportions of ash in the concrete were tried. The UKQAA is also funding work with BRE, which is still ongoing, into the effect of the initial temperature and the resistance to thaumasite attack.

The result of these projects has been to conclude that a 25% fly ash component as a proportion of the total cementitious content does gives a limited resistance to the thaumasite form of attack.

However, higher proportions, >36% and up to the maximum of 55% fly ash content, give a far more enhanced performance with no significant thaumasite attack being observed. The ongoing BRE project to look at curing temperatures as would be experienced in the ground, shows this has little effect other than what one would expect from concrete cured at the average temperature.

2.3 *Soil stabilisation*

The stabilisation of soils using lime has been practiced for some years in road construction. Using the existing soil as a suitable sub grade rather than use vast quantities of imported aggregates has gained favour in recent years as a method of reducing environmental impacts. The process has made many sites accessible and been successfully used.

One issue which has plagued this technique has been the risk of sulfate heave [Britpave 2006]. The lime being added to bind the clays, instead of reacting pozzolanically with the clay, reacts with sulfates present in the clay to form ettringite which expands and disrupts the road surface. As this can occur some weeks or months after the road is constructed, this can prove to be a very expensive problem.

To measure the sulfate content of clays and predict whether such a reaction may occur has been difficult and many contractors have opted for a proven remediation approach. It was found that GGBS [Higgins et al. 1998], when added in with the lime, is able to prevent sulfate heave occurring.

Little work has been carried out in the UK to assess whether fly ash/PFA is able to achieve the same affect, though fly ash has been shown in the USA to work successfully [Dermatas 2001]. Some preliminary UK work suggests that fly ash can prevent sulfate heave and a larger research project has been commissioned to investigate this further.

2.4 *Hazardous waste treatment*

With a ban on the disposal of sludge into landfill and the ever increasing costs of hazardous waste disposal, the stabilising of hazardous wastes in cementitious systems has increasing attractions. Research is ongoing [UCL 2006] into whether additions like fly ash, ggbs, silica fume, etc in combination with cement could be used to stabilise these wastes into a form suitable for disposal.

3 STANDARDS AND SPECIFICATIONS

Standards for fly ash/PFA have been around for 40 years. The majority of these standards related to concrete, and specifically in the UK for the mixer addition of ash. In recent times the cement and concrete industries have begun to use more fly ash, due to increasing pressure to reduce overall CO_2 emissions. The manufacture of Portland cement produces ~960kg/tonne of CO_2 so there are big incentives to use a CO_2 neutral material like fly ash.

3.1 *Cement and concrete*

The cement industry has become a big user of fly ash both as a kiln feed and for blending into cement. Fly ash is used as a kiln feed as a source of silica, replacing the usual clay, marl or sand. Cement chemistry is a complicated area and in order to produce cement consistency of the fly ash is paramount. For blending in with Portland cement, the ash may be added as a Minor Addition Constituent (MAC), which can be up to 5% of cement, or in far greater proportions within blended cements with up to 55%. 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.

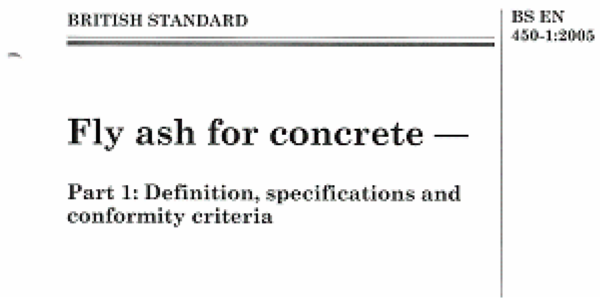
BRITISH STANDARD
BS EN 450-1:2005
Fly ash for concrete —
Part 1: Definition, specifications and conformity criteria

Figure 3. BS EN450 - Fly ash for concrete.

Fly ash for use as a concrete addition at the mixer is normally supplied complying with EN450:2005 [BSI 2005], (Figure 3) 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.

3.1.1 *EN450:2005 Category N fly ash*

Category N (Normal) is fly ash that is taken direct from the power station electrostatic precipitators.

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 associated with conditioning the ash for disposal is taken into account.

3.1.2 *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 9.75kW/h per tonne of Category S fly ash, which equates to ~4.2kg 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.

3.2 *Hydraulic bound mixtures in road construction*

Hydraulically bound mixtures (HBM) are new to the UK, while they have a long history of use in other EU countries. They rely on the binding ability of a range of materials, but principally fly ash/PFA and/or ground granulated blastfurnace slag (GGBS) in combination with lime and/or cement. The aggregates may be recycled aggregates, road planings, incinerator bottom ash, or similar.

HBM's are similar to Cement Bound Mixtures (CBM's) in they are designed to produce a strong durable, hard wearing sub-base for asphalt wearing surfaces. However, HBM's are slow setting and hardening and can be trafficked immediately [Britpave 2005]. Consisting mainly of recycled or by-product material they are very environmentally friendly in comparison with the virgin aggregates alternatives.

There are three standards in which fly ash may be used in hydraulically bound mixtures (HBM) for road construction as follows;

3.2.1 *BS EN14227-1: Cement bound granular mixtures (CBGM) [BSI 2004a]*

This standard specifies requirements, test methods and compliance criteria for cement bound granular mixtures. This permits the use of cements complying with BS EN197-1 [BSI 2000a] and Hydraulic Road Binders (HRB) complying with ENV13282 [BSI 2000b] and therefore can include fly ash as a constituent of the cement or HRB.

It contains the criteria for gradings and design purposes for CBGM's.

3.2.2 *BS EN14227-3: Fly ash bound granular mixtures (FABM) [BSI 2004b]*

This standard specifies the requirements for constituents, composition and laboratory performance of fly ash bound mixtures. Both siliceous and calcareous fly ashes may be used complying with Part 4. It refers to fly ashes added as a binder to the mixture on site. However, this standard permits the use of multiple blends of gypsum and GGBS plus other constituents such as sodium carbonate to aid setting.
Five differing FABM's are described:

- FABM 1 simply requires compliance with a grading envelope.
- FABM 2 specifies limits on grading, compacity and Immediate Bearing Index (IBI).
- FABM 3 is a fine aggregate mixture, i.e. there is no coarse aggregate, which has minimum IBI values.
- FABM 4 is a mixture where the supplier declares a grading, IBI, etc, similar to a proprietary mixture.
- FABM 5 is where fly ash is both the binder and the main constituent of the mixture, e.g. a lime: fly ash mixture would be a FABM 5.

Compressive strength classes may also be specified, but curing conditions and age are in accordance with the practices at the place of use. Compacity is defined as the absolute volume of the constituents calculated from the Particle Densities for each constituent divided by the apparent volume as measured by the Proctor dry density.

3.2.3 *BS EN14227-4: Fly ash for hydraulically bound mixtures [BSI 2004c]*

This details the requirements for fly ash for use in FABM's. The usual properties and limits are given, fineness, loss on ignition, sulfate content, calcium oxide, etc for which UK fly ashes would not have any difficulty in compliance.

The above standards are now incorporated within the Specification for Highway Works 800 [Highways Agency 2006a] series. The design for HBM is contained in Interim Advice Note 73/06 [Highways Agency 2006b], though there have been some issues with this design method, which at the time of writing are being resolved.

3.3 *Regulated dangerous substances and REACH*

Upon the horizon are two additional EU requirements that will impact on all materials, Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and Regulated Dangerous Substances (RDS).

REACH [EU Commission 2006] is supposed to; *"…provide a high level of protection of human health and the environment. At the same time, it will enhance the competitiveness of the EU chemicals industry by fostering innovation and ensuring high safety standards for its products."*

Under REACH, each producer and importer of chemicals in volumes of 1 tonne or more per year and per producer/importer — around 30,000 substances — will have to register them with a new EU Chemicals Agency, submitting information on properties, uses and safe ways of handling them.

In tandem with this RDS [Theilen 2004] is destined to control dangerous substances within EU standards. This is intended to remove environmental barriers to trade resulting from differing local environmental laws. Each EU standard will have list of dangerous substances, which will be tested using harmonised standards. Each country will be able to set its own limits for the RDS, but this in itself should not be a barrier to trade. Currently the work of TC351 is to assess existing test methods and harmonise a series of methods to enable REACH to work.

Apparently how REACH and RDS interact has not been decided by the EU Commission, or it could be construed that they were not aware of the two initiatives.

4 SUSTAINABILITY

While there are many changes in standards, and new directions in the applications for fly ash forthcoming, there is also the issue of sustainability. Increasingly clients, consultants and contractors are under pressure to reduce the environmental impact of construction and operation of a structure.

Fly ash/PFA has been used as a method of offsetting the environmental impacts by substitution. In most applications fly ash replaces virgin aggregate or Portland cement, both of which have an environmental impact in their production and are depleting virgin resources.

The UK power industry has produced fly ash since the 1950's, much of which has been landfilled. Many hundreds of millions of tonnes of this 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 sites have subsequently been redeveloped and the ash disposal sites used for industrial purposes and occasionally for housing. However, on the remaining coal fired power stations 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 [Drax Power Ltd 2006], see Figure 4, is an example of a large fly ash stockpile of in excess of 16,000,000 tonnes.

Figure 4. Barlow Mound at Drax Power Station, UK.

The production of electricity from coal is unlikely to cease in the near future. Potential development of clean coal technologies and the vast reserves of coal that exist within the world, mean that ash in some form or another will continue to be produced for many years. The current production of ash plus the existing stockpiles of fly ash form a readily available mineral resource for future generations.

Stockpile material would need extracting, screening, drying and possibly grinding or classification for some applications, e.g. 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. At the current rates of utilisation stockpile material alone could last for 30 years.

4.1 *Ash processing*

Stockpile ash could form a significant resource for future generations, though much of this material would have to be processed in some manner. This may simply be screening the ash to remove agglomerated lumps but may extend to drying the ash, prior to further beneficiation processes. In addition to stockpile material, the pressure to reduce emissions from furnaces, including coal fired power stations has resulted in changes in the current production ash. The use of low NOx burners has increased Loss On Ignition (LOI) values in fly ash by ~1.5% in recent years. Further changes in EU emissions limits effective in 2007/8 mean that burners on power stations are being modified to further reduce NOx. The result will be even higher LOI [van den Berg 1998] in ash with much of production approaching the LOI limit for use in concrete.

The concrete standards within the UK set limits of LOI at 7.0% and this will force ash producers to process the ash to remove excess carbon if they wish to remain in these markets. Various systems exist that are capable or producing very low carbon ash, which are reviewed in the following section.

4.1.1 *Carbon reduction*

There are two basic ways of removing carbon from ash, by separating the carbon using some form of electrostatic technique or by burning off the carbon.

Within the UK electrostatic separation using the Separation Technologies Industries (STI) [Gasiorowski & Bittner 2006] technique has been adopted. This system has a charged belt over which the ash passes. The carbon is attracted in one direction and the ash in another. Ash with LOI’s as low as 1.5% has been produced with this system.
There are more complex methods of beneficiation that are being proposed at some stations.

4.1.2 *Other beneficiation techniques*

Proposals to build a Rocktron [Smalley et al. 2006] ash beneficiation plant at two power stations have been made. In this system, as well as reducing the LOI of the ash, a variety of other processes are carried out to separate cenospheres, produce a finer ash, extract the carbon, etc. In this manner it is proposed to produce a numbers of marketable products for the construction industry. As one can imagine such processing requires a high capital investment.

4.2 *Enhancing durability*

Using fly ash in many applications has both environmental and technical advantages. For example using 30% fly ash as a replacement for Portland cement will reduce the risk of Alkali Silica Reaction [BRE 2004], improve the resistance to chloride attack of reinforcing, improve the sulfate resistance of the concrete [BRE 2005], reduce the permeability, etc. These benefits have been well documented over the years and are reflected in the British Standard for specifying concrete, BS8500 Parts 1 [BSI 2002a] and 2 [BSI 2002b].

As most concrete mixes are designed for 28 day strength using standard curing, in practice at later ages many fly ash concretes achieve far higher strength and lower permeabilities insitu than would be expected from the equivalent Portland cement concrete, as shown in Figure 5.

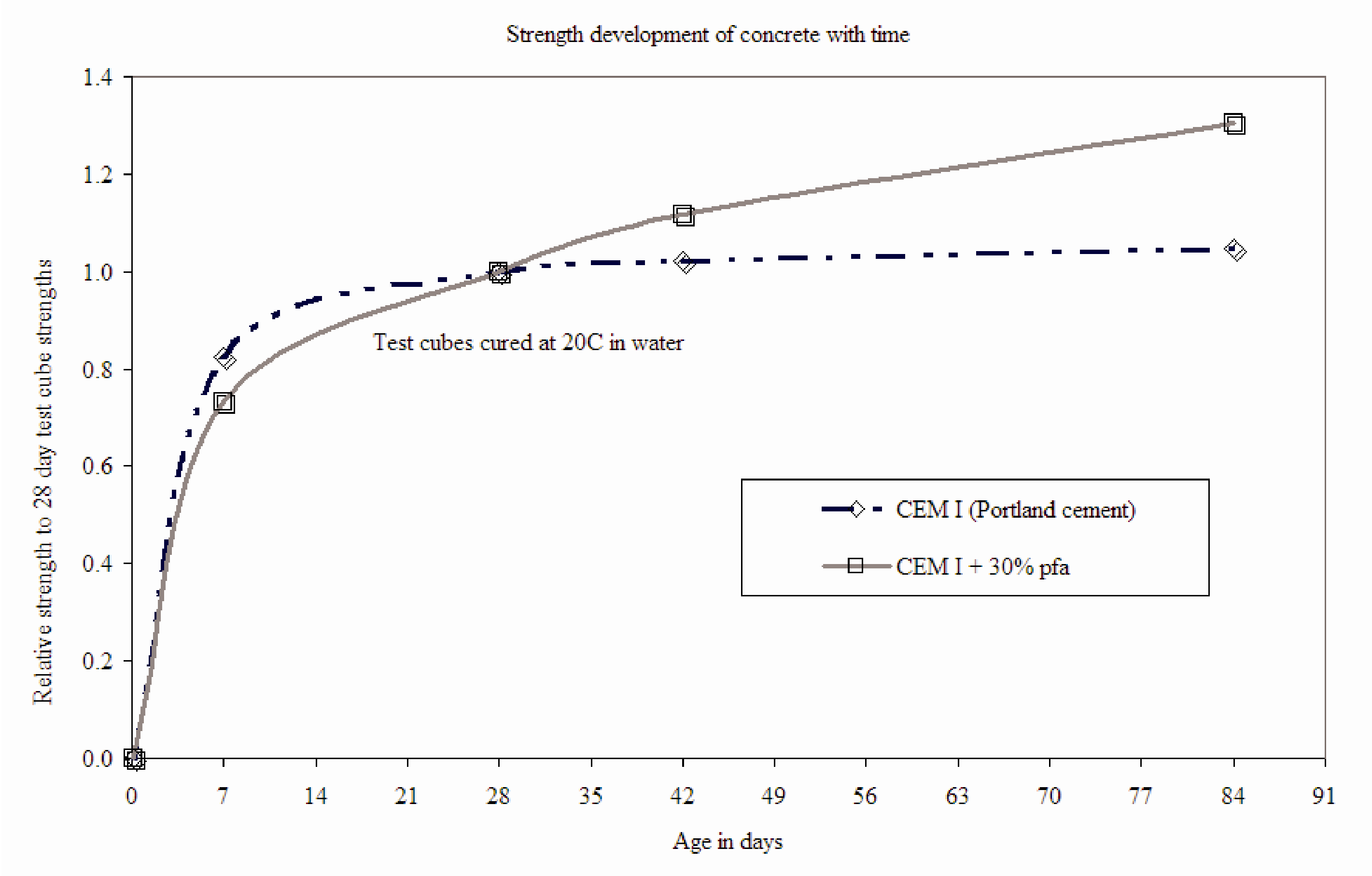

Figure 5. Relative strength gain properties of fly ash concrete.

In practical terms fly ash concrete can be far more durable than implied by the 28 day strength, thus extending the life of the structure. By making structures last longer the environmental impact of building a construction is diluted. Many structures are now designed with 100 year life in mind, in which fly ash can play a major part in achieving this longevity. However, it is hard to find structures that have been required to or have lasted 100 years in practice.

To take advantage of the benefits of fly ash concrete to ensure longevity requires considerable thought on the part of the designer, who must allow for flexibility of use and ease of maintenance. However, the Romans have proven longevity is possible with structures such as the Pantheon [Watson 2002] built between 118 and 128 AD as in Figure 6, the dome being a volcanic fly ash concrete structure.

Figure 6. Pantheon - Roman ash concrete.

4.3 *Environmental benefits*

The environmental benefits of using fly ash are relatively straightforward. Invariably fly ash is substituted for either virgin aggregate or Portland cement in all applications. However, there are often additional benefits associated with its technical performance.

4.3.1 *Aggregate*

Fly ash is used as an aggregate in the following applications [UKQAA 2006b]:

- Fill material - for embankments, raising levels, etc.
- Grouting – for filling of caverns, mines, stabilising poor ground, etc.
- Concrete – used as a filler aggregate when aggregate particle size distribution lacks fine material or a concrete has low cement content.
- As filler – can be used in a wide variety of applications to bulk out products, e.g. rubber, paint, etc.

Typically to produce 1 tonne of aggregate at the factory gate equates to ~21kg of CO_2. Transport [Parrott 1999] will be excluded from all these figures simply because it is very variable. Sometimes a quarry will be farther from a site than a power station and vice-versa.

The Concrete Industry Alliance [Parrott 1999] 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. Though of some significance, the basic calculations of impacts for materials are still valid using at the factory gate assumptions.

As ~ 2,400,000 tonnes of ash [UKQAA 2006a] are used predominately as filler we can conclude by a crude calculation that the use of fly ash reduces environmental impact by ~ 56,500 tonnes of CO_2 per annum. However, the situation is not so simple. The following example explains the problems.

To produce grouts the contractors prefer fly ash. There are good technical reasons why;

1. Fly ash grouts require far less cement for a given strength than for natural aggregate. This is because fly ash reduces the water content of the grout and is pozzolanic.
2. Fly ash has a lower particle density (~2.3 kg/m^3) than natural aggregate (~2.6 kg/m^3), so about 13% less material by weight is required.
3. Fly ash slows the setting time of the grout. This enables more grout to be placed and less injection holes to be drilled.
4. Fly ash grouts do not bleed significantly and can be pumped long distances. This makes them very efficient at filling of the void completely with minimal disruption.

These differences can be very substantial, with one grouting contract [Sear 2004] 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.

There are similar issues with ash as a fill material. The benefits with fly ash are it compacts easily, is lightweight so reducing pressure on sub-soils, produces a stable embankment, naturally sheds rain water, has increasing strength with time, etc.

In aerated concrete block manufacture, a big user of fly ash, the ash is acting both as aggregate and binder. The natural alternative for making such blocks is ground sand, which uses virgin aggregate and energy.

In many applications fly ash, though being treated as an inert filler is in fact reacting pozzolanically enhancing the performance of the material.

4.3.2 *Cementitious binder*

The use of fly ash as a partial substitute for Portland cement is the primary way of reducing environmental impacts. To manufacture 1 tonne of Portland cement produces ~960kg of CO_2 emissions. Using fly ash can significantly reduce the overall environmental impacts when used as a cementitious binder.

4.4 *Reduction in CO_2 emissions using fly ash*

Firstly let us consider the use of fly ash as a mixer addition to concrete. Fly ash is pozzolanic and of lower particle density than Portland cement, a direct replacement mass for mass in not possible. Normally an increase in total cementitious material is needed of about 10%, depending on whether Category N or S ash is used, the strength required and the overall concrete gradation.

Table 1. Comparative environmental impact to produce a 40MPa at 28 days concrete mix

Environmental impact	CEM I only	EN450 Cat N fly ash	EN450 Cat S fly ash	EN450 Cat N fly ash	EN450 Cat S fly ash
Normal replacement level	0%	------ 30% fly ash ------		------ 50% fly ash ------	
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%

Table 2. Comparative environmental impact to produce a 40MPa at 56 days concrete mix

Environmental impact	CEM I only	Cat N	Cat S	Cat N	Cat S
Normal replacement level	0%	------ 30% fly ash ------		------ 50% fly ash ------	
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%

Table 1 shows the relative environmental benefits of using fly ash in concrete for a 40MPa at 28 days concrete. It should be noted that while Category S fly ash is normally processed, the additional environmental burden is offset by the improved reactivity in the concrete mix. Higher proportions of ash, because of the need to compensate for the strength at 28 days, require greater total cementitious contents, offsetting the benefits.

As the pozzolanic reaction is rather a slow reaction at normal curing temperatures, specifying later ages for achieving a given strength does give further environmental benefits. Table 2 shows the results for a 40MPa at 56 day concrete, with the additional benefits. For mixes with lower required strengths or other specific criteria higher benefits per m^3 of concrete may be possible.

As some 400,000 tonnes of fly ash are used in concrete production p.a. as an addition in ~4,200,000 m^3 of concrete, this would suggest an overall reduction in CO_2 emissions of at least 250,000 tonnes p.a. is due to the use of fly ash.

Our second consideration is the use of fly ash in cement manufacture. The cement industry is under a great deal of pressure to reduce CO_2 emissions as Portland cement, by the nature of its chemistry requires the calcining of calcium carbonate. Adding fly ash to cement as a kiln feed material, as a Minor Additional Constituent (MAC) or in the production of blended fly ash cement, reduces the overall environmental impact. Clearly using ash as a MAC or in blended cement has the greatest benefit as it is replacing Portland cement clinker.

The use of fly ash as a MAC will have the greatest environmental benefit as it is a direct weight for weight replacement for the Portland cement. This equates to ~40kg/tonne reduction of CO_2. As some 11,300,000 tonnes of cement are sold annually, this could amount to ~450,000 tonnes of CO_2. For blended cements, similar calculations would apply as given in Table 1. However, it is not publicly known as to what proportion of fly ash is used for MAC/blended cement and what is used in kiln feed, so it is difficult to estimate the overall reduction in impacts.

From the above it is clear that significant reductions in emissions are already being gained by the use of fly ash in concrete and in cement.

4.5 *Overall environmental benefits*

It is difficult to estimate the overall benefits of using fly ash in reducing emissions to air, because detailed data are not available. In addition how does one decide to assign whether a process is simply replacing inert virgin aggregate or benefiting from the pozzolanic reactions and to what extent?

It would seem reasonable to estimate that the minimum benefit of the use of fly ash in the UK in all applications equates to a reduction of ~600,000 tonnes of CO_2 emissions per annum.

4.6 *The future*

Coal fired generation will continue for sometime and the production of ash products will also continue. It is clear that there are the supporting standards to encourage and increase their use in construction.

5 CONCLUSIONS

Fly ash/PFA has a wide range of applications. In cementitious uses it is able to enhance the durability significantly and for other applications it can replace virgin aggregates, usually as a filler aggregate.

These uses reduce the CO_2 footprint significantly, especially when used as both a cementitious material and filler, such as in grouting. It is estimated that this currently equates to over 600,000 tonnes per annum.

This paper can only provide a short overview of fly ash from coal fired power stations, however as a material it is able to enhance the durability of a product, reduce overall greenhouse gas emissions, has a long history of use and is readily available. There are not many secondary or by-product materials that have such credentials.

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