Addition of Class C Fly Ash To Control Expansions due to Alkali-Silica Reaction

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Results of a study to determine the influence of five different Class C fly ashes on inhibiting expansion due to alkali-silica reaction (ASR) are presented. Five different sands with varying degrees of ASR, combined with the five different fly ashes, were investigated. An accelerated test method (ASTM P214) was used to detect potentially deleterious expansion of mortar bars due to ASR. Replacement levels of 0, 10, 15, 20, 25, and 30 percent of cement by weight were investigated for all five fly ashes and for all five sands. Four of the fly ashes were effective in reducing to negligible levels ASR expansions. Varying amounts of fly ashes were needed for effective control of deleterious expansion. Some fly ashes at lower levels of blending (10 and 15 percent) actually increased expansion. One fly ash was not effective in inhibiting expansion as a result of ASR, even at 30 percent replacement. Fly ashes with high alkali contents (1.92 percent) were effective in inhibiting expansion related to ASR. Test results indicated that some Class C fly ashes at adequate replacement levels effectively reduced expansion to negligible levels, even in highly reactive sands.

Alkali-reactive sands or coarse aggregates, when used in concrete structures, can produce severe deterioration. Certain internal chemical reactions between the cement alkalies and the aggregates produce reaction products that can cause harmful expansion. Highly variable and different expansions develop within concrete in the long-term as a result of alkali-silica reactions (ASR), for example. The ASR expansion reaction, characterized by production of a gel-like reaction product, occurs in concrete structures if three requirements have been met: (*a*) reactive forms of silica or silicate in the aggregates; (*b*) sufficient alkali (sodium and potassium), primarily from the cement; and (*c*) sufficiently available moisture in the concrete. If one is not present, then expansion from ASR cannot occur.

The potential ASR problem has gained a lot of attention from product suppliers and state highway departments in nearly every state. Even though the problem has had worldwide attention for the past 50 years, effective measures for inhibiting the alkali-silica reactions have not been available until recently (*1–21*). Such measures are important to improving the durability of concrete structures.

To prevent deleterious expansion the following three options are available: (*a*) use low alkali cement, (*b*) avoid reactive aggregates, and (*c*) partially replace cement with fly ash or other fine siliceous materials.

Low-alkali cements have been used nationwide to mitigate ASR in concrete; however, low-alkali cements also have been associated with severe ASR in pavements exposed to salts used for highway deicing, the salts having increased total available alkali in the concrete. Further, low-alkali cement may not always be available.

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Depletion of good quality aggregate near construction sites has created a need to develop methods that will permit the successful use of marginal aggregates, making the third option more attractive. There is an abundant supply of fly ash. A perusal of the proceedings of three international conferences (7–9) on the use of pozzolans in concrete indicates that fly ashes can effectively control ASR. Factors that influence the ability of fly ash to control ASR are the chemical composition of fly ash, mixture proportions, type of reactive aggregates and amount of fly ash used. Some investigators, using low levels of fly ash replacement, have determined that the alkalies in fly ash participate in ASR (*3,4,18*).

OBJECTIVES

The primary objectives of this investigation were to determine the

- Potential effectiveness of different Class C fly ashes in reducing the deleterious expansions related to ASR in highly reactive and nonreactive sand mortar bars,
- Level of effectiveness for different amounts of fly ash additions,
- Influence of alkali and oxide contents of fly ashes on ASR expansion,
- Reactive potential of various sands currently used in construction of pavements using ASTM P214 test method,
- Influence of selected levels of cement replacements with fly ash on the compressive strength of mortar at different ages and, finally,
- To establish the pessimum limits for fly ash replacement.

RESEARCH PROGRAM

The ASTM P214 test method for accelerated detection of potentially deleterious expansion of mortar bars due to alkali-silica reaction was used throughout the investigation. Five different sands ranging from innocuous to highly reactive were selected, and the chemical and mineral compositions of these sands were determined using reference intensity method (RIM) analysis.

Five ASTM Class C fly ashes were selected, their oxide and alkali contents varying from the low to high levels permitted by ASTM. The chemical and mineral composition of the fly ashes were determined using two different procedures, the atomic absorption inductively coupled plasma method and scanning electron microscope method. Physical properties, such as density, fineness, autoclave expansion, and specific gravity, were determined (ASTM C311). Mortar cubes were made with a standard control sand and cements with 0, 10, 15, 25, and 30 percent fly ash replacement by weight, and then tested at 3, 7, and 28 days to determine the influence of fly ash replacement on their compressive strength.

TEST METHODS FOR ASR DETERMINATION

Alkali-silica reactivity is a slow process. Several test methods, such as the ASTM C227 mortar bar method, the ASTM C289 chemical test, the ASTM C586 rock cylinder test, and CAN/CSA-A23.2-14A concrete tests (*15*) are used to predict ASR in aggregates.

Many researchers report that ASTM C227 procedure does not adequately identify potential alkali reactive aggregates (*10–14*), particularly slowly reacting aggregates. Therefore, on the basis of ASTM C227 alone, a firm recommendation cannot be made that an aggregate is nonreactive. There is a need for an accelerated method that is more severe and would identify all potential aggregates, including slowly reacting aggregates. Among the various methods tried, the one selected by Canadian researchers and recommended as a proposed Canadian standard (*10*) is the best one available. Named the "Standard Test Method for Accelerated Detection of Potentially Deleterious Expansion of Mortar Bar Due to Alkali-Silica Reaction," the method also has been adopted as the ASTM P214 test. Using that method, it is possible to detect within 16 days potentially deleterious expansion of mortar bars due to alkali-silica reactivity. The test procedure is based on the NBRI accelerated test method, and it provides a good supplement to ASTM C227. ASTM P214 is particularly useful for aggregates that react slowly or produce expansion late in the reaction. Berube and Fournier (*13*) recommended accelerated test procedure mentioned above as more appropriate than the other rapid test procedures. The test method has been used successfully to determine the effectiveness of mineral additives, such as fly ash, silica fume, and blast furnace slags.

It is claimed that all potentially reactive aggregates can be identified using this method. However, one drawback is that it also indicates expansions for some nonreactive aggregates. Therefore, the following procedure is recommended. First, identify all potentially reactive aggregates by the accelerated method. Aggregates shown to be reactive would be further investigated using ASTM C227, other tests (ASTM C289 and C856), petrographic analysis (ASTM C295), and by examining field service records.

TEST METHODS FOR IDENTIFYING REACTIVE AGGREGATES

All five sand samples were tested for mineralogical contents. The RIM of quantitative X-ray diffraction analysis was used. Each of the sand samples was powdered, and a thin layer was collected on to a glass filter. The X-ray beam was passed through the sample. Because the layer within the filter was thin, corrections were applied to transform the diffracting layer into one that is infinitely thick. Analysis of the diffracting layer and computations were done by computer, and weight fractions for all components, crystalline and amorphous, were obtained from the print-out. These were then recombined into whole-sample oxide and the element composition of the sand that was analyzed (Table 1). Sand samples also were analyzed for chert content using polarizing light microscopy.

TABLE 1 Mineralogical Content of Sands

SAMPLE NAME	CROFT SAND	EVERIST HAWARDEN	AKRON IA	CONCRETE MATERIALS	OPPERMAN HERRICK PIT
QUARTZ (%)	9.06	34.68	8.71	23.31	33.11
CALCITE (%)	16.47	19.37	24.54	29.17	1.55
OLIGOCLASE (%)	7.17	-	0.089	13.70	26.38
MICROCLINE (%)	5.33	-	0.086	11.23	38.95
DOLOMITE (%)	54.23	12.38	40.16	16.33	-
HEULANDITE (%)	0.64	-	2.31	1.50	-
HORNBLENDE (%)	2.33	0.93	1.70	1.70	-
ILLITE (%)	1.37	0.29	2.69	-	-
KAOLINITE (%)	-	1.59	2.25	1.23	-
ALBITE (%)	-	15.14	-	-	-
HEMATITE (%)	-	-	-	-	-
ORTHOCLASE (%)	-	12.91	-	-	-
CHLORITE (%)	3.33	-	-	1.78	-
CHERT (%)	-	7.7	-	-	13.90

(-) - Unavailable

MATERIALS

- Cement: the cement used was ASTM Type I/II (ASTM C150), obtained from a plant in Rapid City, South Dakota. Its chemical analysis and physical properties are given in Table 2.
- Fly ash: five different fly ashes were obtained from the Midwest. The chemical and mineral compositions of the fly ashes are given in Table 3. The physical properties determined also are given in Tables 2 and 3. According to ASTM C618 classification, all five are Class C fly ashes.
- Sands: five sands currently used in the construction of highway structures in the Midwest were obtained. The mineral composition of the sands was determined by RIM analysis and findings are given in Table 4. Fine aggregates were separated into different sized fractions, thoroughly washed and dried, and recombined to meet specific gradations given in ASTM P214.
- Water: the water used was tap water from the Rapid City municipal supply system.

MIXTURE PROPORTIONS

Accelerated Test Method

Mixture proportions were fixed according to ASTM P214: 1 part of cement and fly ash and 2.25 parts by weight of the test aggregate was used for all the five sands. The water to cement and fly ash ratio was kept at 0.44 for all the mixes. For all mixes without fly ash, 600 g of cement, 1 350 g of fine aggregate and 264 ml of water was used. According to the procedure adopted by the South Dakota Department of Transportation, 10 percent replacement with fly ash is increased to 1.5 times the percent replacement. Similarly, 15, 20, 25, and 30 percent are increased by 1.25 times the percent replacement. Therefore, with fly ash addition, for 10 percent by weight, 90 g of fly ash and 540 g of cement were mixed uniformly, but the same quantities of the fine aggregates and water were used. Similarly, for replacement levels of 15, 20, 25, and 30 percent, the appropriate amount of cement was replaced by fly ash.

The specimens (mortar bars) used for this method were made according to ASTM C227. Molds were stripped at one day and the bars placed in water heated to 80°C. On the second day, initial measurements were taken and the bars stored in 1N NaOH solution at 80°C. The bar expansions were measured when they were hot, within 15 sec of removal from the container. Expansions were monitored for 14 days.

TABLE 2 Chemical and Physical Properties of Cement

CHEMICAL COMPOSITION	WEIGHT (%)
Silicon dioxide (SiO_2) %	22.63
Aluminium oxide (Al_2O_3) %	4.81
Ferric oxide (Fe_2O_3) %	3.17
Magnesium oxide (MgO) %	1.14
Sulfur trioxide (SO_3) %	2.09
Bogue Potential Compounds	
Tricalcium Silicate (C_3S)	47.36
Tricalcium Aluminate (C_3A)	7.39
Tetracalcium Alumino Ferrite (C_4AF)	9.64
Alkalies	0.55
Loss on Ignition	1.40
Insoluble Residue	0.54

PHYSICAL TEST RESULTS

Blaine Fineness (m^2/kg)	387
Autoclave Expansion (%)	0.01
Gillmore Initial set time	2.15
Gillmore Final set time	4.00
Vicat setting time	1.40
3 Day Compressive Strength (MPa)	24.08
7 Day Compressive Strength (MPa)	34.19
Air Content of Mortar (vol.)	8.5

Cube Compressive Strength

Standard test method for compressive strength of hydraulic cement mortar (ASTM C109) was adopted for the procedure, but the cement was replaced with fly ash by 10 to 30 percent by weight and testing was done for compressive strength. Mix proportions were one part of cement and fly ash and 2.75 parts of sand, proportioned by weighing. The water to cement and fly ash ratio was maintained at 0.485 for all mixes. The molds were 50-mm (2-in.) cubes with three compartments.

TEST SPECIMEN

Four mortar bar specimens were prepared for each mix for the accelerated test method. Specimen sizes were 25 × 25 × 290.625 mm (1 × 1 × 11.625 in.). For cube compressive strength with fly ash replacement, 9 cubes of 50-mm (2 in.) were cast for testing—3 cubes each at ages 3, 7, and 28 days.

CHECKING THE ACCURACY OF OUR TEST PROCEDURE

To validate and confirm the accuracy of the work done, crushed Spratts aggregate of known expansion was acquired from the Engineering Materials Office, Ministry of Transportation, Ontario, Canada. It was tested in our laboratory, using the same procedure and equipment. The Spratt aggregate was from a horizontally bedded limestone quarry, containing 3 to 4 percent microscopic chalcedony and black chert with a conchoidal fracture. Results obtained were compared with known results obtained from Ministry of Transportation, Canada, laboratories. A comparison of the measured expansions is given in the in-text table.

Days	*Canadian Lab*	*SDSM&T Lab*
3	0.08	0.10
7	0.29	0.29
11	0.36	0.36
14	0.42	0.41

TABLE 3 Chemical Composition and Physical Properties of Fly Ashes

	FLY ASH #1	FLY ASH #2	FLY ASH #3	FLY ASH #4	FLY ASH #5
CHEMICAL COMPOSITION					
Silicon oxide (SiO_2)	36.5	32.8	29.9	35.1	46.7
Aluminium oxide (Al_2O_3)	20.8	20.0	17.7	20.3	13.4
Iron oxide (Fe_2O_3)	6.6	5.9	5.7	6.4	8.3
($SiO_2 + Al_2O_3 + Fe_2O_3$)	63.9	58.7	53.3	61.8	68.4
Sulfur Trioxide (SO_3)	1.3	3.5	4.3	1.9	1.4
Calcium oxide (CaO)	23.5	26.9	30.1	23.6	18.7
Magnesium oxide (MgO)	4.3	4.7	7.1	4.2	-
Available Alkalies as Na_2O	1.12	0.77	1.70	1.92	-
Moisture Content	0.0	0.1	0.1	0.0	0.02
Loss on Ignition	0.1	0.4	0.2	0.2	0.02
PHYSICAL TEST RESULTS					
Fineness retained on #325 sieve	11.0	11.4	13.2	16.9	16.7
Soundness					
Autoclave Expansion (%)	0.02	0.04	0.12	0.02	0.09
Specific Gravity	2.61	2.61	2.72	2.66	2.51

The measured expansions were reasonably close, confirming the degree of agreement of our test procedure.

EXPANSION LIMITS FOR ACCELERATED TEST METHOD

Expansion limits for the accelerated test method, as suggested by Berube and Fournier (*13*) are as follows:

- If the aggregates show expansion lower than 0.1 percent at 14 days, they are innocuous.
- If the aggregates show expansion between 0.1 and 0.25 percent, they are slowly expansive.
- If the aggregates show expansion above 0.25 percent, they are rapidly expansive aggregates.

These limits were modified by Hooton and Rogers (*10*), who suggested the following classification in their CSA draft proposal:

- Less than 0.10 percent is innocuous,
- Between 0.10 and 0.20 percent is inconclusive, and
- Greater than 0.20 percent is deleterious.

ASTM P214 suggests the same classification that Hooton and Rogers recommend (*10*). When mortar bar expansions greater than 0.10 percent develop within 16 days from casting, it is strongly recommended that supplementary information be developed to confirm that the expansion is actually due to alkali-silica reactivity. Sources of such supplementary information include (*a*) petrographic examination of the aggregate (ASTM C295) to determine if known reactive constituents are present, (*b*) tests of the aggregate for potential reactivity by chemical methods (ASTM C289), and (*c*) examination of the specimens after tests to identify the products of alkali-silica reactivity (ASTM C856).

The 0.20 percent expansion level recommended for reactive aggregates has to be investigated further in relation to the field performance history of an aggregate. However, that limit is too liberal and it should be reduced to 0.15 or 0.10 percent expansion.

TEST RESULTS AND DISCUSSION

Sand Classification by ASTM P214

The total percentage expansion of mortar bars made from the five different sands and the same Type I/II cement is shown in a bar chart (Figure 1). Results represent the average of four specimens. Sands 1 to 4 could be classified as "not conclusive" because the expansions are above 0.10 percent and below 0.20 percent. Sand 5 is a highly reactive sand. Field observation of pavements built with Sand 5 confirms that classification.

Evaluation of Fly Ashes

Mortar bar length measurements and subsequent expansions measured at 3, 7, 11, and 14 days, and the calculated percentage expansions for all fly ashes and sands and their combinations, are given elsewhere (*24*). Figures comparing expansions at 3, 7, 11, and 14 days for mortar bars without and with 10, 15, 20, 25, and 30 percent by weight of cement replacements with fly ash are given elsewhere (*24*).

TABLE 4 Chemical Composition of Sands

SAMPLE NAME	CROFT SAND	EVERIST HAWARDEN	AKRON IA	CONCRETE MATERIALS	OPPERMAN HERRICK PIT
SiO2 %	50.58	55.71	45.38	50.98	74.61
Si %	23.65	26.05	21.22	23.83	34.89
Al2O3 %	5.442	7.040	5.385	4.780	13.33
Al %	2.881	3.720	2.850	2.530	7.050
Na2O %	1.541	2.010	1.602	1.405	2.710
Na %	1.102	1.490	1.146	1.005	2.010
K2O %	1.198	1.950	1.360	1.154	5.860
K %	0.995	1.610	1.129	0.957	4.870
CaO %	10.44	14.46	12.00	10.54	1.950
CaO %	7.468	10.33	8.578	7.534	1.390
FeO %	-	0.650	-	-	0.050
Fe %	-	0.040	-	-	0.040
Fe2O3 %	0.872	0.220	0.859	0.784	0.140
Fe2 %	0.610	0.150	0.601	0.548	0.090
MgO %	1.716	2.700	1.364	1.222	0.040
Mg %	1.035	1.630	0.820	0.737	0.020
H2O %	-	0.540	-	-	0.230
H %	-	0.060	-	-	0.068
CO2 %	-	14.32	-	-	0.682
C %	-	3.900	-	-	0.180
MnO %	0.044	0.250	0.084	0.036	0.100
Mn %	0.034	0.200	0.065	0.028	0.010
TiO2 %	0.095	0.020	0.075	0.177	0.099
Ti %	0.057	0.010	0.045	0.106	0.050
NiO %	-	0.020	-	-	-
Ni %	-	0.010	-	-	-
BaO %	0.039	0.010	0.040	0.035	0.020
Ba %	0.035	0.010	0.035	0.031	0.010
OXIDE TOTAL	71.96	98.99	68.15	68.30	99.74
ELEMENT TOTAL	37.86	49.75	36.49	37.30	50.71

NOTE : Results for all Sand Samples were obtained by Reference Intensity Method (RIM) of Quantitative X-Ray Analysis.

Bar charts comparing the total percentage expansions at 14 days for all fly ashes at various levels of cement replacement with fly ashes for all sands are given elsewhere as well (*24*). A typical bar chart for Sand 1 is given in Figure 2, and a similar bar chart for the most reactive, Sand 5, is provided in Figure 3.

Effect of Fly Ash Addition on Expansion

Earlier investigations (*3,4,18–20*) indicated that replacement of a portion of cement with fly ash reduces expansion caused by the reactivity between alkalies and reactive silica in the aggregate, provided the proper amount of fly ash is added. The amount depends on the type of fly ash used and its mineralogical contents, in particular, its calcium oxide content. For some fly ashes with more than 1.5 percent available alkali content, a "pessimum limit" was observed (*20*). The pessimum limit is the specific percent replacement of cement with fly ash, for which the expansion reaction due to the alkali-aggregate is the greatest. If the percent of cement replaced with fly ash is below the pessimum limit, then the addition of fly ash causes equal or greater expansion in mortars with fly ash than in those without fly ash. The reason for this is the percentage of alkali in the fly ash (all fly ashes contain alkalies) is released into the pore solution, increasing the degree of alkali-silica reactivity in the mortar. Therefore, the higher the alkali content of the fly ash, the larger the mortar bar expansion.

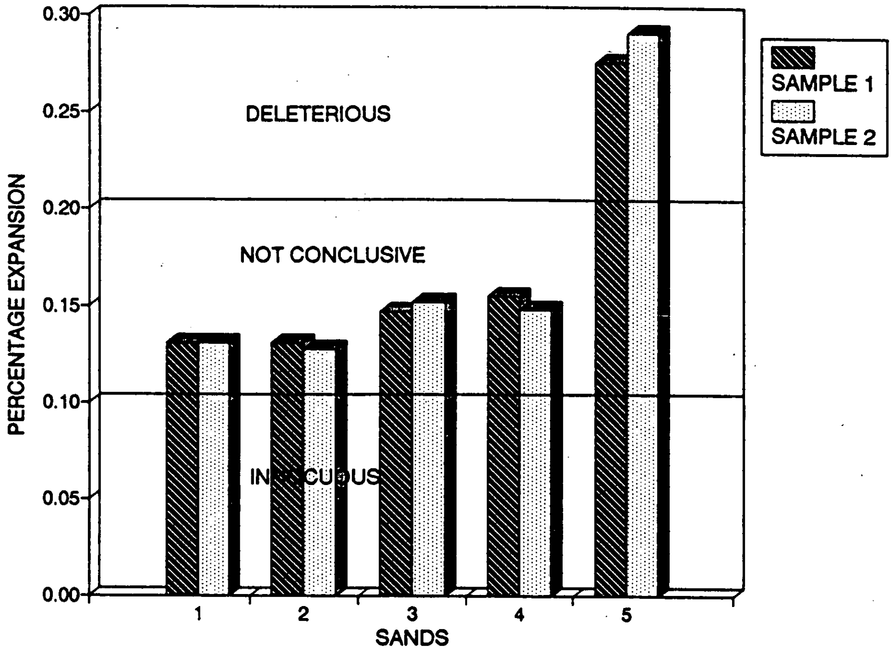

FIGURE 1 Comparison of expansions of five sands using two samples.

The actual mechanisms by which fly ash reduces alkali-aggregate expansions are not clearly understood. The shape and size of fly ash particles affect the watertightness, workability, and mixing water demand of fly ash concrete. Generally, fly ash concretes have reduced permeability, and hence the moisture available for the alkali-aggregate reactivity is less than is available in non-fly ash concrete. That results in reduced expansion in fly ash concretes.

Regarding the chemical composition, it has been suggested that pozzolans reduce or eliminate alkali-aggregate expansion by pozzolanic reaction and by producing lower C/S mole ratio calcium silicate hydrates by reacting with high C/S mole ratio hydrates (*20*). These new hydrates can incorporate large amounts of alkali in their structure, retaining the alkalies and therefore reducing their availability for reaction with silica in the aggregate. However, alkalies

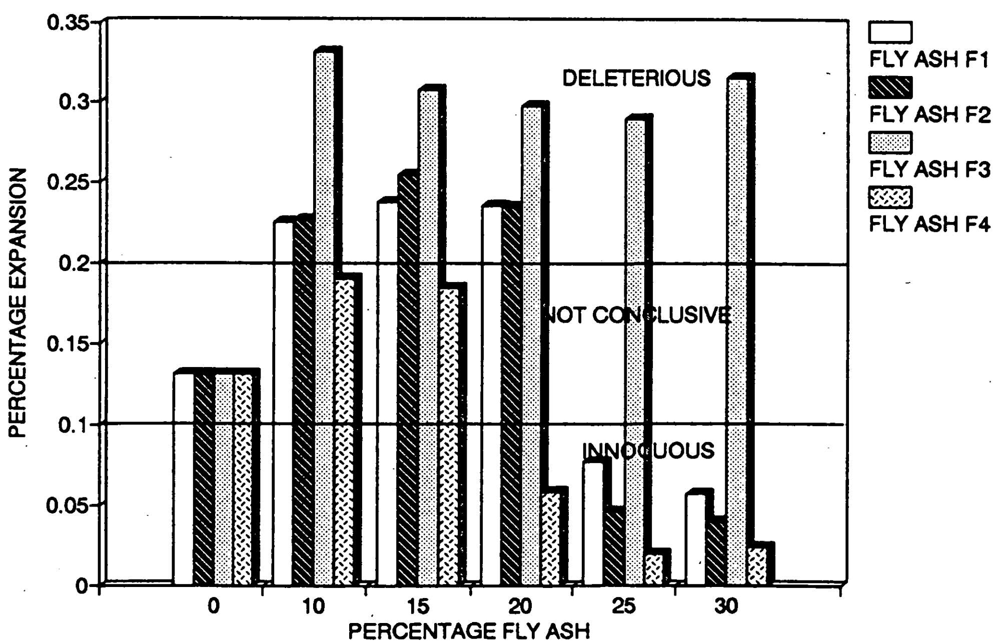

FIGURE 2 Comparison of expansion from accelerated test method for Sand 1 using different fly ashes at 14 days.

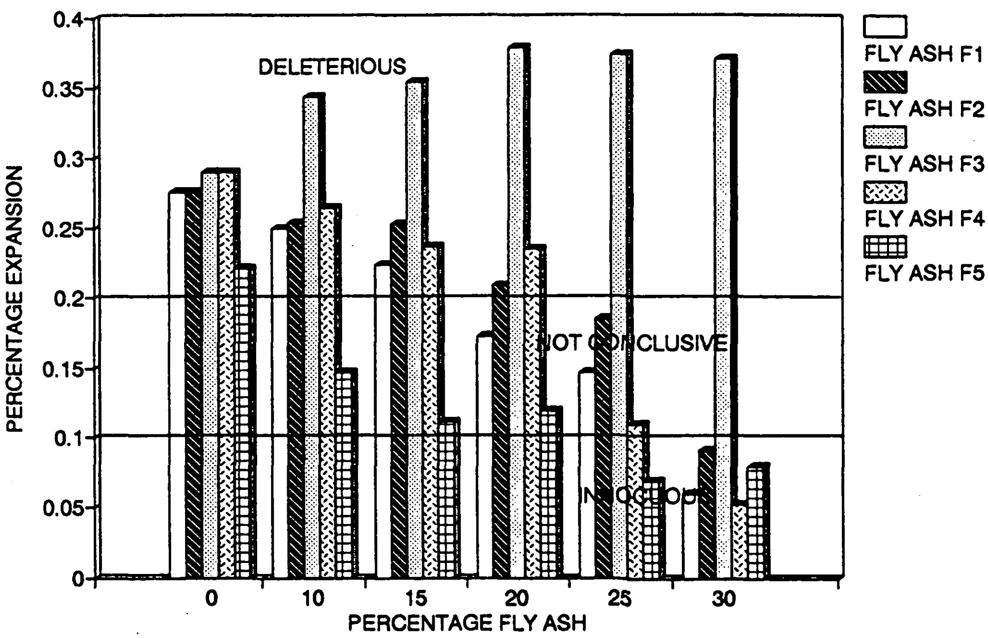

FIGURE 3 Comparison of expansion from accelerated test method for Sand 5 using different fly ashes at 14 days.

in fly ash are also released into the pore solution. Therefore, a balance between the amount of alkalies released by both cement and fly ash into the pore solution and the reduction in expansion related to the combined effect of improved physical properties of concrete and retention of alkali by the pozzolanic activity, and lowered C/S mole ratio silicate hydrates in the mixture, should be achieved (*20*).

Nixon and Gaze (*19*) reported that when low alkali cement and high alkali fly ash are combined, the alkalies in the fly ash contribute to the reactions with the pore solutions at all ages up to 1 year. Hobbs (*18*) observed that, for 30 percent replacement of fly ash, the alkalies in the fly ash contributed to the alkali-silica reaction, which resulted in higher expansion. However, for 50 percent cement replacement, he found that the expansions were negligible. Hobbs stated, therefore, that for 50 percent replacement of cement by fly ash, either no alkali contribution by the fly ash to the reaction appeared to have taken place or the fly ash had effectively neutralized the alkalies of the pore solution (*18*). A similar finding was reported by Alasali (*3*). Alasali observed that in mortars with low level of cement replacement by fly ash, the presence of additional free alkalies had a significant effect on alkali-silica expansion; at higher replacement levels, however, the effect was negligible.

Analysis of the results and observation of the figures indicate clearly that four fly ashes, if added in appropriate quantities, reduced deleterious expansions to a negligible (innocuous) level in mortar bars made with highly reactive Sand 5. However, one fly ash (#3) had slightly increased expansion at all levels of fly ash addition. Results clearly indicate that the addition of any quantity of the four Class C fly ashes (#1, 2, 4, and 5) significantly reduces expansion due to ASR when reactive sands are used. At 30 percent cement replacement with fly ash, the expansions are innocuous. All mortar bar specimens containing one of these four fly ashes had a significant reduction in expansion compared with those specimens without fly ash. However, the influence of fly ash #3 on ASR expansions is the opposite. The reason for that is unknown; further investigation is necessary.

In the case of nonreactive sands (Sand 1, for example 1) a pessimum effect is seen when fly ashes are added. The addition of smaller quantities of fly ash (less than 20 percent for fly ashes #1 and 2, and 15 percent replacement for fly ash #4) had actually increased the total expansion. Above a certain level of replacement, 20 percent for fly ashes 1 and 2, and 15 percent for fly ash 4, expansions due to ASR are reduced. The pessimum limits for these fly ashes are 20, 20, and 15 percent, respectively, for #1, 2, and 4. When fly ashes are added above these pessimum levels, 25 percent for #1 and 2 and 20 percent for #4, deleterious expansions are reduced to innocuous.

The influence of fly ash #3 on ASR expansion in mortar bars made with nonreactive sands (Sand 1), is opposite to that of the other four fly ashes. At every level of fly ash addition up to 30 percent replacement, the expansions are increased. In this case, there is no pessimum limit. Again, the phenomenon cannot be explained without further study.

Influence of Oxide Content of Fly Ashes

Oxide contents of the fly ashes varied from 53.3 to 68.4 percent. Fly ash 3, which had the lowest oxide content (53.3 percent), was not effective in controlling deleterious expansion due to ASR in mortar bars made with reactive and nonreactive sands. Fly ashes with oxide contents of 58.7 percent (#2), 61.8 percent (#4), 63.9 percent (#1) and 68.4 percent (#5) were effective in inhibiting expansion due to ASR, in mortar bars made with reactive and nonreactive sands. Fly ashes with higher quantities of oxides appear to more effectively inhibit expansion; however, the difference is not very significant. As anticipated, the pessimum effect is seen only in nonreactive sands.

Influence of Alkali Contents in Fly Ashes

Alkali contents varied from 0.77 to 1.92. Fly ash 4, which had the highest alkali content of 1.92 percent, was fully effective in inhibiting expansion due to ASR in mortar bars made with reactive and nonreactive sands. Whereas fly ash 3, which had a lower alkali content of 1.70 percent, was not effective in controlling expansion related to ASR.

Effect of Fly Ash Addition on Cube Compressive Strength

Compressive strengths at 3, 7, and 28 days for mortar cubes made either with or without blended cements are given in Table 5. Five fly ashes (1 to 5) were blended with the same cement (Type I/II) at 10, 15, 20, 25, and 30 percent by weight replacement levels. Strengths at 3, 7, and 28 days are compared with the corresponding strengths of mortar cubes made with nonblended cements. The comparison indicates that the replacement of cement, 10 to 30 percent by weight, with fly ash did not adversely affect the compressive strength or the rate of compressive-strength development for all four fly ashes. In some cases the compressive strengths were actually slightly higher for the mortar cubes made with blended cements.

TABLE 5 Compressive Strengths of Cubes With and Without Different Percentages of Fly Ashes

TYPE OF FLY ASH & PERCENTAGE	COMPRESSIVE STRENGTH MPa		
	3 DAYS	7 DAYS	28 DAYS
Fly Ash - F1			
F1 - 0% (Control)	20.96	34.50	39.79
F1 - 10%	23.42	30.94	44.26
F1 - 15%	22.90	28.88	46.90
F1 - 20%	20.27	33.12	49.49
F1 - 25%	18.72	26.75	47.25
F1 - 30%	24.28	24.74	44.32
Fly Ash - F2			
F2 - 0% (Control)	20.96	34.50	39.79
F2 - 10%	26.23	35.43	36.39
F2 - 15%	28.02	27.61	37.49
F2 - 20%	27.27	28.65	38.98
F2 - 25%	27.33	30.08	39.10
F2 - 30%	23.59	34.05	37.84
Fly Ash - F3			
F3 - 0% (Control)	20.95	34.50	39.78
F3 - 10%	31.35	39.21	39.21
F3 - 15%	31.46	39.61	39.78
F3 - 20%	31.46	34.91	37.60
F3 - 25%	32.50	37.60	37.55
F3 - 30%	28.42	39.96	40.42
Fly Ash - F4			
F4 - 0% (Control)	20.95	34.50	39.78
F4 - 10%	30.71	37.77	40.07
F4 - 15%	31.00	37.49	39.84
F4 - 20%	29.62	33.07	37.43
F4 - 25%	29.28	32.55	37.08
F4 - 30%	27.44	32.43	36.39
Fly Ash - F5			
F5 - 0% (Control)	11.98	24.68	36.14
F5 - 10%	8.88	28.11	43.15
F5 - 20%	7.51	23.24	35.29
F5 - 30%	11.45	30.59	25.07
F5 - 40%	14.51	23.46	32.12
F5 - 50%	20.48	27.07	42.04
F5 - 60%	12.80	25.42	40.32
F5 - 70%	15.81	20.34	41.08

CONCLUSIONS

- Accelerated test method results indicate that one sand (Sand 5) is reactive (deleterious) and the other four sands are slow or late to affect expansion (inconclusive).
- Some ASTM Class C fly ashes are effective in inhibiting expansion due to ASR in mortar bars made with reactive and nonreactive sands.
- When nonreactive sands are used, there is a pessimum level below which the fly ash addition slightly increases the expansion related to ASR. However, when fly ashes are added above this pessimum limit, ASR expansions are reduced to negligible innocuous levels. The pessimum levels were 15 or 20 percent for the fly ashes tested.
- When reactive sands are tested, the addition of Class C fly ash at any level considerably reduces ASR expansion. ASR expansions are innocuous, negligible, when appropriate quantities of fly ash are added.
- For the five fly ashes studied, the oxide content of the fly ash seems to have an influence on expansion related due to ASR. Fly ash (3) with low oxides content (53.3 percent) was not effective in inhibiting the expansion from ASR in mortar bars made with reactive and nonreactive sands. The effectiveness improved the higher the oxide content; however the improvement was not significant.
- Alkali content of fly ash did not seem to influence its effectiveness in inhibiting expansion due to ASR in mortar bars made with reactive and nonreactive sands. Additional investigation is necessary to confirm that finding.
- The mortar setting behavior, early strength development characteristics, and their ultimate cube compressive strengths were not affected when part of the cement, (up to 30 percent by weight) was replaced with fly ash and when the fly ash was properly preblended with the cement.

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