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Should you be using more PFA?

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ABSTRACT: Pulverised Fuel Ash (PFA) has been used in concrete for over 50 years. It has been the subject of research for over 70 years with in excess of 10,000 papers being published. It has been shown to improve the durability of concrete by reducing chloride ingress, preventing alkali silica reaction, lowering permeability, improving sulfate resistance, preventing delayed ettringite formation, reducing water content, increasing cohesion, reducing bleeding and enhancing long term strength gain properties as well as reducing the peak concrete temperature and the environmental impact. It can replace the cement and/or the aggregates within a concrete and can even be the main constituent of the coarse aggregates, e.g. Lytag. In addition it is an economical material. It is because of the benefits, that material like High Volume Fly Ash (HVFA) concrete is gaining popularity on environmental and heat of hydration grounds. Foamed and self compacting concretes containing PFA are more stable and easier to use. Airports often use PFA concrete for runways and many road construction jobs use PFA in bridges and carriageways for both environmental and economical grounds. Precast concrete manufacturers widely use it as well as the aerated and lightweight concrete block makers. PFA has found a wide range of uses in concrete with numerous technical and environmental benefits being found.

This paper will review the benefits of using PFA; will look at some of these contracts that have used PFA concrete in recent years, why they used PFA, whether it was successful, etc.

Keywords: Pulverised fuel ash, fly ash, durability, alkali silica reaction, thaumasite, corrosion.

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INTRODUCTION

Pulverised fuel ash (PFA), or fly ash as it is known in many countries, has a long history of use in concrete. As a by-product it can impart many beneficial qualities to concrete, improving durability and reducing overall environmental impacts. These benefits have been researched by many differing bodies, numerous times over the years and yet there is still resistance to overcome in some people's minds. This paper will review the benefits of PFA and some of the research carried out in the UK and the more recent applications PFA has been used in.

RESEARCH INTO PFA IN CONCRETE

At the time of writing this paper, the UKQAA has a bibliography of published research papers totalling 10,499 purely relating to fly ash. The considerable majority of those papers are about concrete, a much researched and often misunderstood material. In recent years research has been concentrating on deleterious reactions, environmental impacts, brownfield land development and ways of encompassing waste materials within concrete successfully. Concrete is attacked by many compounds with the potential to cause deleterious reactions, either to the concrete or something embedded in the concrete. The environmental impact and sustainability issues are increasingly being brought to the forefront of discussions. PFA is able to reduce environmental impacts by replacing both Portland cement and aggregate, as well as acting as an aid to incorporating other waste streams successfully within concrete.

PFA is added in various proportions depending upon the application. PFA is added to many types of cement as a Minor Additional Constituent (MAC); where up to 5% material is permitted under BS EN197-1. Addition rates from 5 to 20% are commonly used in concrete. However, additions of 25 to 35% form the considerable majority of PFA concretes produced. Above 35% and up to 55% addition rates, one is moving into the so-called pozzolanic cement range. These are used where low heat of hydration is needed, where there is a significant risk of alkali silica reaction, chloride ingress or similar. In the range of 50 to 70% PFA contents, these are known as high volume fly ash (HVFA) concretes, primarily designed to reduce environmental impact.

Much of the research carried out in recent years suggests that increasing the proportions of PFA addition within concrete has considerable advantages. The following is a broad overview of the findings of the various projects.

The Thaumasite Form of Sulfate Attack

There have been numerous research projects on the Thaumasite form of Sulfate Attack (TSA). These projects were precipitated by severe deterioration being found in bridge support piers on the M5 in 1997. Subsequently, further examples have been found in other structures. However, in the UK examples they are predominantly associated with clay containing pyrites, such as the lower lias clays, that have oxidised therefore increasing the sulfate concentrations dramatically over the original assessment of the ground conditions. As a result, the method of assessing sulfates in the ground has been changed to reflect the oxidation of pyrites and the higher sulfate conditions.

At the same time the ground assessment system was enhanced, the specification for the concrete was also raised. One secondary cementitious material supplier, i.e. the Ground Granulated Blast Furnace Slag (GGBS) industry, had been fortunate, or clairvoyant, and had carried out a series of experiments that proved their material was excellent at resisting TSA. Others, including the PFA industry, then had to play “catch up” in the research stakes. So over a period of 6 years various research projects looked at how to prevent TSA damaging concrete.

Many of the following research projects were carried out at 5°C, the optimum temperature at which TSA occurs. However, such a temperature is not conducive to the pozzolanic reaction and probably why PFA is found to be prone to some attack as found in many of these experiments. Subsequently it was found that increasing the proportion of PFA in the concrete appears to enhance its performance. Holton & Crammond [1] found that “Concrete with 45% cement replacement offered better resistance to TSA than those made with 30% at the same W/C ratio”. So the quantity of PFA, as found with GGBS, has a marked bearing on its performance. PFA concretes most commonly contain ~30% PFA content. These findings are supported by Bellman [2] who researched the Gibbs free energy aspects of thaumasite formation and concludes the use of pozzolanas such as PFA forms additional C-S-H, which reduces Portlandite. In the absence of Portlandite, higher sulfate concentrations are required for thaumasite to form.

While using the optimum temperature for the formation of TSA of 5°C is logical, it is not the average temperature of the ground in the UK, as seen in figure 1. This annual temperature cycle will enhance the performance of pozzolanic material like PFA.

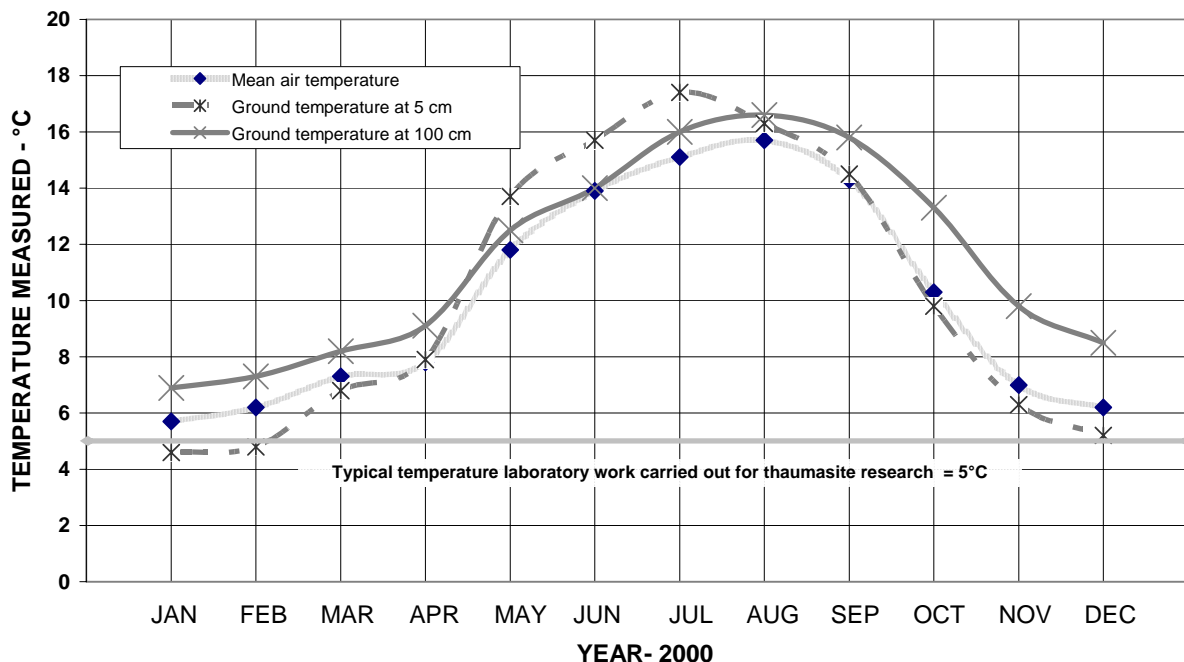


Figure 1 – Typical ground temperature profile – Llansadwrn, Anglesey

In site experiments all the PFA concrete mixes seemed to have performed well. Crammond[3] found that all concretes stored at a test site at Shipston on Stour made with blended cements containing PFA (including BRECEM), microsilica and metakaolin performed satisfactorily irrespective of aggregate type.

Further experiments are currently being carried out using temperature cycling to mimic real conditions and we predict these will demonstrate that PFA is very good as resisting TSA, especially with higher ash contents – but only time will tell. It is important to remember that there has never been a case of deleterious TSA occurring involving PFA concrete to the knowledge of the UK PFA industry.

Alkali Silica Reaction

One would have expected that Alkali Silica Reaction (ASR) had been fully researched and understood, since its discovery in the early 1970's. While this is probably true and further work was felt necessary with the introduction of European standards. Work was carried out by two research bodies within the last 5 years to assess the performance of fly ash conforming to BS EN450. For many years within the UK, PFA has been predominantly supplied to BS3892 Part 1 for use in concrete. This material is generally classified to have less than 12% retained on a 45µm sieve in order to improve water demands and increase reactivity. Most of the research in the UK has been carried out on this relatively fine material. However, with the advent of the European standard BS EN450, it was felt the ability of coarser ash to resist ASR needed to be proven. As it has transpired, both BS3892 Parts 1 and 2 PFA's and BS EN450 fly ash, even the very coarsest material, were found by Dhir[4] et al to be able to resist ASR equally effectively. As a result of this and BRE's own work, BRE Digest 330 and the complementary British Standard to EN206-1, BS8500, have been changed to reflect these findings.

Resistance to Chloride Penetration

The ability of PFA concrete to resist the ingress of chloride is well documented. There are some 450 papers on the subject to our knowledge. It is the low permeability and relatively high alumina content of PFA concrete that gives excellent properties of preventing chloride ingress into the concrete. It is well known that the greater the proportion of PFA the better the chloride resistance found in the concrete.

High Volume Fly Ash

Reducing environmental impacts and the consideration of sustainability issues in construction are becoming increasingly important, especially in the USA [5]. High Volume Fly Ash (HVFA) concrete containing 50 to 70% PFA is one way of reducing impacts, by an extension of the principles established in Parrott's work, as discussed below. HVFA concretes are successful because they rely on the performance of super plasticisers to reduce water contents to very low levels with water/cementitious ratios of ~0.30. This makes for very low permeability concrete with good sulfate resistance, good resistance to chloride ingress, etc. In addition, the peak temperatures in larger sections are significantly reduced, reducing the risk of thermal cracking problems.

To ensure the successful use of HVFA good construction practice must be used. Formwork stripping times may need to be extended for thin sections or for cooler weather conditions, curing regimes have to be extended and allowance made for the fact that the strength gain takes place over a longer time period. However, it is possible to significantly reduce the overall impacts of building a structure by making the best use of benefits of PFA.

Carbonation

The pozzolanic reaction also uses up lime, which is very important in maintaining the alkali environment that protects the reinforcing steel. 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%. Increasing the proportions of PFA within a concrete has often lead to the cry, what about carbonation? In most research organisations it is normal to assess the carbonation of concrete using accelerated testing regimes, by increasing the proportion of CO₂ to which the concrete samples are exposed. While this accelerates the ingress of CO₂, 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 CO₂ to the concrete. A comparison of accelerated testing with real exposure is shown in figure 2.

Thomas and Matthews carried out extensive work on the durability of concrete. Thomas [6] states in relation of 28 day compressive strength versus 2 year carbonation depth that:

- a. the correlation coefficients are high and the relationships appear to be independent of the PFA level, duration and temperature of initial curing and the temperature and relative humidity of early storage (i.e. up to 28 days)
- b. However, it is not carbonation per se that is of interest, but the potential for corrosion of reinforcing. Corrosion requires the presence of oxygen and increasing the PFA content reduces oxygen permeability significantly. Thomas considers the two factors of carbonation and permeability and concludes that with 50% PFA mixes, extended curing times are required if they are to be exposed to carbonation and subsequent corrosion conditions.

Matthews also published a report [7] into the 10 year carbonation depths from various projects containing up to 50% PFA. Three of his conclusions are that:

- a) Good relationships were obtained between carbonation depth at a given age and the 28 day strength of similarly cured specimens irrespective of PFA content.
- b) Factors such as curing period, long term exposure conditions and concrete strength have a greater influence on overall carbonation rate than PFA content.
- c) Carbonation is only one factor influencing the corrosion of steel. Environmental conditions, especially relative humidity, and concrete quality factors including permeability to moisture and oxygen, must also be taken into account in determining corrosion risk.

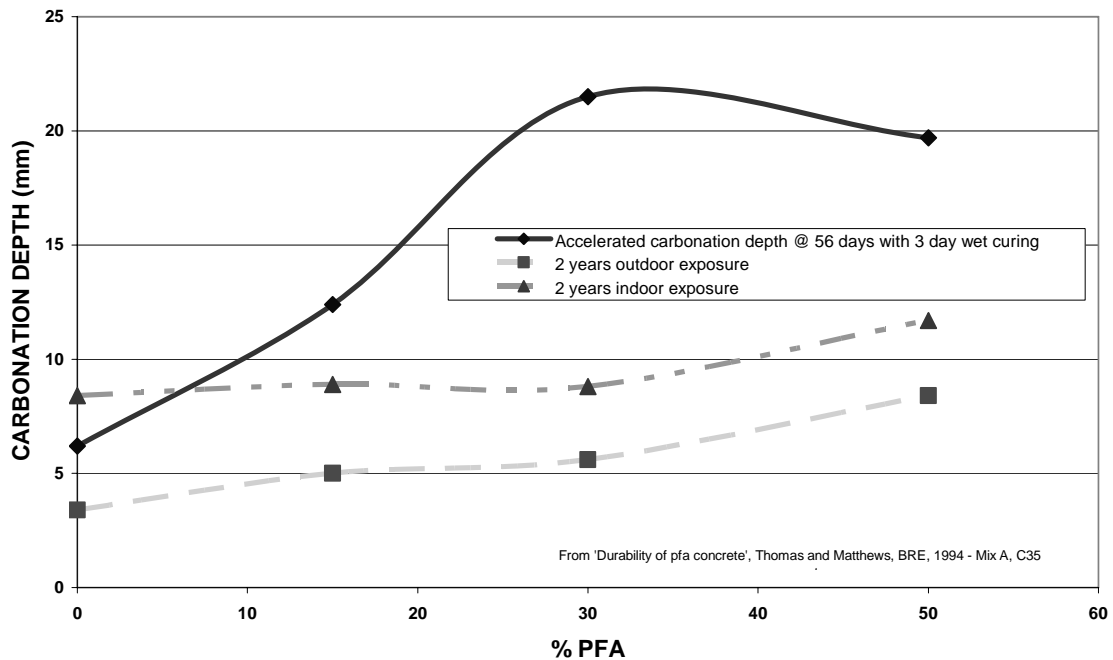


Figure 2 – Comparison of accelerated testing and natural exposure - Carbonation vs. PFA content for C35 concrete

High Fly ash Content Concrete (HFCC), the forerunner of HVFA, was extensively researched and reported by Cripwell et al in 1993[8]. Various HFCC structures were examined after 10 years including Didcot Power Station (51 to 56% fly ash), Wincaton Sewerage Works (54% fly ash) and the Mumbles Slipway (52% fly ash). With the exception of one of the Didcot structures, all carbonation depths for HFCC concretes were low, ranging from 1 to 6mm of carbonation in 10 years. The authors concluded that HFCC concretes were no more susceptible to the effects of carbonation than conventional PC and fly ash concretes designed for equivalent strength. Other notable facts found were no evidence of ASR, average to low oxygen permeability and low chloride permeability and significant increases in strength since 28 days, e.g. 46% found with the Mumbles slipway concrete.

Other benefits of using PFA in concrete

Foamed concretes have gained a foothold in many applications as a lightweight fill material, such as pipelines, service ducts and shafts, bridge arches or subways, culverts, redundant sewers, cellars and basements, etc. By the incorporation of PFA in the product formulation it has been found the cellular structure of the resulting material is more stable and it reduces segregation and air loss. Much of the work on this product has been carried out at Dundee University. Similar benefits are found in self compacting concretes, they are less prone to segregation and bleeding and they flow well, etc. Other benefits of PFA include its ability to prevent delayed ettringite formation in heated precast concrete.

Environment aspects

Portland cement, by the nature of its chemistry, produces large quantities of CO₂ for every tonne of final product. About 550kg of CO₂ is produced to reduce the CaCO₃ to CaO required in the manufacturing process, with a further ~400kg per tonne produced in heating and processing the cement clinker. By replacing proportions of the Portland cement in a concrete mix with a secondary cementitious material like PFA, the overall environment impact of the concrete is reduced. Parrott[9] showed that replacing 30% of the Portland cement with PFA reduced greenhouse gas emissions by 17% based on equal 28 day strength concretes. As PFA is a pozzolana, using later strength performance gives increased advantage, for example for equal 56 day strength 30% PFA concrete reduced greenhouse gas emissions by 24%.

In addition, PFA can be used as an alternative to aggregate, as in the foamed concrete above.

Some recent contracts

Over 1.25 million tonnes of PFA are used in cementitious applications, e.g. in cement and concrete and 1.1 million tonnes in block manufacture per annum. A further 1.3 million tonnes are used as an alternative aggregate for fill and grouting applications and as lightweight aggregate for concrete. PFA concrete has been used on numerous contracts over the years and its growth continues for the above reasons. More recently the more notable contracts where it has been used include Canary Wharf, Heathrow Airport Terminal 5 and the M6 Toll road, though this list is not meant to be exhaustive. The following outlines why PFA was chosen at some of these contracts:

Heathrow Airport Terminal 5, London

In a period of 5 years ~135,000 tonnes of PFA will be used in a variety of concrete applications in the construction [10]. One novel application is a new design of pavement concrete for taxiways for the airplanes. The greater flexural strength of this new concrete means that a reduced thickness is required, even though load is increasing from 23 tonnes to 28 tonnes per wheel for aircraft like the A380 Airbus [11]. Less concrete means less cement and as up to 40% of the cement content is PFA; the overall amount of CO₂ is significantly reduced compared to Portland cement. All PFA deliveries to the T5 site are being made by rail as opposed to road tankers, thereby reducing CO₂ emissions even further.

Canary Wharf

This project has used in excess of 300,000m³ of concrete in a single year, with some 80% of the concrete containing PFA. 'Environmental Design considerations' [12] were cited as playing a key role in the decision to adopt PFA in the contract. Mixes containing 40% PFA were used to reduce heat of hydration problems and eliminate cracking.

M6 Toll Road

Again PFA was used for its economy, its durability and reduction in the heat of hydration properties. Over 22,000 tonnes was used in the road pavement and 16,000 tonnes for associated structures, in the construction of the 43km of highway with 72 bridges and culverts.

Conclusions

PFA has had a long history of use in concrete structures. It has been extensively researched over a period of more than 50 years and found to be beneficial in resisting many deleterious reactions as well as improving the durability of concrete. There is increasing evidence that the use of higher proportions of PFA as a cementitious material than the normal 20 to 30% has considerable benefits to concrete as in Figure 3.

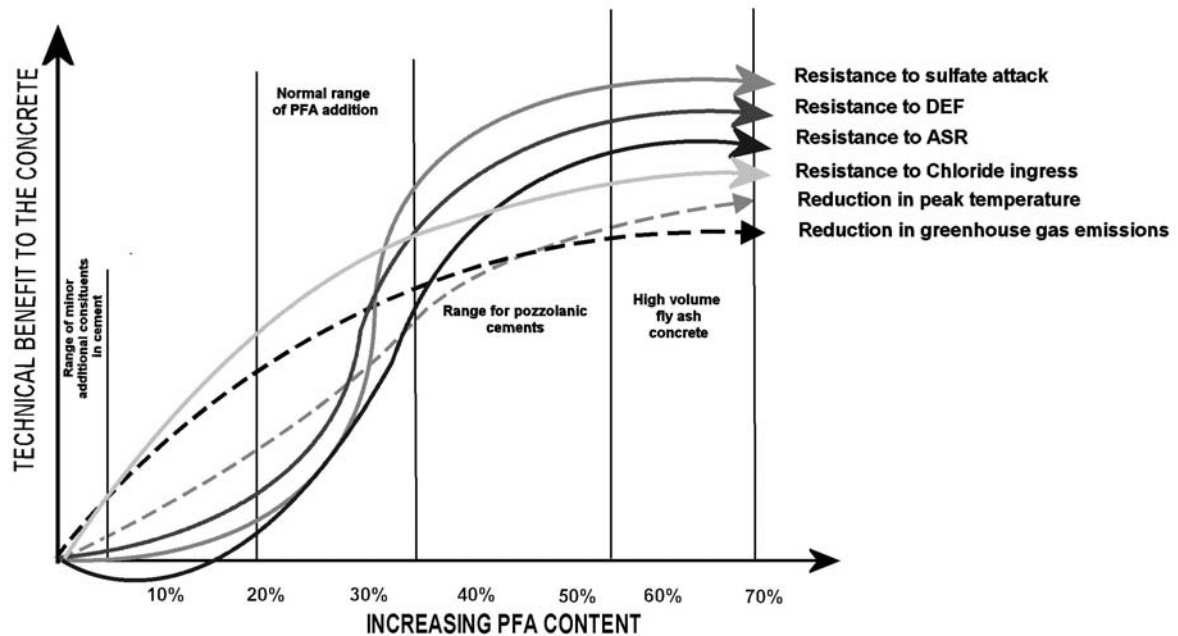


Figure 3 – The more PFA the better the performance

In addition to these benefits, PFA can enhance fresh concrete properties, e.g. reducing bleeding and lower peak temperature. So are you using enough PFA in your concrete – only you can decide?

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