USING COAL FLY ASH IN ROAD CONSTRUCTION

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RESEARCH AND PRACTICAL APPLICATIONS USING SUSTAINABLE CONSTRUCTION MATERIALS AND TECHNOLOGY IN ASPHALT AND PAVEMENT ENGINEERING

ABSTRACT

Coal fly ash, or Pulverised Fuel Ash (PFA) as it has been traditionally known in the UK, has been used for many years in road construction. The applications range from the use as a simple general fill material, because it is lightweight and cost effective, through to its use in concrete as an addition to improve the chloride resistance, prevent alkali silica reaction, etc thereby enhancing durability. In more recent times it has been fully accepted both as a binder and aggregate in hydraulically bound mixtures complying with BS EN14227-3 and endorsed by the UK Specification for Highway Works. While fly ash is often specified because of technical and commercial advantages, there are significant environmental and sustainability benefits associated with its use.

In many of the applications fly ash is a direct replacement for virgin aggregate so there are issues of resource depletion, reduction in overall CO_2 emissions, diverting material from landfill and reducing vehicle movements that require consideration. In some applications it partially replaces Portland cement or lime, both of which, during their manufacture, are high CO_2 emitters. Here the use of fly ash can result in significant overall reductions in green house gas emissions, as well as sustainability benefits associated with its durability and resulting extended life expectancy.

This paper will review the various applications for coal fly ash associated with road construction, summarise the technical benefits and discuss in detail the environmental and sustainability considerations of its use.

INTRODUCTION

Coal fly ash, or Pulverised Fuel Ash (PFA) as traditionally known within the UK, has been used for many years in road construction as a fill material, in concrete, lean mix sub-bases and in more recent years as a binder and aggregate in hydraulically bound materials. There is an excess of PFA produced annually within the UK and some 55,000,000 tonnes of material (UKQAA a, 2007) that are accessible from stockpiles. Its use reduces material being sent to landfill and preserves virgin aggregate stocks and is a major mineral resource for future generations. There are many environmental and sustainability reasons for using PFA in preference to virgin aggregates, reducing the overall greenhouses gas emissions.

APPLICATIONS FOR PFA

PFA as a fill material

PFA has been used for many years as an alternative to virgin aggregates for embankments, especially in road construction projects (UKQAA b, 2007). PFA is used for fill applications because:

- It is lightweight when compared to most materials, having a particle density of 2.10 to 2.3 and a dry bulk density ranging from 1100kg/m^3 to 1450kg/m^3. This leads to savings in material, transport costs and reduces settlement in underlying soils.
- When properly compacted, PFA settles less than 1% during the construction period with no long-term settlement. It is an easy material to compact with readily available equipment when used at the optimum moisture content.
- The self-hardening properties of some PFA's offer considerable strength advantages over natural clay and granular materials. As PFA is pozzolanic, the small quantity of free lime normally present will enhance the strength of the resulting embankment. This reaction can be increased by mixing lime with the PFA when being placed. It is the pozzolanic reaction that is principally used in soil stabilisation and hydraulically bound sub-bases as the binder.
- PFA can exceed the design strength immediately after compaction. The design figures normally quoted are fresh saturated data which are conservative.
- The immediate strength of PFA means simple shallow trenches have a reduced need for shoring.
- With proper profiling PFA fill can be trafficked in all weathers.

PFA embankments should be constructed on a free draining layer that acts as a capillary break. Materials like concrete that may be attacked by sulfates should also isolated from PFA with a capillary break and metallic items should not be placed closer than 500mm from PFA. Reinforced earth embankments can also be constructed if an alkali resistant geo-grid polymer is used, see Figure 1. This allowed self supporting vertical faces to be constructed.

Figure 1 – a reinforced earth PFA embankment

The PFA is normally placed in 150mm layers, compacted to 100mm, using standard vibrating rollers. As with all fine grained materials, the surface of the PFA embankment should be capped either with the construction, a capping layer, top soil, etc. It should be profiled to ensure adequate drainage, especially during the construction period. PFA, if properly profiled, will shed rain water easily, allowing construction to continue in poor weather conditions. If it should become saturated with water, it can be dug out, spread out and allowed to dry before being reused without any detriment.

It can be used as both a General Fill, complying with Class E, or as a Structural Fill complying with 7B of the Specification for Highway works. For general fill, 95% of maximum bulk density and moisture content are the critical control parameters, whereas for structural applications the effective angle of internal friction φ' and effective cohesion c' are required in addition to the 7B parameters.

PFA in concrete construction

While PFA is the preferred UK term, in order to avoid confusion with other ashes from other furnaces, European Standards always refer to fly ash, , such as EN450-1 (BSI a, 2005). PFA has been used in UK concrete since the 1950's. There are a number of benefits in using PFA based concrete as follows:

- Improves long term strength performance and durability.
- Reduces permeability, which reduces shrinkage, creep and gives greater resistance to chloride ingress and sulfate attack.
- Minimises the risk of alkali silica reaction.
- Reduces the temperature rise in thick sections.
- Makes more cohesive concrete that has a reduced rate of bleeding, is easier to compact, gives better pumping properties and improves the surface finish of the finished structure, e.g. when used in Self Compacting Concrete.

It is fully incorporated with EN206-1 (BSI b, 2004) and BS8500 (BSI c, 2006), the Specification of Concrete and therefore the Specification for Highway Works within the UK.

The benefits of using PFA stem from the pozzolanic reaction. This is when Portland cement hydrates it produces quantities of alkali calcium hydroxide (lime). Pozzolanas, like fly ash, react with this lime to form stable calcium silicate and aluminate hydrates. These hydrates fill the voids within the concrete, removing some of the lime and thus reducing the permeability. This process improves the strength, durability, chloride and sulfate resistance of the concrete. The pozzolanic reaction occurs relatively slowly at normal temperatures enhancing strength in the longer term relative to normal Portland Cement (CEM I) concrete. It is the pozzolanic reaction that imparts most of the benefits in many applications.

The finer fraction of fly ash, i.e. those particles that pass the 45µm sieve, act as a solid particulate plasticiser. These particles are spherical and act like ball bearings within the concrete reducing the water requirement for a given workability. A reduction in the water content further lowers the permeability and increases strength and durability. In addition the concrete is more cohesive, has a lower rate of bleeding and is less prone to segregation.

Fly Ash Bound Mixtures (FABM) for highways and other pavements

Fly ash bound mixtures (FABM) are mixtures of PFA/fly ash and other constituents that are compatible with compaction by rolling and a performance that relies on the pozzolanic properties of the fly ash. The first use of FABM in the UK was on the A52 at Froghall some 10 years ago (UKQAA c, 2007), see Figure 2, which has performed very well, however, it must be remembered the French have been using HBMs for many years for their roads and motorway network very successfully.

FABM can be specified and formulated to meet capping, sub-base and base requirements of all classes of road, airfield, port, residential and commercial pavements.
In FABM, fly ash is the main constituent of the binder with lime, quick or hydrated, usually the other constituent. Cement can substitute for lime but is not as effective in mobilising the full pozzolanic and thus cementing potential of the fly ash, see Table 1.

Table 1: Compressive strength in MPa of treated fly ash

Age of 1:1 sealed cylindrical specimens cured @ 20C	Fly ash with 2.5% CaO	Fly ash with 5% CaO	Fly ash with 7% CEM 1	Fly ash with 9% CEM 1
7 days	1.5	2	3	5
28 days	4	4	4	8
91 days	5	7.5	6	9

Compared to mixtures based on cement, FABM based on lime are slow-setting, slow-hardening, self-healing mixtures. This more protracted rate of hardening has distinct advantages in pavement construction. In the short term, FABM have extended handling times and thus the versatility of unbound granular pavement materials. In the medium term, FABM are autogenous, in that they possess a pozzolanic reserve which allows them to re-heal should say cracking occur under differential settlement. In the long term, FABM develop significant stiffness and strength with the performance and durability of bituminous and cement bound mixtures.

Where quicker hardening is required, say in cold weather, the addition of gypsum or the partial or complete replacement of lime with cement can be employed. FABM based on cement however, behave like cement bound mixtures (CBM) and do not have the advantages of laying flexibility and autogenous healing described above.

Standardisation

Both FABM and CBM are hydraulically-bound mixtures (HBM). There are European standards for the overall family of materials that make up HBM including FABM.

FABMs are standardized in BS EN 14227-3 (BSI d, 2004) as follows:

- FABM 1: 0/31.5 mm graded mixture
- FABM 2: 0/20 mm well-graded mixture with a compacity (air voids) requirement. 0/14 & 0/10 mm versions are also available
- FABM 3: sand mixture with an immediate bearing index (IBI), in other words an immediate traffickability requirement
- FABM 4: mixture with a producer-declared grading
- FABM 5: fly ash (as aggregate) treated with lime or cement.

BS EN 14227-3 specifies:

- requirements for the constituents of the mixtures e.g. the quality of the fly ash, the lime and the aggregates
- requirements for the various mixtures e.g. grading and, where applicable, compacity and immediate bearing index (more later)
- Laboratory mechanical performance classes for the mixtures e.g. the permitted classes of compressive strength (Rc) and tensile strength/modulus of elasticity class (RtE).

FABM 1 & 2 are mixtures formulated for use in the main structural layer, the base, of a pavement. Highways Agency (HA) design recommendations for the bases of trunk roads and motorways are found in departmental standard HD 26 (HA a, 2006). This standard specifies FABM 1 as the base material across the full traffic spectrum. FABM 1 & 2 can provide the contractor and client with the convenience that they can be immediately trafficked and yet will have the long term performance associated with cement bound lean mix materials, without the cracking associated with lean mix concretes used in the past.

FABM 3, 4 & 5 and SFA are for use in sub-base and capping and thus the foundation layers underneath the base layers. HA design recommendations for foundations are found in IAN 73 (HA b, 2006), which permit the use of FABM 3, 4 and 5 and SFA for sub-base. Unlike FABM 1 & 2 above, these FABMs cannot be assumed to be capable of immediate trafficking but require verification of this ability.

FABM 3 is a sand mixture and verification of its ability to sustain traffic immediately is measured using the immediate bearing index (IBI) test, which is an immediate CBR test without surcharge.

FABM 4 is a mixture where the producer declares the grading and other relevant properties such as IBI. FABM 4 is particularly relevant where the aggregate is not capable of complying with FABM 1, 2 or 3 requirements, but in all other respects would produce a material that is eminently suitable for use.

FABM 5 is a treated fly ash using either lime (the resulting mixture known as LFA) or cement (the resulting mixture known as CFA).

Table 2: Examples* of FABM with constituent proportions by dry mass

FABM	Conditioned fly ash %	CaO or $Ca(OH)_2$ %	CEM I %	Graded coarse aggregate %	Fine aggregate %	Soil %	Typical water content (%)
1, 2	8.5 – 13	1.5 - 3	-	50 - 55	30 - 40	-	6 – 8
1, 2	4 – 6 (dry*)	1*	-	55 - 60	35 – 40	-	5 – 7
1, 2	6 – 8	-	2 – 4	50 - 55	35 - 40	-	6 – 8
3	9 – 12	2 – 4	-	-	84 - 89	-	~ 10
3	6 – 8	-	2 – 4	-	88 - 92	-	~ 10
5	93 – 97	3 - 7	-	-	-	-	Depends on soil
5	90 – 95	-	5 - 10	-	-	-	Depends on soil
SFA	6 – 8 (dry*)	1 – 2*	-	-	-	90 - 93	Depends on soil
SFA	3 – 6	-	2 – 4	-	-	91 - 94	Depends on soil

* Examples are illustrative proportions for factory blended lime with dry fly ash or site blended through the mixer.

Figure 2 - Laying FABM on the A52

FABMs are able to utilise recycled aggregates, road planings and many other secondary and by-product materials. A recent project carried out by TRL (Hassan et al, August 2007) consisted of a detailed assessment of hydraulically bound mixtures. Trial sections were constructed with recycled aggregates (RA) and recycled asphalt (RAP) as Recycled Secondary Aggregate (RSA) and combinations of cement (CBGM), pulverised fuel ash (FABM), ground blastfurnace slag (SBM) and lime as binders and activators. All the sections gave satisfactory performance over the one year period of monitoring with all the HBM sections performing similarly in the field.

ENVIRONMENTAL IMPACTS

Overview of CO_2 emissions

In order to estimate the reductions in environmental impact of using PFA/fly ash in road construction, we need some reasonable estimates of the impacts of the primary materials it is replacing. As fly ash is a by-product of the production of electricity from coal fired generation, it is usual to consider the environmental impacts wholly assigned to the electricity. Therefore, the fly ash would be considered to have a zero impact at the power station gate.

One issue is transportation which will vary from contract to contract. Comparisons between differing sources of materials are difficult to make accurately if there are significantly differing distances and modes of transport being used. However, depending on the location of the contract in relation to quarries, power stations, cement works, railway terminals, etc can all have a significant bearing on the environmental impact associated with material use. In respect of PFA, there has been increasing interest in transporting the material to site using trains for the larger contracts. For example, some 1,100,000 tonnes of PFA were sent to a single grouting contract in Northwich during 2006/7 using trains hauling 2,000 tonnes per day. While these modes of transport are appropriate for larger contracts, the reliable tipping vehicle will be the main mode of transportation for PFA in the foreseeable future. For the following comparisons of environmental impacts, transportation has been left from the equations, e.g. materials are taken as from cradle to production facility gate.

In order to make comparative estimates knowledge of the impacts of producing the various materials is needed, whether it is for making concrete, an embankment, etc is needed. The Environment Agency V.2 (EA, 2007) carbon calculator uses CO_2 for a variety of materials ranging from concrete, aggregates, timber, metal, plastics, etc. Additionally there is the Waste & Resources Action Programme carbon calculator for recycled aggregates (WRAP, 2006) which is aimed at road construction. For the purposes of this paper, I shall concentrate on CO_2 emissions as the important parameter.

The impact of producing aggregates from quarries varies greatly depending on the data source. The Environment Agency V.2 carbon calculator uses CO_2 data ranging from 21kg/tonne for crushed stone, through to 5.3kg/tonne for sand. The Quarry Products Association annual report for 2006 (QPA, May 2007) reports a value of 9.98kg of CO_2 per tonne for all aggregates for 2006. Other papers, (Flower, 2007) quote values of 45.9 to 13.9 for crushed rock and sand aggregates respectively. For the purposes of this paper an average CO_2 figure of 21kg/tonne of aggregates has been used.

For Portland cement (CEM I) a wide array of figures for CO_2 are quoted in many publications Flower quotes a range from 700 kg/tonne to 1,000kg/tonne. Other figures are 740kg.tonne to 970kg/tonne within the Environment Agency Carbon Calculator and 801kg from WRAP calculator. For the purposes of this paper a CO_2 figure of 860kg/tonne has been used. For hydraulic lime WRAP quotes a CO_2 figure of 800kg/tonne.

The depletion of natural aggregate sources has not been considered within these calculations. However, it is arguable that readily available by-products like PFA should be used in preference to the quarrying of virgin materials, which should remain for the use of future generations.

The current environment benefits of using PFA

Some 3,000,000 tonnes per annum are landfilled in the UK and in addition there are some 53,000,000 tonnes of available material on stock. The UK power industry is able to supply large quantities of materials suitable for many applications with ease. These stockpiles represent a major mineral source for future generations. However, it is beholden to this generation to minimise the use of high quality virgin aggregates and cement to leave sufficient resources for future generations and reduce global warming effects.

Currently about 191,000 tonnes of PFA are used annually in embankment construction, representing an overall CO_2 emissions saving of ~4,100 tonnes per annum. As all PFA produced, plus the stockpiled ash, is suitable for use as a fill material, this represents a major potential mineral resource for such applications.

When PFA is used as a cementitious binder, considerably greater environmental benefits are achievable than the simple displacement of virgin aggregates. Portland cement inherently produces a large quantity of CO_2 during its manufacture as it involves the calcination of calcium carbonate. This releases ~550kg of CO_2 for each tonne of cement made. In addition to this chemical release, the raw materials and resulting cement clinker have to be ground to a fine powder, which in itself is an energy intensive process. Even with the most efficient cement work, figures of 700kg/tonne of CO_2 for CEM I are only just possible.

As well as a cementitious binder, PFA can be used as a raw material within the cement manufacture process. It is used as a source of silica and alumina replacing the clays and sands traditionally used. This market is increasingly significant in the PFA marketing industry.

Replacing some of this Portland cement with pozzolanic materials like fly ash has considerable environmental benefits without compromising technical aspects, e.g. strength and durability. In fact fly ash enhances many durability aspects of the resulting concrete, e.g. improved sulfate resistance, prevention of alkali silica reaction, reduced permeability to chloride ions, etc.

The degree of benefit varies depending on the exact specification for the concrete mix and its application. Using BS8500 criteria, Table 3 are some estimates of the relative benefits of various mixes;

Table 3: Comparison of CO_2 emissions associated with some concrete mix types (excludes aggregates, which are considered constant for mixes)

Mix designation	Portland cement (CEM I)	Fly ash equivalent mix	Overall CO2 savings
C30/37 design strength concrete	280 kg/m^3 of CEM I ≡ 241 kg/m3 CO_2	320 kg/m^3 of CEM I + 30% PFA ≡ 193 kg/m^3 CO_2	-48 kg/m^3 (-20%)
RC25/30 MCC260 W/C 0.65	270 kg/m^3 of CEM I ≡ 232 kg/m^3 CO_2	290 kg/m^3 of CEM I + 30% PFA ≡ 175 kg/m^3 CO_2	-57 kg/m^3 (-25%)
XS1 50mm cover	C40/50 MCC380 W/C0.40 395 kg/m^3 CEM I ≡ 330 kg/m^3 CO_2	C25/30 MCC320 W/C0.55 320 kg/m^3 of CEM I + 30% PFA≡ 193 kg/m^3 CO_2	-137 kg/m^3 (-42%)
		C25/30 MCC260 W/C 0.65 330 kg/m^3 of CEM I + 50% PFA≡ 142 kg/m^3 CO_2	-188 kg/m^3 (-57%)

Currently about 500,000 tonnes of PFA are used in concrete, both as an addition and within blended cements. Additionally cement companies take ~420,000 tonnes of PFA as a raw material. A further 1,000,000 tonnes are used within block and precast concrete sectors both as aggregates and cementitious binders. (UKQAA e, 2006)

With respect to FABM formulations things become increasingly difficult, as producing environmental comparisons with traditional materials that are used as capping and sub-base materials are complex. Spreadsheets like the WRAP carbon calculator are specifically designed for HBM mixtures. With respect to FABM's, often the content of PFA is small in comparison with the total material used unless one uses FABM 5 designs. The PFA has to be combined with CEM I or Lime when used as a binder, which increases the overall CO_2 emissions in comparison with unbound solutions. However, the considerable majority of FABM's produced so far have used recycled and secondary aggregates in their formulations. The use of CEM I lean mix concretes was relatively rare in recent years, so direct comparisons with these mixes are questionable. Nevertheless, though the overall impacts may be increased in comparison with using both bound and unbound virgin aggregates, FABM's should prove more durable with extended lifetimes.

The use of PFA in the various applications reduces overall CO_2 emissions significantly. It is estimated that with the various applications ~720,000 tonnes of CO_2 emissions were avoided by the use of PFA in 2006. However, there were about 2,800,000 tonnes of material disposed of in landfill which had the potential to save at least another 60,000 tonnes CO_2 emissions (as a replacement for virgin aggregates) if not considerably more.

CONCLUSIONS

PFA/fly ash has considerable benefits when used in road construction, whether it is for embankment construction, for concrete in roads and bridges or for sub-base materials as in Fly Ash Bound Mixtures. Where PFA replaces virgin aggregates, or acts as a cementitious binder, significant reductions in overall CO_2 emissions are possible to the benefit of the environment. In addition the existing stocks of material represent a large mineral reserve for future generations ensuring the sustainable construction of our road infrastructure. However, we are all responsible for the future of this planet and by maximising the use of by-products materials, such as PFA, this will reduce virgin aggregate depletion and leave resources for the future.

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