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Effect of fly ash on the expansion of concrete due to alkali-silica reaction – Exposure site studies

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ABSTRACT

In this study 45 concrete blocks (915 × 915 × 815 mm or 350 mm cubes) containing alkali-silica reactive aggregates, and various levels of high-alkali cement and fly ash were placed on an outdoor exposure site in S.E. England for a period of up to 18 years to determine the efficacy of fly ash in controlling damaging alkali-silica reaction (ASR). The reactive aggregates used included a variety of flint sands and a crushed greywacke combined coarse and fine aggregate. Length-change measurements were conducted periodically throughout this period. All concrete blocks without fly ash showed excessive expansion and cracking within 5–10 years of production and in many cases the ultimate expansion exceeded 1.0% after 15–18 years. Fly ash used at replacement levels of 25% and 40% was effective in significantly reducing expansion and cracking with all three flint aggregates at all levels of alkali. Of the 27 blocks containing fly ash and flint sand only two blocks showed evidence of damage after 16–18 years. The expansion of these blocks was significantly lower than similar blocks with the same Portland cement content without fly ash. None of the blocks with greywacke aggregate and fly ash exhibited cracking (expansion data were not available for these blocks). Collectively the data confirm that fly ash, when used at levels of 25–40%, does not effectively contribute alkalis to the alkali-silica reaction.

1. Introduction

The potential use of pozzolans as a measure to prevent deleterious expansion due to ASR was first reported in Thomas Stanton's formative work on ASR [1] in 1940 and he went onto confirm the efficacy of a number of natural pozzolans in this role in a later publication [2]. Soon thereafter research at the US Corps of Engineers [3] showed that fly ash, also a pozzolan, could be used to control ASR expansion. In the more than 50 years that have followed these discoveries there have been literally hundreds of papers dealing with the effect of fly ash on ASR. By now it is generally accepted that fly ash is an effective measure for minimizing the risk, but there is still a question regarding how much fly ash is required to reduce the risk to an acceptable level. A review of the published data [4] indicates that the amount of fly ash required to prevent damaging expansion of concrete varies depending on the composition of the fly ash, the nature of the reactive aggregate, the amount of alkalis available in the system (e.g. from the Portland cement) and the exposure conditions to which the concrete is subjected. There are a number of test methods that can be used to determine the safe level required to prevent damage and in North America the most widely used of these tests today is the accelerated mortar bar test (ASTM C 1567). Another test that is used is the concrete prism test (ASTM C 1293), but the test duration (2 years for evaluating preventive measures) is too long for many applications and the test is less popular than the accelerated test which takes 2–4 weeks to run. These tests are similar to RILEM ASR-2 and ASR-3, respectively. Unfortunately, the test methods do not necessarily produce the same result in terms of determining the safe level of fly ash or other pozzolan or slag required with a specific aggregate and, furthermore, there is no consensus regarding the most suitable performance criteria to evaluate the outcome of the test [5,6]. Another problem is that neither test is able to determine how the level of the preventive measure required changes as the alkali provided by the Portland cement changes [5].

Given the problems with the existing test methods a number of workers have established exposure sites to evaluate the performance of large concrete blocks produced with a wide range of materials and exposed to natural weathering [5,7,8]. These sites not only provide invaluable information on the performance of preventive measures, such as fly ash, but also provide the means for benchmarking accelerated short-term laboratory performance tests.

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One such ASR field exposure site was developed at the Building Research Establishment (BRE) in the UK in 1989. Initially the site was set up to evaluate the effect of fly ash on ASR but later studies were conducted on slag, metakaolin and lithium-based chemical admixtures. This paper presents the findings from the fly ash studies. The test program included both laboratory and field studies. The results from the laboratory studies were published between 1996 and 2004 in a series of papers [9–11] which concluded that 25% (Class F) fly ash was sufficient to control expansion with reactive flint sands, but increased amounts (e.g. $\geqslant$35%) may be required with more reactive aggregates that react at lower alkali levels. In this paper, the conclusions from the laboratory study are re-examined in the light of long-term data from the exposure site.

It should be noted that this research program was concerned with the use of fly ashes that were commercially-available and produced in the UK and, as such, the fly ashes used in the laboratory and field studies were produced from bituminous coal and have relatively low calcium contents (<4.0% CaO).

2. Experimental details

Concrete blocks were produced using a single source of high-alkali cement, two sources of fly ash and four different reactive aggregates. The chemical analyses of the cement and fly ash are given in Table 1. One of the fly ashes (DX) was deliberately selected because it did not meet the requirements of the then current British Standard for fly ash, BS 3892-1, with regards to the 45 μm sieve-retention value. Three of the reactive aggregates are flint sands and are described as follows:

TV sand	River sand from the Thames Valley containing approximately 50% flint with lesser amounts of quartz, meta-quartzite and carbonates
BT sand	Crushed sand comprised predominantly of flint (55%) and quartz
PB sand	Sea-dredged sand reportedly from one of the sources of reactive aggregates implicated in ASR-affected structures in the south-west of England. No petrographic information available, but it is similar in composition to the TV sand

These sands were combined with coarse and fine non-reactive limestone aggregate such that the mass of reactive sand represented 25% by mass of the total aggregate. Flint sands can show a pronounced pessimum effect and previous laboratory studies [9] indicated that the maximum concrete expansion occurs when the TV sand content is approximately 25% of the total aggregate.

In addition, results are reported for concretes containing greywacke aggregate (GW) from Wales as both coarse and fine aggregate. This is an aggregate that had been found, in laboratory tests, to produce expansion at lower alkali levels than the flint aggregates. Unlike flint the greywacke does not exhibit a pessimum effect.

A total of 45 concrete mixtures were produced between 1989 and 1991: 39 mixes with flint sands and six mixes with greywacke. Details of the 38 different mixtures with flint sand are shown in Table 2; one of these mixes was repeated. The batch water contents were approximately 171, 158 and 150 kg/m^3 for mixes with 0%, 25% and 40% fly ash, respectively. Mixes were produced with a target slump of between 50 and 100 mm by the addition of superplasticizer. Details of the six mixtures cast with greywacke aggregate are presented in Table 3. The batch water content ranged from 225 to 230 kg/m^3 for these blocks.

For mixes with greywacke and for the mixes in the series designated TV–FF (TV sand and FF fly ash) large blocks measuring 915 $\times$ 915 by 815 mm high were produced. These blocks were cast in two lifts and compacted into plywood formwork using a poker vibrator. The blocks were cast and stored outside in the formwork for 7 days. After striking the formwork the blocks were covered by damp sacking and polyethylene until 28 days old, the sacking being re-wetted periodically. At 28 days, reference points were attached to vertical and horizontal surfaces of the blocks (approximately 10 pairs) and initial readings taken together with ultrasonic pulse velocity (USPV) readings. For some blocks, 100 mm diameter cores were taken for determination of gas pressure tensile strength (not reported). After taking initial readings the blocks were "ponded" (such that the lower 50 mm was submerged in water) and stored on an external exposure site at BRE, Fig. 1. Length changes and USPV readings were monitored periodically. Length-change measurements were made using a Demec type gauge with a gauge length of 200 mm.

For all other mixes, smaller 350 mm cubes were produced. These cubes were stored at 20 °C for 28 days (7 days in the plywood mould and 21 days under damp sacking and polyethylene). After 28 days the cubes were stored externally on the same site as the larger blocks and monitored for length change and USPV in the same way.

Four prisms (75 $\times$ 75 $\times$ 200 mm) with stainless steel inserts for length measurements were cast from each mix. The prisms were demoulded at 24 h and stored over water in containers at 20 °C. At 7 days, all prisms were measured prior to being wrapped in moist towelling and polyethylene. The wrapped prisms were then returned to the containers and two prisms were stored at 20 °C and two at 38 °C. Length-change measurements were made on the prisms up to 3 years of age. Prisms stored at 38 °C were allowed to stabilize at 20 °C for 24 h prior to length-change measurements being made.

Two of the aggregates, TV sand and BT sand, were tested in the accelerated mortar test (ASTM C 1567) using FF and DX fly ash to determine how much fly ash was required to control expansion in this test. In this test the length change of mortar bars is measured over a 14 day or 28 day period during which time the mortar bars are stored in a 1 M NaOH solution at 80 °C.

3. Results

The final expansion measurements for the blocks produced with the different flints sands are presented in Table 2. These measurements were made in September 2007 when the age of the blocks was between 16 and 18 years. It was intended that monitoring of the blocks be continued indefinitely. Unfortunately, the blocks were inadvertently disposed of during construction on the exposure site in 2008 and no data are available beyond the last measurements made in 2007.

Table 1
Chemical analysis of Portland cement and fly ash.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Na_2Oe	LOI	>45 μm
Portland cement (PC)	20.7	4.9	3.30	62.9	2.70	1.10	0.43	2.9	1.15	0.8	
Fly ash (FF)	53.8	27.8	8.84	2.49	1.27	3.54	1.13	3.6	3.46	3.4	8.0
Fly ash (DX)	53.7	27.9	8.76	1.86	1.80	3.60	1.32	2.6	3.69	2.6	28.3

Table 2
Details of concrete mixes and expansion values of blocks at 16–18 years.

	Mix proportions[a] (kg/m^3)			Expansion (%)			
	PC	FA	PC Alk	TV–FF	TV–DX	BT–FF	PB–FF
PC only	550		6.325	1.482	1.504	1.482	0.927
	475		5.463	0.726	1.371	0.726	
	412		4.738	1.231	1.117	1.231	1.115
					1.032[b]		
25% fly ash	450	150	5.175	−0.009	0.061	−0.009	
	412	138	4.738	−0.030	0.044	−0.030	0.000
	356	119	4.094	−0.009	0.003	−0.009	
	300	100	3.450	−0.015	−0.016	−0.015	
40% fly ash	390	260	4.485	−0.013	−0.010	−0.013	
	360	240	4.140	−0.014	−0.010	−0.014	
	330	220	3.795	−0.007	−0.015	−0.007	
	285	190	3.278	−0.005	−0.009	−0.005	
	240	160	2.760	0.000		0.000	

[a] Mix proportions, PC = Portland cement, FA = fly ash, PC Alk = alkali (Na_2Oe) from PC.
[b] Mix repeated.

Table 3
Details of concrete mixes with greywacke aggregate.

	Mix proportions[a] (kg/m^3)			Observations made at 14 years
	PC	FA	PC Alk	
PC only	450		5.175	Extensive cracking, crack widths up to 5 mm
	440		5.060	Extensive cracking, crack widths up to 5 mm
	350		4.025	Light cracking, crack widths up to 1 mm
25% FF fly ash	450	150	5.175	No cracking
	338	112	3.887	No cracking
	270	90	3.105	No cracking

[a] Mix proportions, PC = Portland cement, FA = fly ash, PC Alk = alkali (Na_2Oe) from PC.

Fig. 1. View of BRE exposure site showing 915 mm blocks and 350 mm cubes.

Table 3 shows observations made during a visual examination of the blocks containing greywacke aggregate in May 2005 when they were approximately 14 years old. These blocks were cast as part of a separate program and length-change measurements are not available. These blocks are stored on a separate site from the blocks containing flint sand and are still available for future inspection.

3.1. Repeatability of expansion measurements

Fig. 2 shows the range of expansion measurements and the calculated mean expansion for one each of the 915 mm and 350 mm blocks. There was a wide range in the individual expansion readings taken at various locations on the same block. No trend between the magnitude of the expansion and the location of the reference points was observed for the larger blocks, but it was observed for the smaller blocks that expansion initiated on the top surface and the magnitude of expansion was generally higher at all ages on the top surface (pins numbered 1 and 2 in Fig. 2 are located on the top surface). The mean expansion for each block was calculated by taking the average of the individual readings; there were ten individual readings for the large blocks and six for the smaller blocks. Occasionally pins would become detached from the block and future average expansion readings were based on a reduced number of individual readings.

3.2. Effect of flint aggregate source

Fig. 3 shows the average expansion of the control blocks (no fly ash) with the different flint aggregates and produced with two different cement contents. With a cement content of 550 kg/m^3 the concrete block with the crushed flint sand (BT) expanded more rapidly than blocks with the other sands and visible cracking was observed between three or four years. At the same cement content, the concrete block with the sea-dredged sand (PB) showed the slowest expansion rate and cracking was not observed until 7 years. At the lower cement content of 412 kg/m^3 the differences between the onset to expansion and the rate of expansion was less marked for the blocks with different flint sands.

3.3. Effect of specimen type and exposure condition

Fig. 4 compares the expansion of blocks on the exposure site with the expansion of prisms cast from the same concrete mixture (550 kg/m^3 cement and TV sand) and stored under laboratory conditions. The prisms expand very rapidly, but the expansion is

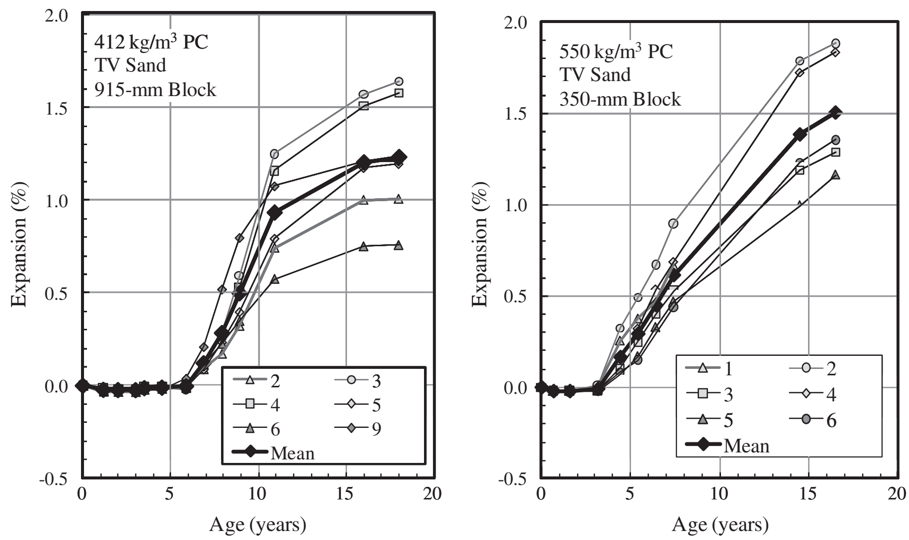

Fig. 2. Variation in expansion with pin location for 915 mm (left) and 350 mm (right) blocks.

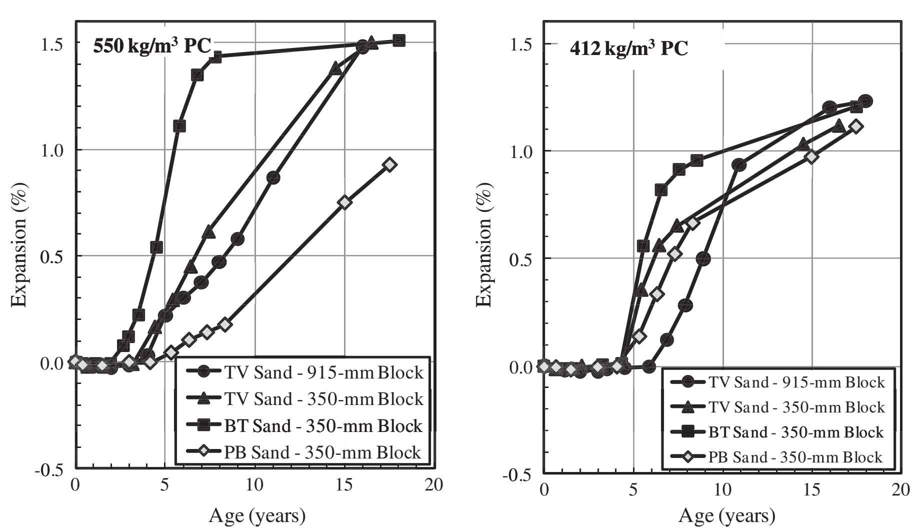

Fig. 3. Expansion of blocks with flint sand and 550 kg/m^3 (left) or 412 kg/m^3 (right) Portland cement.

exhausted after 1–2 years. The larger blocks stored on the exposure site do not start to expand until 4–5 years, but continue to expand throughout the duration of the project. There is surprisingly little difference between the expansion of the larger 915 mm block and the 350 mm block. The expansion of the blocks had reached 1.5% by 2007 (16 years) whereas the prisms reached an ultimate expansion of just 0.30–0.35% after 2–3 years. Also shown in Fig. 4 is the effect of the alkali content of the concrete on the highest measured expansion of prisms and blocks. It is clear that a much higher level of alkali is required to produce damaging ASR in the smaller laboratory specimens and this has been attributed [5] to alkali leaching in the small samples which can rapidly reduce the internal supply of alkalis. This also explains why the prisms show much lower amounts of expansion. This figure also includes data for small mortar bars, 25 $\times$ 25 mm in cross section, stored over water at 38 °C (ASTM C 227 test). The leaching effects are more pronounced in these small bars than the prisms and much lower expansions are recorded for a given alkali content.

3.4. Effect of fly ash

Fig. 5 shows the effect of fly ash (FF) content on the expansion of 915 mm blocks with TV sand. No expansion was observed for any of the blocks with TV sand and FF fly ash at replacement levels of 25% and 40% after 16–18 years exposure on the outdoor site. Fly ash (FF) at 25% and 40% is effective in suppressing expansion even when the Portland cement content of the mix and the alkali content of the mix is sufficient to cause considerable expansion and damage in mixes without fly ash. Fig. 6 shows photographs of 915 mm blocks with and without 25% fly ash after 18 years on the exposure site at BRE. The block without fly ash is extensively cracked with crack widths exceeding 10 mm in some locations. No cracking was observed in any of the blocks with FF fly ash.

The same observation was made for BT sand and PB sand as shown in Fig. 7. No expansion or cracking was observed on any of the specimens containing FF fly ash regardless of the size of the block or the type of sand. Significant cracking, with crack

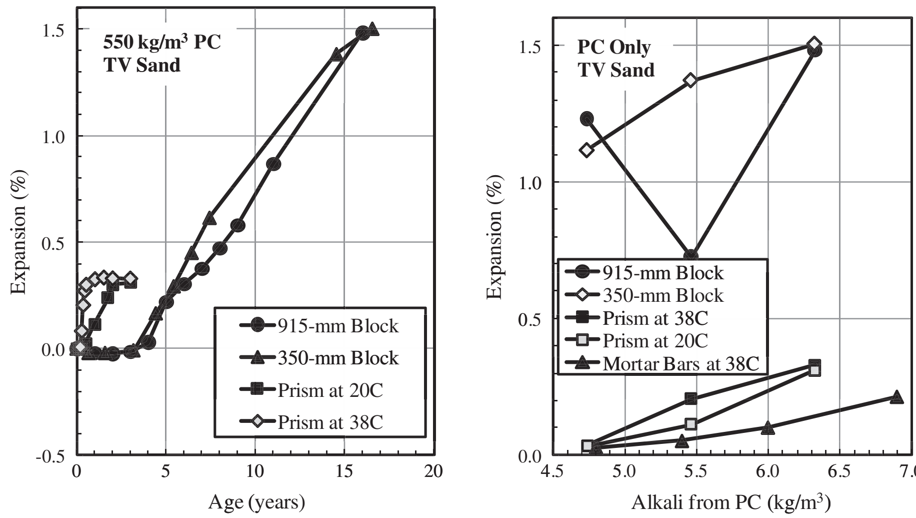

Fig. 4. Effect of specimen size and alkali content on expansion of concrete with TV sand.

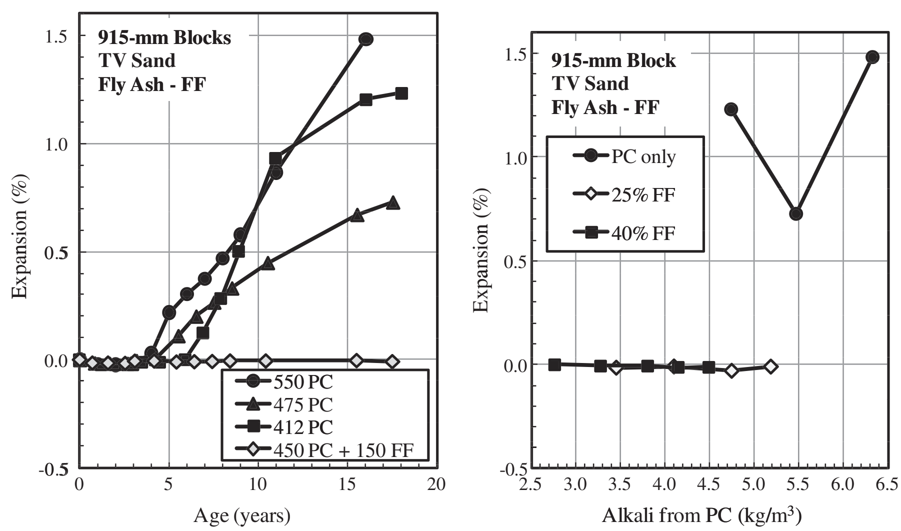

Fig. 5. Effect of fly ash (FF) and alkali content on expansion of concrete with TV sand.

Fig. 6. Photographs of 18 year-old 915 mm blocks with TV sand on BRE exposure site block with 550 kg/m^3 PC (left) and block with 450 kg/m^3 PC + 150 kg/m^3 FF fly ash (right).

widths exceeding 10 mm in some blocks, were observed in all the control blocks (without fly ash) containing BT and PB sand.

Fig. 8 shows the expansion of 350 mm blocks with TV sand and with DX fly ash. The blocks containing 25% DX fly ash significantly

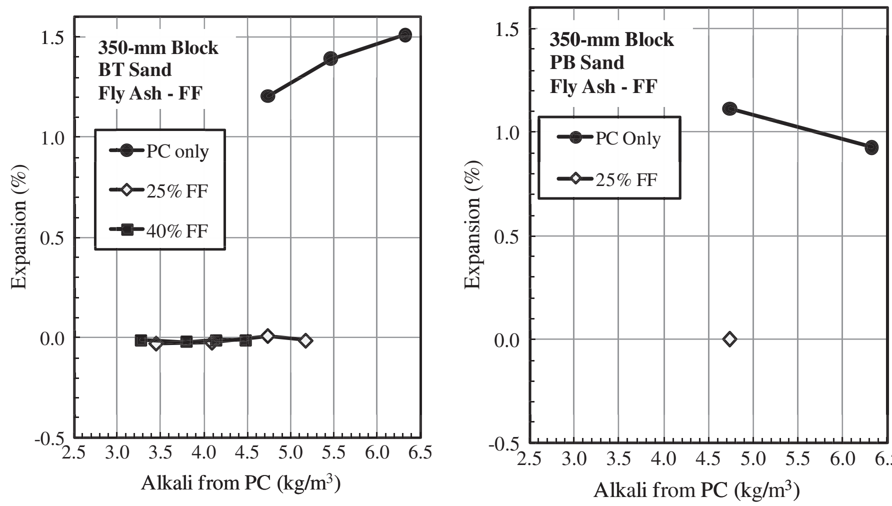

Fig. 7. Effect of fly ash (FF) and alkali content on expansion of concrete with BT sand (left) and PB sand (right).

reduced expansion compared to the control blocks without fly ash, however, some level of deleterious expansion (0.044% and 0.061%) was observed for the two blocks with 25% DX fly ash and the higher levels of Portland cement (450 and 412 kg/m^3 PC) after 17 years. These two blocks exhibited a small number of very fine cracks (<0.5 mm) when they were last examined in 2007 (see Fig. 9). Neither the two blocks with 25% DX fly ash and lower amounts of Portland cement, nor the four blocks with 40% DX fly ash, showed any deleterious expansion nor any cracking after 15–16 years.

Table 3 reports visual observations made in 2005 when the 915 mm blocks were 14 years old. At this time all of the control samples (without fly ash) exhibited signs of cracking. The cracking was severe with crack widths up to 5 mm for the two concretes with the highest cement contents (440 and 450 kg/m^3) and alkali contents (5.060 and 5.175 kg/m^3 Na_2Oe). The block with 350 kg/m^3 and 4.025 kg/m^3 Na_2Oe showed significantly less cracking and the crack widths were limited to approximately 1 mm. None of the blocks containing fly ash exhibited cracking at 14 years.

Fig. 10 shows the expansion of two 350 mm blocks with nominally the same mixture proportions. The blocks were cast 1 week apart and contained 412 kg/m^3 PC (no fly ash) and BT sand. Although the time to the onset of expansion was different by about 1 year, the subsequent expansion rate and the amount of long-term expansion were similar.

3.5. Comparison of field data with accelerated mortar bar test

Fig. 11 shows the effect of fly ash and aggregate type on the expansion of mortar bars containing TV sand and BT sand in the accelerated mortar bar test (ASTM C 1567) at 14 and 28 days. In mortars without fly ash, BT sand produces slightly more expansion than TV sand at 14 and 28 days. At 14 days, 25% fly ash FF is effective in reducing the expansion of mortars with TV and BT sand below the commonly-used expansion limit of 0.10%, but 25% DX fly ash is border line in this regard and slightly higher replacement levels of DX fly ash are required to meet the limit. At 28 days, 35% FF fly ash is not quite effective in reducing expansion below 0.10% for TV and BT sand, but 35% DX fly ash does control expansion with the TV sand.

4. Discussion

When this field study commenced in 1989 parallel laboratory studies were also initiated. The laboratory testing consisted of

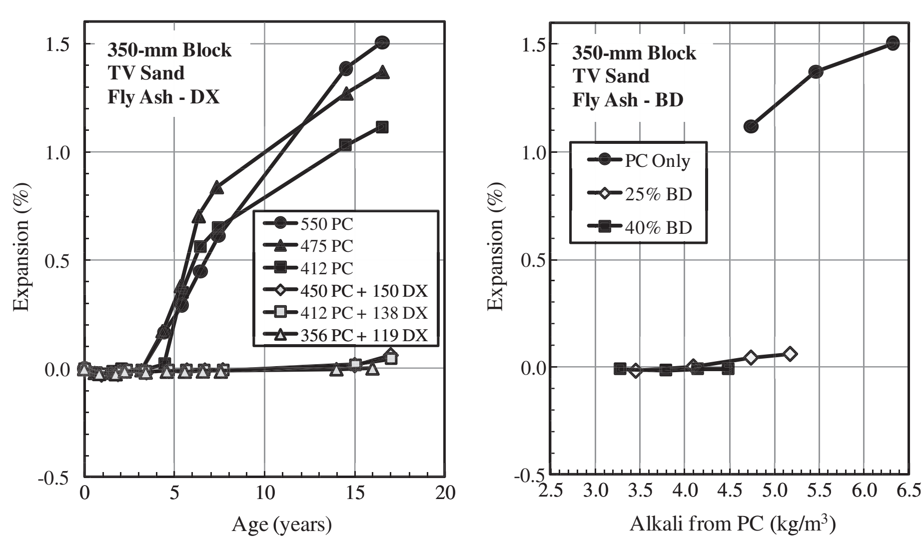

Fig. 8. Effect of fly ash (DX) and alkali content on expasion of concrete with TV sand.

Fig. 9. Fine cracking on 350-mm block with 450 kg/m^3 PC and 150 kg/m^3 DX fly ash at 17 years.

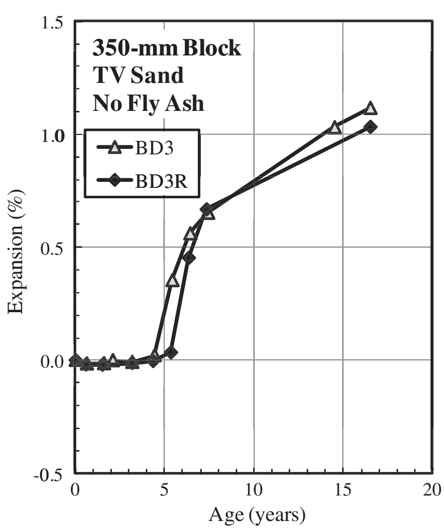

Fig. 10. Expansion of 350 mm blocks with TV sand and 412 kg/m^3 PC-replicate mixes.

expansion measurements made on relatively small concrete prisms stored at 20 °C and 38 °C. Concrete prisms stored under these conditions expand rapidly compared with field-exposed blocks and the findings from the laboratory test were reported between 1996 and 2004 [9–11]; the main conclusions were as follows:

- Fly ash is effective at controlling expansion with UK flint aggregates provided it is used at a minimum level of replacement of 25%.
- Fly ash can be considered to contribute no alkalis when it is used at a 25% level of replacement with flint sands.
- Indeed, 25% fly ash controls ASR expansion even when the alkalis contributed by the Portland cement component of the mixture are sufficient to cause ASR expansion in the absence of fly ash. This means that the beneficial role of fly ash with regards to ASR goes beyond that of an inert diluent.
- Coarser fly ash with high 45 μm sieve retention values (28–36%) are equally effective in controlling ASR expansion as finer fly ashes of similar alkali contents.

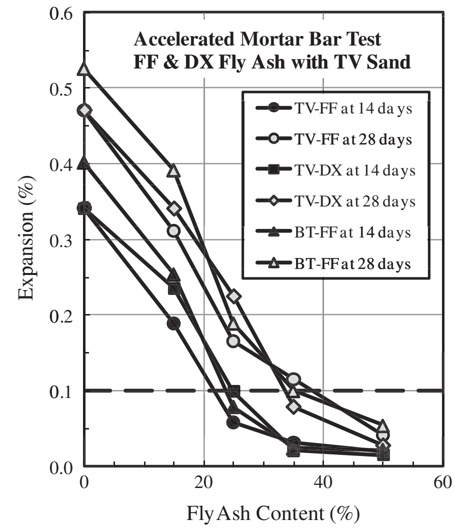

Fig. 11. Effect of fly ash and aggregate type on the expansion in the accelerated mortar bar test.

- Higher levels of fly ash may be required if more reactive aggregates (that is aggregates that react a lower alkali content) are used. In such cases, 35%–40% fly ash may be required.

The main purpose of the field study was to verify those findings in large specimens stored under natural conditions. However, data from field studies like this are also very useful for benchmarking rapid laboratory tests such as expansion tests conducted on concrete prisms or mortar bars where the alkali-silica reaction is accelerated by providing additional alkali and/or elevating the exposure temperature.

Generally, the results from the field study reported here support the main findings from the laboratory study for flint aggregates. Fly ash at replacement levels of 25% and 40% were highly effective in reducing ASR expansion in blocks with flint sands. The FF fly ash was effective in eliminating deleterious expansion and cracking even when the alkali contributed by the Portland cement component of the concrete mixture was 5.175 kg/m^3 Na_2Oe. Control blocks without fly ash showed excessive expansion (0.7–1.5%) and severe cracking at alkali contents as low as 4.738 kg/m^3 Na_2Oe. As with the laboratory study, this indicates that fly ash does not contribute alkalis and can be considered to have a positive effect on controlling ASR expansion that goes way beyond mere dilution of the Portland cement alkalis.

Two blocks containing 25% DX fly ash did show small levels of expansion (0.044–0.061%) and very light cracking (<0.5 mm width) at 17 years when the alkali content from the Portland cement was 4.738 kg/m^3 Na_2Oe or higher. However, this level of fly ash was still highly effective in reducing expansion compared to blocks without fly ash containing the same level of alkali and can, thus, be considered to contribute no alkali. It should be noted that none of the concrete prisms from these mixes with 25% or 40% DX fly ash expanded significantly.

Fly ash DX was selected for the program because it has a relatively high 45 μm sieve-retention value compared to fly ash FF (28.3% versus 8.0%). At the time the program was initiated there were concerns in the UK about the new European specification for fly ash (EN 450) which was to replace the existing British specification (BS 3892-1). The European specification permitted fly ashes with a 45 μm sieve retention value up to 40% which compared with a 12% limit in the British specification. The laboratory test program [11], which included, in addition to DX fly ash, a fly ash with 36.3% retained on the 45 μm sieve, indicated that fly ashes of varying fineness (up to the EN 450 limit) were equally effective in controlling expansion provided the alkali content of the fly ash was similar. Furthermore, the study concluded that fly ashes meeting the EN 450 requirements could be safely used to prevent deleterious ASR with reactive flint aggregates provided that the level of replacement was at least 25% as per the existing BRE recommendations in IP1/02 [12] for fly ashes meeting the requirements of BS 3892-1.

The data from the field studies indicates that the coarser DX fly ash was not as effective as the finer FF fly ash, and that 25% DX fly ash was not effective in completely eliminating damaging ASR in mixes with high alkali contents. However, the BRE guidelines, IP1/02 [12], also require that the alkali content contributed by the Portland cement be limited to be below 3.0 kg/m^3 Na_2Oe when 25% fly ash is used together with high-alkali Portland cement in concrete containing reactive flint aggregates. The data reported here (see Table 2) show no expansion or cracking in concrete with 25% DX fly ash in mixes where the alkali content contributed by the Portland cement was between 3.450 and 4.094 kg/m^3 Na_2Oe. This would indicate that the BRE recommendations are sufficiently conservative with regards to using fly ash to minimize the risk of expansion at least with the flint aggregates used in this study.

The BRE guidelines, IP1/02, require 40% fly ash with an alkali limit of 2.5 kg/m^3 Na_2Oe for concrete containing highly-reactive aggregates such as the greywacke used in this study. The observations from the field study are that 25% fly ash seems to be effective in controlling ASR damage in concrete with greywacke aggregate containing as much as 5.175 kg/m^3 Na_2Oe alkali contributed by the Portland cement. However, these blocks were just 14 years old at the time they were last inspected. These blocks are still located at BRE and are visually examined periodically to determine the long-term efficacy of the fly ash.

Although the data generally support the efficacy of 25% FF fly ash for controlling expansion with flint aggregate even at very high alkali contents, it is considered prudent to limit the amount of alkalis contributed by the Portland cement in specifications. The data presented here suggest that a maximum Portland cement alkali content in the range of 3–4 kg/m^3 Na_2Oe might be appropriate. Such a limit is likely to also prevent expansion with the DX fly ash.

It is of some concern that the results of the concrete prism test do not correlate well with the observations from the field exposure blocks. In a number of cases concrete mixes cast from the same mixes as large blocks failed to expand in the laboratory over a 2–3 year period, whereas the blocks showed significant expansion and cracking in the field. The difference in expansion observed for the prisms in the laboratory and the large blocks on the exposure site is attributed to the leaching of alkalis during storage of concrete prisms which results in a significant reduction in the alkali content of the concrete as the test progresses and this limits the potential for ASR [5]. It is possible that this problem may be overcome by adding additional alkalis when the concrete prisms are fabricated to compensate for the loss during the test. However, it would preferable to develop a storage condition that does not permit the loss of alkalis during test.

The results of the accelerated mortar bar test at 14 days appear to give a reasonable indication of the amount of fly ash required to control alkali-silica reaction in concrete. However, it should be noted that this test method is not able to determine the effect of the alkali contribution from the Portland cement. There is some disagreement in North America regarding what are the appropriate performance limits for this test [6], recommendations ranging from 0.10% at 14 days to 0.10% (or even 0.08%) at 28 days. The results from this study do not support the use of a 28 day limit as 35% or more fly ash would be required to control expansion with the flint aggregate in this test.

5. Conclusions

Expansion data are presented from a field exposure study aimed at determining the long-term effectiveness of fly ash in terms of controlling the expansion of concrete blocks containing reactive flint aggregates and exposed to natural weathering for 16–18 years on an outdoor site near Watford, UK. Visual observations are also presented for 14 year-old concrete blocks containing reactive greywacke aggregate stored under the same conditions. The following conclusions are drawn from the data:

5.1. Effect of aggregate type in control mixes

a. Excessive expansion (0.7–1.5%) and cracking (some crack widths greater than 10 mm) was observed for all 915-mm and 350-mm blocks containing flint aggregate and high-alkali Portland cement.
b. Differences were observed in the rate of the reaction with concretes containing BT sand showing deleterious expansion and cracking first and concrete with PB sand showing expansion last.
c. Excessive cracking (1 to 5 mm) was observed for all the control blocks containing greywacke aggregate.

5.2. Effect of fly ash

a. Fly ash used at replacement levels of 25% and 40% was effective in significantly reducing expansion and cracking with all three flint aggregates at all levels of alkali. There appears to be no contribution of alkali by the fly ash. In fact, fly ash was effective in reducing or eliminating deleterious expansion even when the alkali that was contributed by the Portland cement component of the mixture was in excess of that required to produce excessive expansion in concrete without fly ash.
b. None of the blocks containing 25% or 40% FF fly ash exhibited deleterious expansion or cracking during 16–18 years field exposure.
c. Of the 27 blocks containing fly ash and flint sand only two showed evidence of damage after 16–18 years. These concretes contained 25% of a relatively coarse fly ash and high alkali levels. The expansion and cracking of these blocks was, however, less than one tenth of that of control blocks of similar composition. Concrete blocks with 25% of the same fly ash did not show deleterious expansion or cracking at lower alkali contents.

5.3. Relevance to BRE recommendations

a. The current BRE recommendations for preventing expansion with aggregates of "normal reactivity" by using 25% fly ash together with a maximum alkali limit ranging between 3.0 and 3.5 (depending on the alkali content of the Portland cement) appear to be supported by the results of this study.

5.4. Comparison with accelerated laboratory tests

a. For a number of concrete mixes the outcome of the laboratory concrete prism test did not match the field performance of blocks from the same mix. Significantly greater levels of alkali are required to produce expansion in laboratory-stored concrete prisms compared to field-exposed blocks.
b. The accelerated mortar bar test seems to provide a reasonable prediction on the amount of fly ash required to prevent expansion with flint aggregates using the expansion results

at 14 days. However, this test is not capable of determining the effect of the Portland cement alkalis on the amount of fly ash required.

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