ABSTRACT. Since the industrial revolution, human activities have had increasing environmental impact on our world. We must ensure that we leave sufficient resources for future generations and the impacts of our lifestyle do not destroy the planet. As a considerable proportion of electricity is derived from coal fired power stations, this results in many millions of tonnes of fly ash, or pulverised fuel ash (PFA) as it is known in the UK, being produced worldwide. PFA has many beneficial uses as a raw material in the manufacture of cement, as a cementitious material in its own right and as a replacement for naturally occurring aggregates, etc. However, in reality approximately 50% of the PFA produced throughout the world is stockpiled/landfilled as a waste. This paper reviews the existing knowledge on the environmental benefits of using PFA in cementitious applications including the potential for reducing both overall carbon dioxide (CO_2) emissions and virgin aggregate usage.

Keywords: Fly ash, Pulverised fuel ash, Environment impact, Carbon dioxide emissions, Cement manufacture, Mix design, Greenhouse effect

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INTRODUCTION

Invariably modern construction involves the use of Portland cement based products, e.g. concrete, mortar, grouts, building blocks, etc. The production of Portland cement involves calcining calcium carbonate, an energy intensive process contributing approximately 2.5% to the total UK CO_2 emissions. In addition, naturally occurring aggregates are used in many construction products, amounting to 120,000,000 tonnes per annum. The UK government has agreed to significantly reduce CO_2 emissions by 12% of the 1990 levels at the Kyoto conference. These reductions are planned to occur by 2012 and because of these agreements; the government is applying increasing pressure to the cement and aggregate industries to improve efficiency, lower fuel consumption and reduce the extraction of naturally occurring aggregates. A significant reduction in overall greenhouse gas emissions has taken place in recent years, mainly due to the switch from coal to gas and nuclear power generation by the electricity generation industry. However, coal fired generation still represents a significant source of electricity within the UK. Further reductions in CO_2 emissions are being sort by the government on other industries by using a wide number of initiates including aggregate and energy/carbon taxes.

The UK is not a profligate country in its cement consumption with only some 210 kg/year [1] per capita being used, about half that of the rest of Europe. Concrete production accounts for around one third of the UK mineral extraction, but the subsequent environmental impacts range between 0.1 to 4% of UK totals depending on the factor selected. Relative to the impacts of domestic use/occupancy, transport, services and other industries concrete production is environmentally friendly. Around 50% of the UK's emissions of CO_2 relate to the occupancy of existing buildings. Reducing emissions due to transport and domestic energy consumption are probably the biggest challenge to the UK, see figure 1.

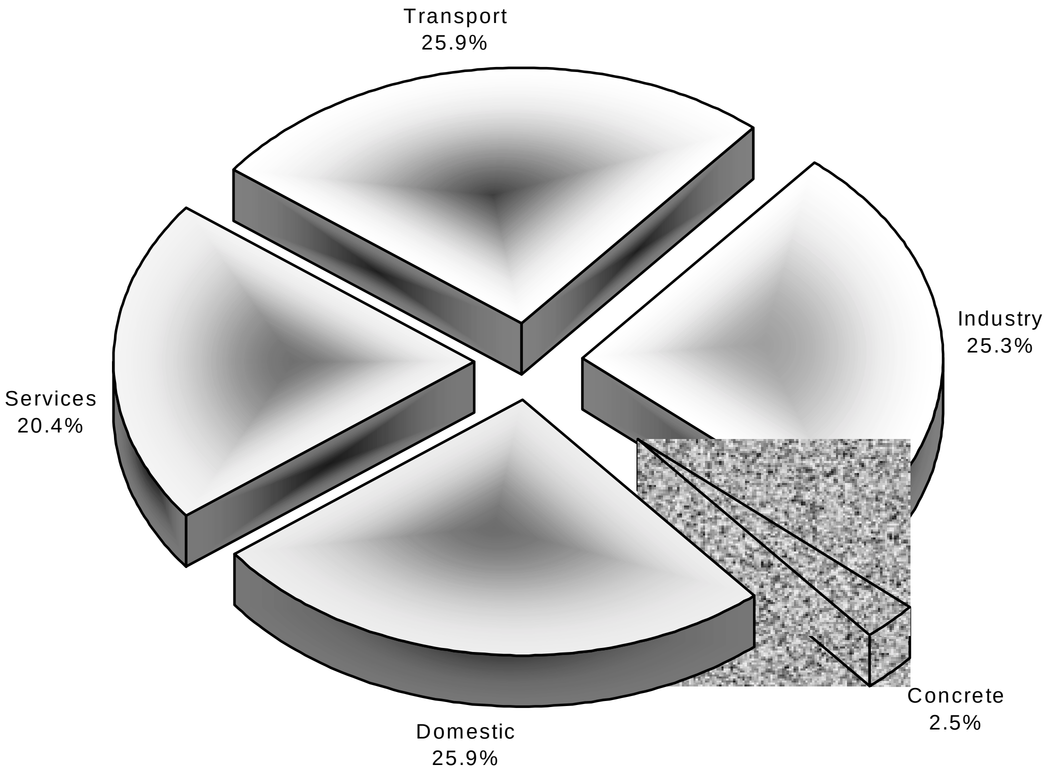

Figure 1 – CO_2 emissions by source – 1997 data

Fly ash, or PFA as it is known in the UK, from coal fired power stations has been around for a considerable number of years. There is a wealth of knowledge resulting from both research and the practical use of PFA. It can be used in the cement manufacture process, as a pozzolanic addition and a replacement for aggregates in some applications. However, about half of the PFA produced annually is not used, see Figure 2 [2], and therefore stockpiled every year. In addition, there are many hundred millions of tonnes of fly ash in stockpiles that could be utilised. There are significant environmental benefits to be enjoyed by fully exploiting this by-product material. This paper reviews the existing knowledge and the benefits that could be achieved with full utilisation.

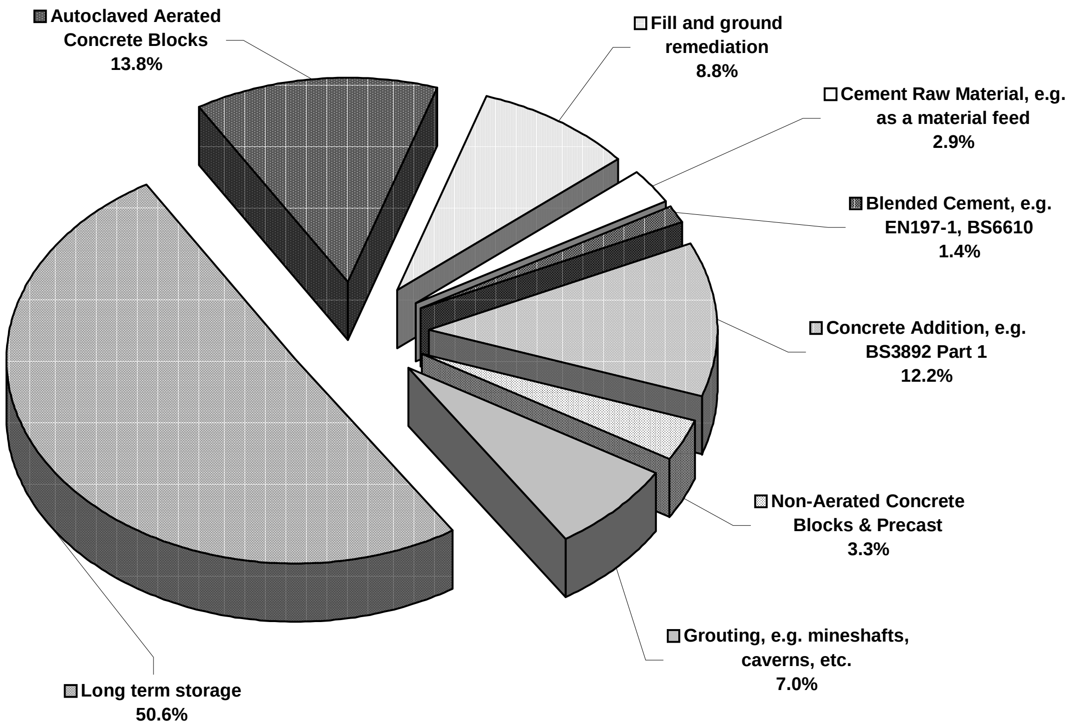

Figure 2 – PFA utilisation statistics for 1999

Fly Ash in Cement Production and as a Concrete Addition

Portland cement is commonly manufactured from limestone or chalk as a source of calcium and clay or sand as a source of silica. The blended materials, known as raw meal, are fired in a rotary kiln at a high temperature, about 1450°C, and inevitably involve the consumption of significant quantities of fuel. Traditionally the fuel used was coal. However, in modern kilns a variety of differing fuels will be used. Over the last forty years, the UK cement manufacturers have made great efforts to improve fuel efficiency. The fuel consumption during this period has reduced by 40% per tonne [3], with a consequent reduction in the atmospheric emissions such as CO_2. However, some 550kg of CO_2 per tonne of cement produced relate to the chemical dissociation of the calcium carbonate. As a result there is little further that can be achieved, without changing the basic chemistry of the cement, except by further utilisation of secondary and waste fuels to fire the kiln. Considerable progress is being made in using such fuels with waste liquid fuels, scrap tyres, petroleum coke, etc. being used.

Fly ash is the best known pozzolana, which is used to reduce the Portland cement component in both factory-produced cements and as a mixer addition in concrete. Fly ash consists of oxides of silica, alumina, iron and some calcium. As the ash results from the burning of coal in power stations, at temperatures of between 1250 and 1400°C, these oxides are chemically, or pozzolanically, active.

Fly ash can be used to some extent as the source of silica to replace the 20% clay/sand used in cement manufacture. However, in practice, cement works are normally sited near sources of limestone and clay and the practicality, and environmental impacts, of transporting the fly ash to the works have to be carefully assessed. In some cement works mindfully sourced fly ash is used to alter the chemistry of the cement. This is designed to reduce the sodium and potassium alkalis in the final product by adding low alkali fly ash to the raw meal. This has environmental and practical benefits reducing the kiln temperature and producing a more saleable, lower alkali product.

The addition of fly ash as a pozzolana to cement and concrete mixes is well understood. Cabrera [4] analysed the potential benefits of using fly ash as an addition in cement and concrete and concluded that reductions of 30% in CO_2 emissions were achievable. However, these calculations did not allow for transport effects and for the extra cementitious often required for the mixes to attain equal 28-day strength. Parrott [5] reviewed the environmental benefits of using fly ash and ground granulated blast furnace slag in more detail allowing for transport. For an addition of 30% PFA of the cement content for equal 28 day strength in comparison with Portland cement concrete he concluded that the following can be achieved:

- Greenhouse gas emissions can be reduced by 17%.
- ‘Acidification’ reduced by 15%.
- ‘Winter smog’ reduced by 5%.
- ‘Eutrophication’ reduced by 13%.
- ‘Primary energy’ requirements reduced by 14%.

An overall reduction in the environmental impact using the ‘Eco-indicator 95’ was 14% with fly ash replacement. If equal 56 day strength was compared this increased to 19%. Similar results are quoted by Galvind et al [6]. Davidovits [7] paints a more depressing picture and points out that if all the fly ash produced was fully utilised in concrete this would only replace 8% of the world market for cement. However, replacement of 8% is a step in the right direction.

Whichever data one uses the inevitable conclusion is that a significant reduction in environmental impact is feasible by adding fly ash to Portland cement. A doubling of fly ash utilisation is feasible and beneficial to the planet.

Fly ash in Road Construction - Sub-base systems

Traditionally naturally occurring aggregates have been used with little thought for concrete, fill applications, road construction, etc. For many of these applications, such high quality materials are inappropriate and by-product materials could easily be used. Even for the high quality uses in concrete, lightweight sintered fly ash aggregates can be utilised.

Fly ash can be extensively used in the construction of road sub-bases as an alternative to crushed aggregate materials. These are known as Fly Ash Bound Mixtures (FABM) for which European standards are currently being prepared. Table 1 [8] gives examples of FABM mix designs, which can contain up to 97% fly ash and significant amounts of recycled aggregates.

Many FABMs are made using lime rather than Portland cement, relying on the pozzolanic reaction with fly ash to act as a binder. The use of lime has a number of advantages over normal cement bound material (CBM) sub-bases. Lime/fly ash FABM acts as a traditional granular sub-base material during its early life allowing it to be trafficked as one would a traditional crushed rock sub-base. However, in the long term the strength development gives excellent durability properties, similar to CBM, see figure 3. Although relatively high strengths can be achieved in the fullness of time, reflective cracking does not seem to occur, probably due to the large numbers of micro cracks formed during the hydration process.

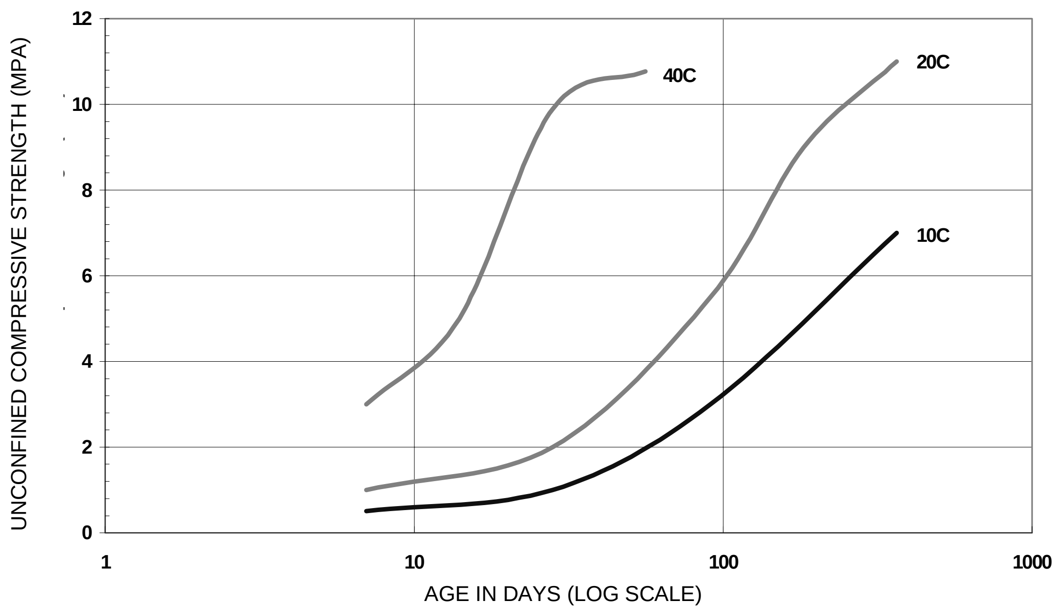

Figure 3 – Unconfined compressive strength of Granular Fly Ash (GFA)

By using these mixtures, fly ash and recycled aggregates can be utilised reducing the environmental burden on Portland cement and natural aggregates sources for road construction.

Fly Ash for Fill Applications

Fly ash has a long history of use in fill applications [9]. Its use reduces the need for extraction of virgin aggregates, however, there appears to be a reluctance to use this material apparently purely because it is a by-product. There are a number of advantages in using fly ash for fill applications as follows:

- It is lightweight when compared to most materials. 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.
- With proper profiling PFA fill can be trafficked in all weathers.

Table 1 - Examples of fly ash bound mixtures (FABM) for road and airfield pavements

		TYPICAL PROPORTIONS AS A PERCENTAGE OF DRY MASS (%)							
Type of FABM	Abbreviation	Conditioned (or dry) PFA	Lime (CaO) or $Ca(OH)_2$	Portland Cement	Graded crushed coarse material Maybe recycled aggregate	Sand	Soil/ earth	Other material	Typical Water content %
Lime PFA	LFA	93 - 97	3 – 7						15-25
Lime gypsum PFA	LFA	91	4					5% gypsum	15-25
Cement PFA	CFA	90 - 95		5 - 10					
Lime PFA granular material	GFA	8.5 - 13	1.5 – 3		50 - 55	30 - 40			6-8
Lime PFA granular material	GFA	4-6% dry PFA	1 - 1.5*		50 - 55	40 - 45			6-8
Cement PFA granular material	GFA	3-6		1 - 3	50 - 55	40 - 45			6-8
Slag PFA granular material	GFA	5 - 7	0 – 2		50 - 55	30 - 40		5-7% GBS**	6-8
Lime PFA sand	SFA	9 – 12	2 – 4			84 - 89			Approx. 10
Cement PFA Sand	SFA	6 - 8		2 - 4		88 - 92			Approx. 10
Lime PFA soil	EFA	6-8% dry PFA	1 – 2*				90 - 93		Depends on soil
Cement PFA soil	EFA	3 - 6		2 - 4			91 - 94		Depends on soil

* Lime can be pre-blended with PFA. ** Granulated Blastfurnace Slag.

Fly Ash as a Binder in other Applications

There has been a variety of potential applications for fly ash as a pozzolanic binder. Recently, one of the novel uses is in landfill liners [10] made from waste and by-products materials. Experiments have shown that various waste metal slags and foundry sands can be used as coarse and fine aggregates. Binders of fly ash, blastfurnace slag, cement kiln dust and waste alkalis have all been used. The systems are currently being developed further into full scale liners for landfill operations.

In many ground remediation applications and products, fly ash has been used for both its pozzolanic properties and its inherently low permeability. Fly ash is also widely used in grouts acting as a binder and aggregate. These have been extensively used for filling old limestone, coal and similar mines. Within the West Midlands area, it is estimated that over 4,500,000 tonnes of fly ash has been used in grouting. Fly ash grouts have excellent pumping and low bleed properties.

Fly Ash as an Aggregate

Fly ash products have a great potential for replacing naturally occurring aggregates in a variety of applications. Many people will have heard of the trade name Lytag, which is sintered fly ash lightweight aggregate [11]. This is manufactured by pelletising fly ash and heating the pellets until they fuse into expanded lightweight aggregate. While energy is used in fusing the pellets, the unburned carbon within the fly ash provides much of the fuel and any additional heat is derived from waste oil. Typical Lytag concrete densities range from 1600 kg/m^3 to 1900 kg/m^3. As this is significantly less than for normal dense concrete, considerable savings in the design of building support structures are possible. The result is the use of less concrete, less cement and less aggregate.

An alternative method of producing aggregate from fly ash is the Aardelite process. In this process, the binding of the fly ash particles is achieved pozzolanically using lime. The energy consumption of this process is less than the Lytag process as binding occurs at ~70°C. Again, the aggregate is a lightweight material that can be used to make structural concrete.

Another application in which fly ash is particularly suitable is for grouting applications [12]. It acts partially as a binder and an aggregate. Fly ash grouts inherently have excellent properties, e.g. they are easy to pump, they bleed less than naturally occurring fine aggregates, they need less water for a given flow, etc. Many millions of tonnes of fly ash have been used in filling mines and caverns created since the start of the industrial revolution.

Fly ash in Block Production

About 16% of the PFA produced is used in the manufacture of both aerated concrete and lightweight concrete blocks. A block can contain over 80% by-product material. However, natural aggregates still account for a significant proportion of blocks produced.

The Environmental Impacts of fly ash

From current annual production, around 3,000,000 tonnes of PFA are stockpiled. Considering the numerous potential applications, as above, why is fly ash not fully utilised? One problem is the general perception that fly ash is a waste material and somehow must be inferior to naturally occurring materials. This view is propagated by many researchers, environmentalists and government officials one meets. However, one must consider that fly ash is produced as a by-product. This material may only require minimal processing and is supplied at a relatively low cost. Conversely, many naturally occurring aggregates are highly processed, e.g. crushing, screening, washing, etc. in order to make them suitable for use.

Processing fly ash to improve acceptability.

Fly ash can be processed, as found in BS3892 Part 1 PFA for concrete. Here it is possible to show that PFA's from a wide range of sources are 'demonstratively similar' and can be interchanged without detriment to the concrete quality. Such compatibility across natural aggregate or cement sources is very rare.

One problem is the seasonal electricity consumption. Only a few coal fired stations are 'base load', that is continuously operational during the summer months. The others 'double shift', that is they operate to supply the peak demand for electricity. The inevitable result of this mode of operation is the quality of the fly ash suffers with high loss on ignition (LOI) and variable fineness. However, the power generation industry is actively researching ways of improving the quality of PFA and availability. The ways includes carbon reduction, methods of cleaning the material and increased dry storage capacity. The latter allows the more consistent winter PFA to sell during the summer months alleviating shortages.

For many years fly ash has been classified to BS3892 Part 1 PFA as an addition in concrete. This type of processing produces a very consistent material and improves the properties of the concrete, e.g. lowers the water demand and produces less variable concrete. This has proven successful and QSRMC now accept that many sources of PFA can be classed as demonstratively similar. This coupled with an increased storage capacity, that allows PFA to be supplied throughout the year without shortages, is increasing availability.

Chemistry and the environmental impacts

One other perception is that PFA is a toxic material that pollutes the planet. The minerals in PFA are those laid down with the coal measures, that is they are naturally occurring materials. The water-soluble properties of PFA can be summarised as follows [13]:

1. The majority of the ash is present as an alumino-silicate glass;
2. Most elements are present in very small quantities and are largely entrained in the glassy material;
3. Typically less than 2 % of the PFA is water-soluble; calcium and sulfate constitute the majority of the water-soluble fraction. There are smaller amounts of sodium, potassium and, in low pH leachate, magnesium;
4. The pH is mainly determined by the water-soluble calcium and sulfate;
5. The water-soluble fraction, though small, can be sufficient to produce a pH above 11.5, but dilution can rapidly reduce the water-soluble fraction and therefore the pH.

Fly ash is naturally of low permeability and in many applications is used with a binder, e.g. cement, lime etc. Inherently it is a low permeability material making it difficult, if not impossible, to both saturate and extract the water-soluble fractions. CIRIA [14] reported that

'Subsequently the material (fly ash) could not be saturated during testing' and concluded that '… when they (fly ash) are used in road construction and in the permeameter an almost impermeable bed is created.' Although such statements were made the report groups fly ash in Group 2 – 'May need some restrictions based on the potential to affect water quality'.

Conclusions

From the various sources of data, there are a number of conclusions:

1. The increased use of fly ash or PFA both in cement and concrete manufacture is beneficial to the environment. A 14% reduction in overall environmental impact for concrete of equal 28 day strength is possible by using 30% PFA addition as part of the total cement content.
2. Fly ash could be employed in sub-base application in road construction. It can encompass recycled planings and can bring the benefits of traditional granular sub-base and cement bound materials without many of the drawbacks.
3. Fly ash can be used as a fill material for general and structural applications reducing the demand for natural aggregates. Fly ash grouts have superior properties to many natural aggregate grouts.
4. Lightweight aggregates made from fly ash could reduce the demand for naturally occurring aggregates by both replacing them and reducing the quantities of concrete required.
5. The inherent low permeability and pozzolanic binding capacity make fly ash ideal for a wide range of environmental applications including ground remediation, landfill liners, etc. as well as road construction.
6. Though a by-product, that many consider a waste, fly ash does not have any significant environmental leaching problems. With careful management and application, any such problems can be easily overcome.

In order to be sustainable for future generations we must fully exploit by-product materials like fly ash/PFA. Both current production and stockpiled material should be fully utilised. These will both reduce greenhouse gas emissions and the use of naturally occurring aggregates. It is our duty to take sensible engineering judgements based on the facts about by-products and not on the prejudice of assuming a 'waste' is somehow inferior or less suitable.

It is our duty to adopt a more sustainable approach to construction and fly ash/PFA is an important by-product we must exploit in achieving this aim.

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