SUMMARY OF BRE RESEARCH ON THE EFFECT OF FLY ASH ON ALKALI-SILICA REACTION IN CONCRETE

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ABSTRACT

This paper summarizes the findings from a five-year research programme on the effect of fly ash (Class F) on ASR in concrete containing a range of U.K. aggregates. The study included expansion testing, pore solution analysis and microstructural examinations of laboratory concretes stored under a range of conditions and larger specimens under field conditions. In addition, field studies were made of fly ash concrete structures incorporating reactive aggregates. Only a small proportion of the data is presented here for the purpose of highlighting the principal findings of this investigation.

Collectively, the results from these studies do not support the concept of an "effective alkali contribution" from fly ash. The efficacy of Class F ash depends on the level of ash replacement and the reactivity of the aggregate, whereas the alkali level of the ash appears to have little effect. Higher levels of ash are required to control the expansion of more reactive aggregates (i.e. those that react at lower alkali contents in OPC concrete).

The implication of these findings for the specification of fly ash with reactive aggregate are briefly discussed.

Keywords: alkali-silica reaction, effective alkalis, expansion, fly ash, specifications

INTRODUCTION

Current U.K. guidelines (BRE, 1988; Concrete Society, 1992) for minimizing the risk of damage due to alkali-silica reaction (ASR) in concrete containing potentially reactive aggregate permit the use of fly ash to mitigate the effects of ASR. However, there is conflicting evidence regarding the efficacy of fly ash in this role and this is reflected in the lack of consensus advice. Much of the controversy is centered around the alkalis in the fly ash and whether they are potentially available for reaction. This is of particular concern when the total alkali burden of the concrete is being controlled to a specified maximum to avoid damaging reaction when potentially reactive aggregates are used. The Concrete Society recommends that the water-soluble alkali content of the fly ash is used when calculating of the total alkali content of the concrete. More conservative advice from the Building Research Establishment suggests that one-sixth of the total alkali content of the fly ash be used. Use of the "one-sixth rule" results in "available" alkali levels in the range 0.4% to 0.7% Na_2O_e for most U.K. ashes, which compares with values around 0.1% for water-soluble alkali.

In response to the conflicting advice regarding the role of alkalis in fly ash (and slag), the U.K. Concrete Society set up a technical sub-committee to review the subject of alkali contribution from fly ash (and slag). Under the guidance of this committee, further research was initiated to study the effect of fly ash on the expansion of concrete containing natural reactive U.K. aggregates and cristobalite. The programme on fly ash and cristobalite was carried out at the British Cement Association and results from the study have recently been reported by Hobbs (1994). A parallel programme using natural aggregates from U.K. sources was carried out at the Building Research Establishment (BRE). This paper presents a brief summary of some of the findings from the ongoing studies at BRE.

EXPERIMENTAL STUDIES

BRE carried out an extensive programme on the effect of fly ash on ASR in concrete containing reactive U.K. aggregates, which included the following studies: (i) expansion testing of concrete prisms stored under laboratory conditions, large specimens (up to 1m cubes) stored under field conditions and concrete specimens stored in various alkali salt solutions; (ii) pore solution analysis of concrete containing reactive flint; (iii) analysis of hydrate composition in concrete with a range of OPC, fly ash and aggregate combinations; (iv) field studies of concrete structures (with and without fly ash) constructed with reactive aggregates.

Five reactive aggregate sources were used in this study; these were: Thames Valley river sand (<5 mm), a crushed flint sand (<5 mm), a sea-dredged sand, a quarried siltstone (5-20 mm), and a quarried siliceous limestone (5-20 mm). Results are also reported for a greywacke aggregate from Wales. Greywacke has recently been implicated in a number of ASR-affected structures in the U.K. (Thomas et al. 1992) and its reactivity is currently the subject of an extensive investigation at BRE.

A number of Portland cements were used throughout the study to provide a range of alkali levels. Fly ash samples from four sources were included; all four of these ashes are marketed commercially for use in concrete.

RESULTS

Standard Concrete Prism Tests

The effect of fly ash on the expansion of concrete containing reactive flint (Thames Valley sand), siliceous limestone, siltstone and greywacke aggregate is shown in Figure 1. In these figures, the latest expansion data (at either 3 or 4 years) at 38°C is shown plotted against the alkali content of the concrete calculated on the basis of OPC alkalis only, i.e. disregarding the alkalis from the fly ash. From these relationships it is possible to estimate the "effective alkali contribution" from the fly ash using the approach developed by Hobbs (1986; 1994).

This *alkali contribution* from the ash is clearly dependent on the type of reactive aggregate and the level of ash replacement used. With flint aggregate, 25% ash is sufficient to prevent damaging expansion regardless of the alkali content of the concrete (within the range tested). Cracking was not observed after 4 years, even when the alkali content from the OPC was in excess of that required to induce cracking in control specimens. In other words, the ash has a positive role in suppressing expansion beyond that of merely diluting the cement. Other studies have shown lower levels of ash (e.g. 20%) to be equally effective (Nixon et al. 1987; Thomas et al. 1991). Similar behaviour was observed with the other sources of flint aggregate used in this study.

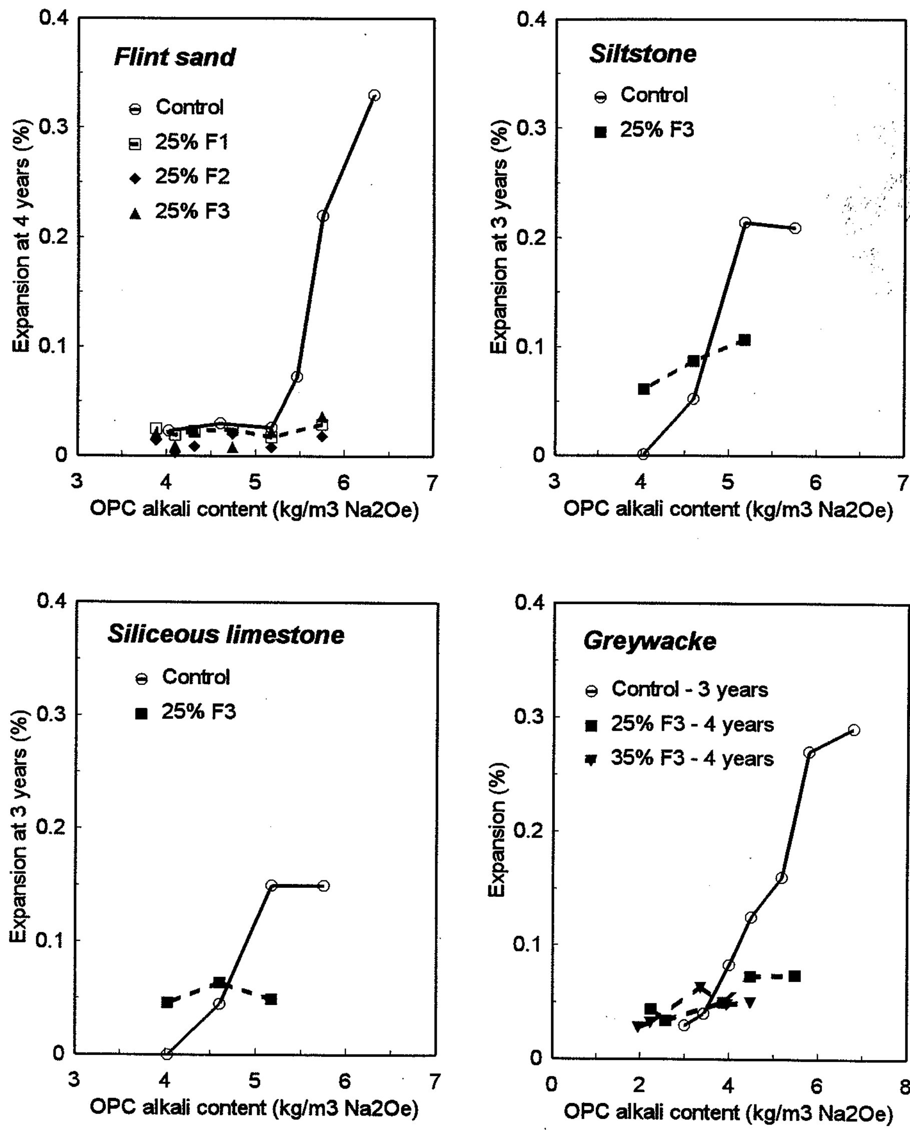

Figure 1 Expansion results for fly ash concretes

However, 25% fly ash was not effective in totally eliminating damaging expansion in concrete cast with the siltstone, siliceous limestone and greywacke aggregate. With these aggregates, significant expansion (> 0.05%) was observed in the ash concrete at lower OPC alkali levels than in the control specimens, indicating that the fly ash *contributes* alkalis to the concrete. At higher alkali levels, the ash appears to reduce expansion compared to control specimens at the same OPC alkali content. Indeed, examination of the relationships shown in Figure 1 suggests that the ultimate expansion of these fly ash concretes is not strongly influenced by the availability of alkalis from the OPC. Effective control of cracking with these aggregates may be achieved through the use of higher levels of ash, as shown by the results for 35% fly ash with greywacke aggregate.

Figure 2 shows the relationship between the *effective alkali contribution* estimated from expansion tests and the fly ash replacement level for the different aggregates; results from Hobbs' tests (1994) using artificial cristobalite as a reactive aggregate. This indicates that the quantity of ash required to control cracking increases with the reactivity of the aggregate. In this context, aggregate reactivity refers to the level of alkali necessary to induce cracking in the control specimens; i.e. more reactive aggregates induce cracking at lower alkali levels. The data is replotted in Figure 3 to show the *effective alkali contribution* as a function of the "threshold alkali content" of the aggregate.

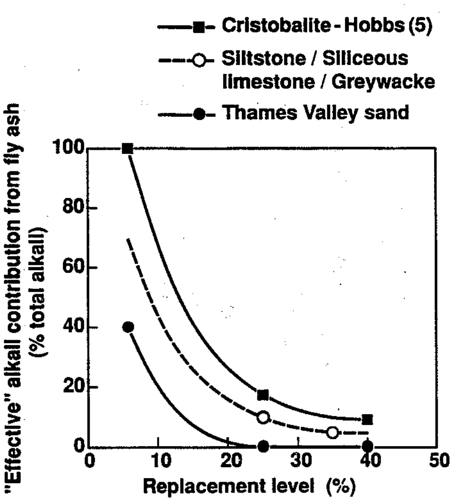

Figure 2 Effect of replacement level on alkali contribution from fly ash

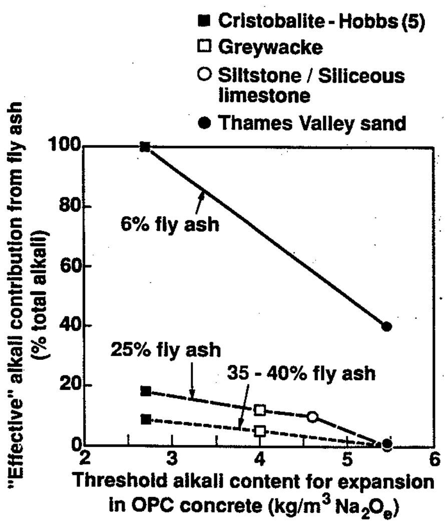

Figure 3 Effect of aggregate reactivity on alkali contribution from fly ash

Field Exposure of Large Concrete Blocks

Large concrete specimens (1.00 m or 0.35m cubes) of various cement-ash-aggregate combinations have been placed outdoors at BRE to study the effect of fly ash on ASR under field conditions. To date, some of the control specimens have cracked whereas all the fly ash concrete specimens are undamaged. However, considerably longer exposure periods are required before any conclusions can be drawn from these studies.

Pore Solution Studies

The pore solution composition of concrete, with and without reactive flint, was determined at various ages from 1 day to 2 years. The effect of reactive aggregate and fly ash is shown in Figure 4 for concrete cast with high alkali cement. For concrete without flint (i.e. 100% "inert" aggregate), the hydroxyl ion concentration of the pore solution at 1 day was lower in the fly ash concrete, the reduction being almost equal in proportion to the level of cement replaced. However, the ionic concentration in the fly ash concrete increases over the next 7 days and ultimately becomes very similar to that of the control. This indicates that fly ash has an affect beyond that of dilution and may be considered to "contribute" alkalis to the pore solution.

The addition of reactive aggregate has a marked effect on the pore solution, reducing alkalinity as early as 1 day after casting. The reductions continue for approximately 1 year and reach a steady value beyond this time. The behaviour of fly ash and control concrete was similar in this respect. Similar effects were observed for ashes with higher and lower alkali contents, indeed, in some cases the alkali concentration was higher in ash concretes compared to control samples with high alkali cement only.

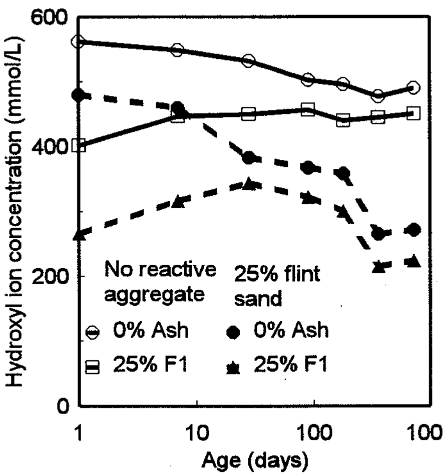

Figure 4 Pore solution evolution - effect of reactive aggregate and 25% fly ash

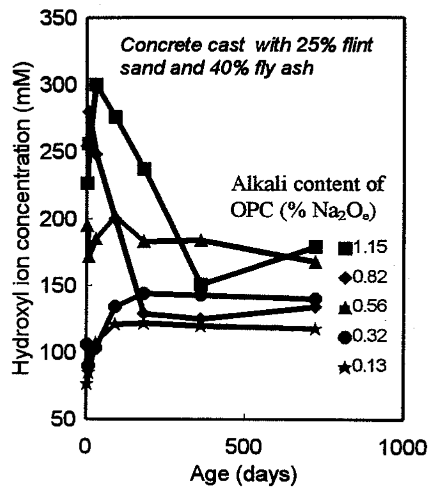

Figure 5 Pore solution evolution - effect of 40% fly ash

Figure 5 shows the effect of 40% fly ash on the pore solution of concrete cast with a range of Portland cements (0.13% to 1.15% Na_2O_e). The fly ash reduces the OH^- concentration when blended with high alkali cements and increases the concentration with low alkali cement. After 1 year, the OH^- concentration of all the concretes containing 40% ash lie in a fairly small range (120 to 190 mmol/L OH^-), suggesting that the ash has a buffering effect on the pore solution. The significance of the "buffering" effect will depend on the reactivity of the aggregate. If the reaction of the aggregate is not sustained at the buffered alkali level, then fly ash will be effective in suppressing the reaction and resulting expansion; this is the case with concretes containing reactive flint sand. If, however, the threshold alkali level for reaction of a particular aggregate is below the buffered alkali level, fly ash will not be effective in preventing reaction and may actually provide a reservoir of alkalis (i.e. its own) to fuel the reaction.

Alkali Immersion Tests

Concrete cylinders were immersed in a wide range of alkali salt solutions at various temperatures. Figure 6 shows the expansion of concrete specimens stored in 1N NaOH at 80°C. Concrete specimens with 40% ash showed no significant expansion and were uncracked after 2 years' exposure to this environment. Despite the lack of expansion, there was abundant evidence of reaction in these concretes; signs of reaction ranged from silica gel oozing from the surface of the specimens to complete dissolution of flint grains within the concrete. Samples examined by SEM/EDX showed distinct differences in the nature of the reaction and the reaction product due to the presence of 40% ash. The addition of lime at the mixing stage increased the expansion of all concrete containing reactive aggregate. The results from these studies are discussed in greater detail elsewhere (Thomas, 1995).

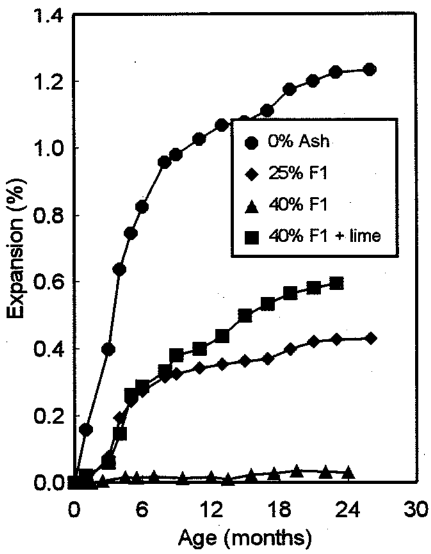

Figure 6 Expansion of concrete in NaOH solution - effect of fly ash and lime

Field Studies

Field data undoubtedly provide the most reliable indication of concrete performance. Fly ash has been used in concrete for many decades and, to date, there are no substantiated cases of damaging ASR in structures containing sufficient levels of Class F fly ash. However, in order to determine the positive effect of fly ash in suppressing ASR in a particular concrete structure, there has to be some means of assessing the likelihood of damage had the ash not been present. The use of fly ash in the Nant-y-Moch Dam in Wales, U.K. and the Lower Notch Dam in Ontario, Canada, has recently been documented by the authors (Thomas et al. 1992; Thomas, 1996). Both these structures contain reactive greywacke/argillite rock which has been implicated in damaging ASR in other hydraulic structures in the vicinity of the dams. However, both fly ash concrete dams are in excellent condition, despite the use of high alkali cement at Lower Notch.

DISCUSSION

The need to determine the alkali contribution of fly ash (and other supplementary cementing materials) stems from the now widely adopted use of maximum concrete alkali contents to reduce the risk of damage in concrete incorporating potentially reactive aggregates. Most fly ashes contain significant quantities of alkalis and there is a perception that these must be accounted for in the calculation of the total alkali content of the concrete. Other workers have attempted to determine the alkali contribution from supplementary cementing materials using leaching tests such as the "available alkali" test in ASTM C-311 and modified versions thereof (using cement in place of lime), or by analyzing pore solutions expressed from paste, mortar or concrete specimens. Hobbs (1986) developed an approach for estimating the "effective" alkali contribution from fly ash (and slag) using expansion data, and it may be argued that this is more relevant for specification purposes since, in practice, the concern is one of expansion and not pore solution effects. The term "effective" alkali contribution is used to distinguish the contribution calculated from expansion results from the proportion of alkalis actually released by the fly ash into the pore solution; these quantities are <u>not</u> the same.

The expansion tests reported in this paper were carried out to determine what proportion (if any) of the fly ash alkalis "effectively" contribute to the expansion of concrete containing natural U.K. aggregates. The results from this study and parallel studies at the BCA using cristobalite (Hobbs, 1994) demonstrate that the "effective" alkali contribution varies with fly ash replacement level and the nature of the reactive aggregate; other factors (e.g. fly ash chemistry and mineralogy) may also have an influence but were not adequately investigated in this study. Consequently, the adoption of a single value, such as one-sixth of the total ash alkali, is clearly inappropriate. This value is based on fairly specific circumstances (i.e. 25% ash with opal or cristobalite) and is too conservative for concretes with less reactive aggregates (e.g. flint) or higher ash replacement levels, and may actually preclude the use of ash in these situations.

The determination of "effective" alkali contributions from fly ash, whether from expansion or pore solution studies, for use in specifications where the alkali content of the concrete is to be limited, presupposes that availability of alkalis for reaction is the governing factor controlling ASR expansion in concrete containing ash. Such an argument is not sustained by the studies discussed in this paper.

The results and discussion presented here refer specifically to the use of low-calcium fly ash from bituminous coals (e.g. ASTM Class F). High-calcium, low-silica ashes are less effective in controlling expansion due to ASR, when used in the same proportion as Class F ashes, and may have to be used at higher replacement levels to suppress damaging alkali-silica reaction (Thomas, 1994).

SPECIFICATIONS

There is conflicting information from laboratory studies concerning the ability of fly ash to control ASR expansion. This is in contrast to the evidence from the field performance of fly ash concrete, which unanimously supports the use of fly ash as an effective "cure" for ASR. It is incongruous that when we have been unable to make the results of laboratory studies tally with field performance, we have based our specifications on the "artificial" tests in preference to the "real world".

The specification of fly ash for use with reactive aggregate should take cognizance of the need for increasing levels of ash as the reactivity of the aggregate or calcium content of the ash increases. The main problem with such a specification is the designation of aggregate reactivity since a well-defined basis for ranking aggregates according to their level of reactivity does not exist at this time. Knowledge of the reactivity of the aggregate is critical for optimizing the use of fly ash to control ASR and has application beyond the use of mineral admixtures as it would also allow more flexibility in selecting an appropriate alkali level for all concrete (with or without admixtures) based on the type of aggregate being used. Without knowledge of aggregate reactivity, specifications for fly ash (and slag) will have to either: (i) be overly conservative to cover all aggregate types; (ii) accept the chance of failure if a highly-reactive aggregate is inadvertently used; (iii) limit the use of fly ash to certain aggregate types (which implies some level of aggregate classification).

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