# LONG-TERM EFFECTIVENESS OF FLY ASH IN PREVENTING DELETERIOUS EXPANSION DUE TO ALKALI–AGGREGATE REACTION IN CONCRETE

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## ABSTRACT

A non-reactive and several reactive aggregates were used in concrete specimens with and without two low calcium fly ashes at binder (cement + fly ash) alkali levels ranging from 0.46 to 2.5% and a binder content of 500 kg/m$^3$ and fly ahs/binder ratio of 0.25. The specimens were stored either at 23°C (fog room) or 40°C, 100% RH. Some specimens were steam cured at 75°C for eight hours, and then transferred to 40°C, 100% RH. The expansion behaviour of the specimens was monitored over nearly six years, and showed that the effectiveness of the fly ash in preventing deleterious AAR expansion depended on the alkali content of the concrete. At the highest alkali content of 12.5 kg $Na_2O$ equiv./m$^3$, the fly ashes only had a delaying effect (one to several years), whereas at 6.9 kg $Na_2O$ equiv./m$^3$ they eliminated deleterious AAR expansions. Generally, for more highly reactive aggregates, and at the 2.5% alkali level, fly ash was less effective at 40°C than 23°C because the rate of AAR expansion was much higher at 40°C. At lower alkali levels and for less reactive aggregates, the temperature was not important. Fly ashes were also effective under steam-curing conditions. A measurable amount of chemical shrinkage occurred in the first few months in concretes containing fly ash and high alkali contents, although some of these concretes later expanded and cracked as a result of aggregate reactivity.

It is concluded (based on six-year results and the shapes of expansion cures) that the two fly ashes can be used to prevent deleterious AAR expansions in practical situations.
*Keywords:* Alkali–aggregate reaction; fly ash; steam curing.

## INTRODUCTION

The effectiveness of fly ash and other mineral additives in preventing the deleterious effects of alkali–aggregate reaction (AAR) has been known for a long time, and recent reviews (Berry & Malhotra 1986; Hobbs 1986; 1987; 1989; Helmuth 1987) have summarised most of the previous work. The controversy on the effectiveness of fly ash in suppressing AAR expansion is related to the composition of the fly ashes and cements used, as well as to the degree of reactivity of the aggregate employed.

For instance, a range of fly ashes and other mineral admixtures were found to stop any deleterious expansion in concrete caused by slowly reactive aggregates when 20 or 30% of cement (by mass) was replaced by fly ash (Nixon & Gaze 1983; Nixon *et al.* 1986; Pepper & Mather 1959; Stark 1978). However, Hobbs (1981; 1986; 1987; 1989) used highly reactive opal as aggregate, in its most expansive combination with cement. In such cases, even very effective fly ashes may not reduce the expansion to safe levels.

Other factors that may influence the results include the level of replacement and the fineness of the admixture (Dunstan 1981). The amount of fly ash needed to suppress AAR also depended on the Ca content of the fly ash. Lee (1989) suggested that for each fly ash a critical $Na_2O/SiO_2$ ratio determined maximum expansion due to AAR. Nagataki *et al.* (1991) found that suppression of AAR expansion depended on the amount of soluble alkali and amorphous $SiO_2$ content of fly ashes and their fineness, but not on their total alkali content.

Thomas *et al.* (1991) noted very little evidence of AAR in concrete specimens containing a reactive aggregate and a high alkali fly ash, when the level of replacement was 20% or more. Blackwell *et al.* (1992) showed that a fly ash of 4.0% $Na_2O$ equiv. prevented expansion of concrete containing a reactive greywacke and 7.0 kg $Na_2O$ equiv./$m^3$. However, their results are only short term (15 months). Thomas *et al.* (1992) provided long-term (30 years) evidence on the effectiveness of a high alkali fly ash in a dam structure to prevent damage due to AAR.

Hobbs (1994) also found that expansion due to AAR was influenced by the interaction between the level of alkali in cement (0.6–1.2% $Na_2O$ equiv.), fly ash (3.0–3.9% $Na_2O$ equiv.), and the level of replacement, determining the total alkali content of the concrete. The influence of mineral admixtures on the alkalinity of the pore solution of concrete and the consequences of this on AAR also depend on the alkali content of the cement (and concrete), as well as the available alkali content of the admixture and its replacement level (Nixon *et al.* 1986; Canham *et al.* 1987; Farbiarz & Carrasquillo 1987). Generally, low alkali mineral admixtures are more effective than high alkali ones in reducing pore solution alkalinity and expansion caused by AAR, and their effect is greater than a mere dilution of high alkali cements (Oberholster & Westra 1981; Diamond 1983; Canham *et al.* 1987). However, the variability of fly ashes in this respect has clearly been shown by Diamond (1981; 1983). Duchesne and Berube (1994) found that expression and analysis of the pore solution is the best method of estimating the contribution of fly ash alkali to the pore solution of concrete.

Australian fly ashes have been found to be effective in reducing AAR expansion (Shayan 1990; 1992), although the reported results related to short-term monitoring (one year). This paper provides long-term data for nearly six years, showing that at very high alkali contents (12.5 kg $Na_2O$ equiv./$m^3$) AAR expansion may not be prevented, although the fly ashes employed have an excellent tolerance for all practical levels of alkali, even as high as 7.0 kg $Na_2O$ equiv./$m^3$.

## EXPERIMENTAL WORK

### Materials

The aggregates used (all from Queensland) were a non-reactive basalt, a reactive basalt, two river gravels, a greywacke, a quartzite and an ignimbrite, all being reactive in laboratory testing. A detailed petrographic description of the aggregates has been given elsewhere (Shayan 1992). Two cements, designated D and N, were used with alkali levels of 0.79 and 0.46% $Na_2O$ equiv. The fineness of the cements and their compositional features were similar. Two low calcium fly ashes, designed (1) and (2), were used with $SiO_2$ contents of 72.6 and 57.7% respectively. Glass content comprised 80 and 93% of fly ashes (1) and (2) respectively, which also contained alkali contents of 0.21 and 1.35% $Na_2O$ equiv. Cement D and fly ash 1 were used in combination with all the aggregates except the ignimbrite for which cement N and fly ash 2 were used. This choice was governed by the geographical location of sources. The sand used in this work has been shown (Shayan *et al.* 1994; and unpublished work) to be non-reactive in concretes containing less than 7 kg $Na_2O$ equiv./$m^3$, but it caused moderate expansions in concrete containing 10 kg $Na_2O$ equiv./$m^3$ and deleterious expansions in concrete with 12.5 kg $Na_2O$ equiv./$m^3$. This sand is regarded as non-reactive by local practice.

## PROCEDURES

Concrete prisms measuring 75 × 75 × 285 mm were used for the evaluation of expansion potential of the various aggregate–cement–fly ash combinations. The concrete mixture contained 500 kg cement per $m^3$ concrete, with a water/cement ratio of 0.40. To evaluate the effectiveness of the fly ashes in controlling AAR, in some mixes 25% of the cement was replaced by fly ash on a mass basis. The water/binder ratio was kept at 0.40, and this caused a reduction of compressive strength of the concretes containing fly ash.

Three levels of cement alkali were employed in this work, viz. the native level of alkali as well as cement alkali levels of 1.38 and 2.5% $Na_2O$ equiv. achieved by adding NaOH to mixing water. Considering the cement content of the concrete, these cement alkali levels correspond to concrete alkali contents of 6.9 and 12.5 kg $Na_2O$ equiv./$m^3$. The corresponding mixes containing fly ash also had the same alkali contents. The addition of alkali also resulted in a considerable reduction in compressive strength of the concrete, as previously observed for mortar and cement paste (Shayan & Ivanusec 1989). The preconditioning, storage and measurement of length change for specimens at 40°C, 100% RH, was described earlier (Shayan 1992).

Similar specimens were stored at 23°C in a fog room and measured the same way. Another group of specimens were steam cured at 75°C for eight hours and, after initial length measurement on demoulding, were transferred to storage conditions of 40°C, 100% RH for monitoring their expansion behaviour.

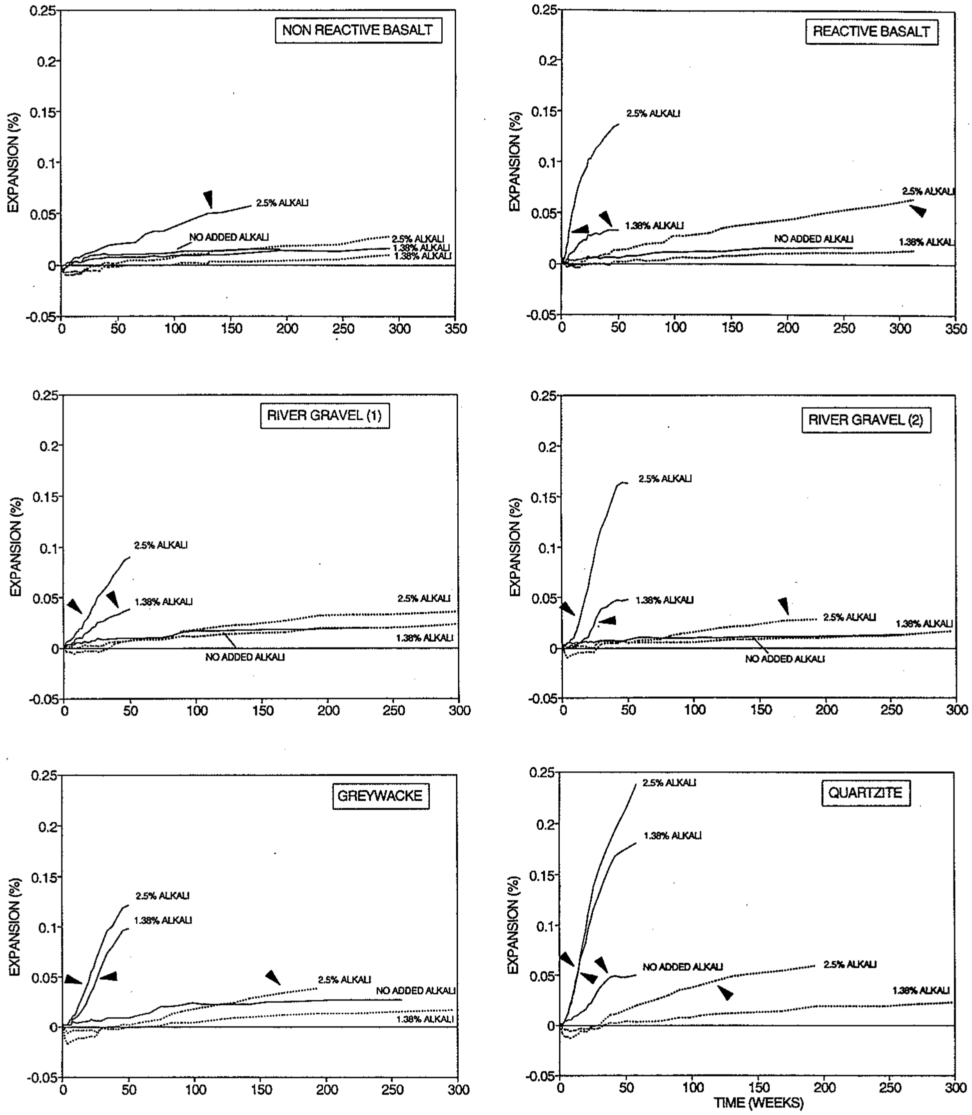
## RESULTS AND DISCUSSION

Expansion curves for concrete prisms containing each of the aggregates tested, and stored under the storage conditions of 40°C, 100% RH, are presented in *Fig. 1.*

The expansion and cracking of concrete prisms made with the non-reactive basalt (without fly ash) at 2.5% alkali level (*Fig. 1*), is attributed to the reactivity of the sand component at this high alkali content, as shown by Shayan *et al.* (1994). All the other aggregates caused relatively rapid deleterious expansion and cracking of concrete at both the 1.38 and 2.5% alkali levels.

The quartzite aggregate was the most rapidly reactive among those tested and caused cracking in concrete prisms at the lowest alkali content (3.95 kg/$m^3$, i.e. no added alkali). However, all of the reactive aggregates may react in field concretes of this alkali content due to probable redistribution of alkali and local high concentrations that could be produced as a result of the moisture movements and drying out of concrete.

*Figure 1* also shows that 25% mass replacement of cement by fly ash has been very effective in eliminating the AAR expansion in concretes that contained the 1.38% alkali level (6.9 kg $Na_2O$ equiv./$m^3$). However, it only delayed the expansion and cracking at the highest alkali level of 2.5% (12.5 kg $Na_2O$ equiv./$m^3$), although this alkali level would be outside the usual range of concrete alkali content. This was not evident from the short-term results (Shayan 1992) that showed only the ignimbrite aggregate caused cracking in the fly ash concrete at the 2.5% alkali level. These results emphasise the need for long-term monitoring of specimens to verify the effectiveness of a certain treatment. Field concretes containing fly ash have been reported to undergo AAR expansion and cracking, and Hobbs (1987; 1994) mentions two such cases in the USA and Japan.



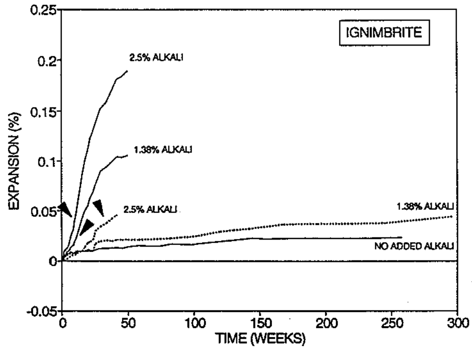




*Figure 1. Expansion of concrete prisms made with various aggregates and containing various levels of alkali with and without fly ash. Arrows refer to time when cracking was noted. The expansion and cracking of specimens containing the non-reactive basalt at 2.5% alkali level was due to the reactivity of the sand at high alkali. 'No added alkali' refers to 0.79% $Na_2O$ equiv. in the original cement. —— no fly ash; ······ fly ash.*

In earlier work (Shayan 1990; 1992), it was shown that the accelerated mortar bar test (Shayan *et al.* 1988) could predict the effectiveness of fly ash in suppressing AAR expansion in concrete. From the above results, it is clear that the predictions only relate to certain ranges of alkali content in concrete. This is to be expected because mortar bars immersed in 1 M NaOH solution would have equilibrium pore solution concentrations around 1 M. Therefore the prediction is limited to this upper concentration value. In concrete specimens at the 1.38% alkali level, the pore solution concentration would be about 1 M NaOH, and the prediction of the accelerated test agrees with long-term concrete expansion results. At the 2.5% alkali level, which gives a pore solution concentration of 1.4 M in the concrete, the prediction of the accelerated test is no longer valid.

*Figure 2* compares the storage conditions of 23°C (fog room) with 40°C, 100% RH for two aggregates, at the 1.38 and 2.5% cement alkali levels. The other aggregates show similar trends. The expansion curves for the concretes without fly ash show that expansion at 40°C, 100% RH is much more rapid, but that the same magnitude of expansion is reached at 23°C (fog room) at much later times, varying from about one year to a few years. None of the specimens made with fly ash and stored at 23°C (fog room) showed deleterious expansion up to the age of six years, regardless of the level of alkali, whereas most of those made at 2.5% alkali level and stored at 40°C, 100% RH have cracked. This effect was more evident for the more highly reactive aggregates. The difference is probably related to the much faster rate of AAR expansion of such aggregates at 40°C, 100% RH.

*Figure 3* represents the behaviour of steam-cured (75°C) fly ash concretes made at 1.38% binder alkali level and stored at 40°C, 100% RH, and compares the effects of the

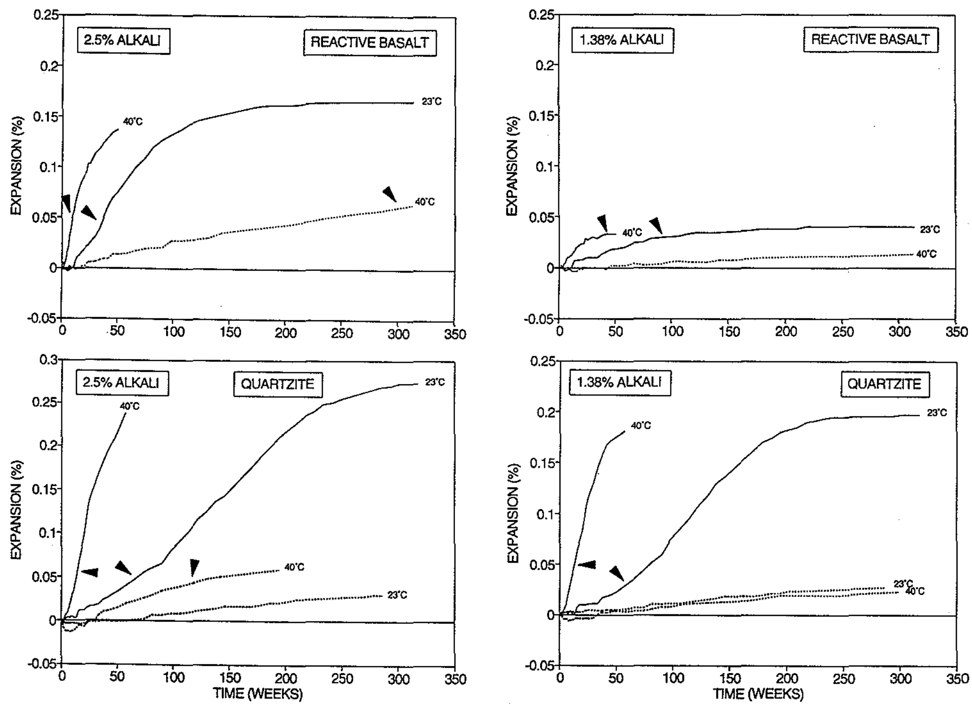



*Figure 2. Expansion of concrete prisms made with reactive aggregates with and without fly ash at alkali levels of 1.38 and 2.5%, and stored at 40°C, 100 RH, or 23°C (fog room). Arrows refer to time when cracking was noted. —— no fly ash; ······ fly ash.*

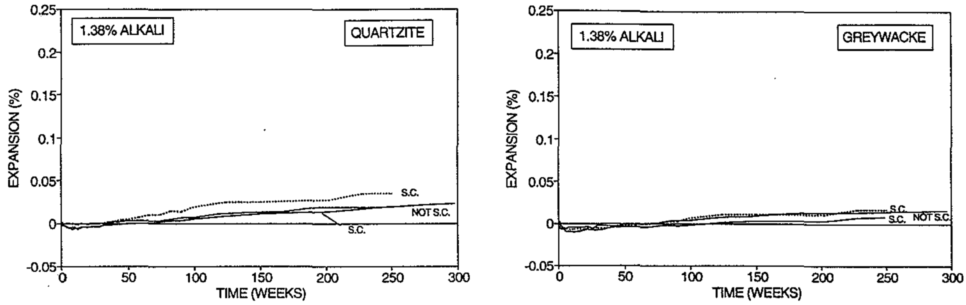



*Figure 3. Expansion of concrete prisms made with reactive aggregates and the two fly ashes at 1.38% alkali level. Steam curing is designated by 'S.C.' on the curves. The fly ashes behave similarly despite large differences in total alkali contents. —— no fly ash; ······ fly ash.*

two fly ashes under these conditions. Steam curing does not influence the effectiveness of fly ash in suppressing AAR expansion, and that fly ash (2) which contained a much higher total alkali content caused only a slightly higher expansion than fly ash (1). The higher glass content of fly ash (2) probably contributes to its effectiveness.

The effectiveness of various mineral admixtures in reducing deleterious expansions caused by AAR has been attributed to various factors. These include reduction in permeability (Smolczyk 1975; Bakker 1981), formation of various hydration phases which bind the alkali ions (Tenoutasse & Marion 1986; Quillin *et al.* 1993; Hogan 1985), and the consumption of the $Ca(OH)_2$ produced by cement hydration (Tang & SU-Fen 1980; Chatterji & Clausson-Kaas 1984; Bhatty & Greening 1986). The reaction of fly ash and $Ca(OH)_2$ produces hydrated phases with a low Ca/Si ratio and a high affinity to bind alkali ions. Results of Qian *et al.* (1994) are also in agreement with this mechanism.

An interesting observation made as a result of this work is that the specimens containing fly ash, particularly those also containing high alkali contents, exhibited an initial shrinkage during the first few months before some expansion took place. This phenomenon is not due to drying shrinkage because it was also observed in large blocks immersed in water. It is suggested that the observed shrinkage in early age is due to the chemical attack of alkali on the glassy phase of the fly ash and its dissolution and formation of a denser CSH-type hydration phase. Therefore, this phenomenon could be regarded as a chemical shrinkage such as that taking place when concentrated NaOH solutions react with unstable silica (Knudsen 1986). Further studies are needed to explain the mechanism of this shrinkage and its implications for the use of fly ash as an AAR preventive mineral admixture.

## CONCLUSIONS

Long-term results presented in this work have shown that the two Australian fly ashes studied have been effective in preventing deleterious AAR damage in concretes with alkali contents as high as 7.0 kg $Na_2O/m^3$, but they produced only a delaying effect in concretes containing 12.5 kg $Na_2O/m^3$. The delay was between two and six years, depending on the type of aggregate. A measureable chemical shrinkage occurred in the first few months in the presence of fly ash in the latter concretes, although some of them later expanded and cracked due to AAR.

For highly reactive aggregates and at high alkali contents, the fly ashes were more effective in preventing AAR expansion under the storage conditions of 23°C (fog room) than at 40°C, 100% RH, due to the much faster rate of AAR under the latter conditions.

Although the accelerated mortar bar test (1 M NaOH, 80°C) can be used to predict the long-term effectiveness of fly ash in suppressing deleterious AAR expansions, this prediction only applies to concretes having alkali contents which would produce pore solution concentrations around or below 1 M NaOH.

As field concretes contain usually less than 7.0 kg $Na_2O$ equiv./$m^3$, the two fly ashes should be effective in suppressing AAR in practical applications.

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