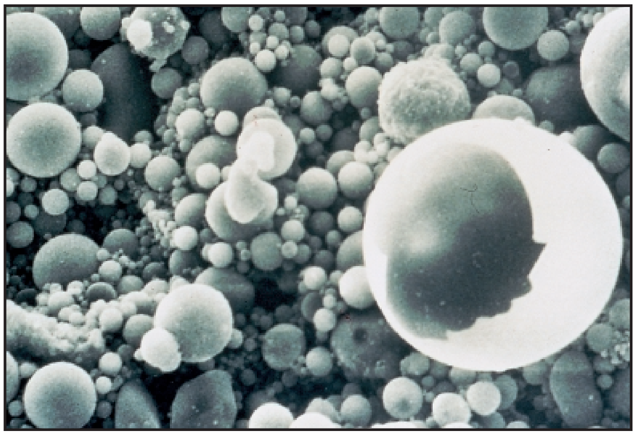
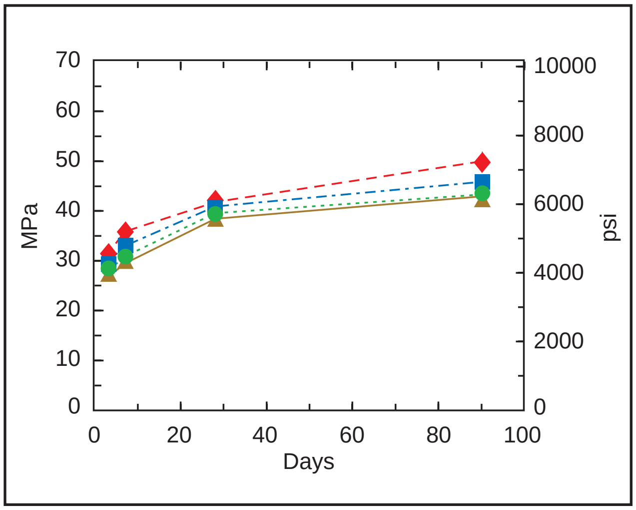
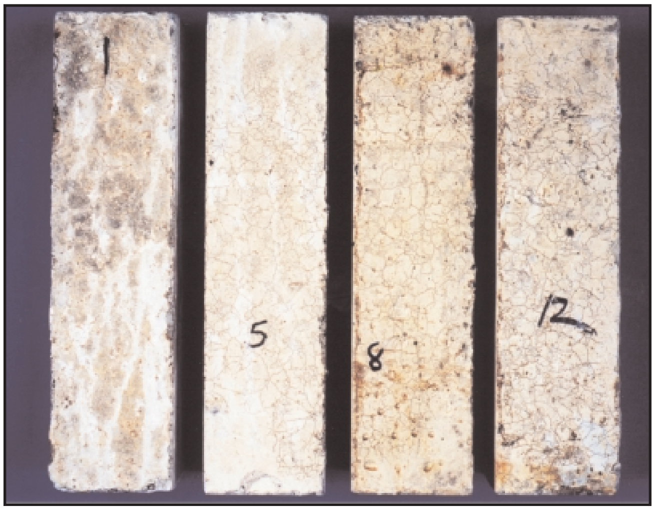


SUBSTITUTION OF FLY ASH FOR CEMENT OR AGGREGATE IN CONCRETE: STRENGTH DEVELOPMENT AND SUPPRESSION OF ASR

by Rachel J. Detwiler

Research & Development Bulletin RD127





PORTLAND CEMENT ASSOCIATION

Abstract: Class F fly ash may be used in concrete pavements to control expansions due to alkali-silica reaction. However, since it generally reduces the rate of strength gain, highway departments and ministries of transportation often allow its use only before the weather turns cold. This paper reports on the effectiveness of additions or partial substitutions of Class F fly ash for cement in producing adequate strength gain at cool temperatures while still controlling expansions. The control concrete mix design was typical for concrete pavements. Each of two Class F fly ashes was used at the rates of 20% and 30% by mass of cement by addition, substitution, or partial substitution. The highly reactive Spratt aggregate was used as the coarse aggregate, while a nonreactive sand was used as the fine aggregate. The Class F fly ash retarded the strength gain at early ages, particularly when the concrete was cured at low temperatures; however, maintaining the cement content mitigated this effect. ASTM C 1293 data showed that in some cases addition or partial substitution of Class F fly ash for the cement was adequate to control expansion, while in other cases it was not. Taken together the results of this study show that for late fall concreting, the use of Class F fly ash with increased cement contents offers the possibility of good control of expansions due to alkali-silica reaction with adequate rates of strength gain. However, tests using the local materials would be necessary to determine appropriate mix designs.

Keywords: Alkali-silica reaction, ASTM C 1293, Class F fly ash, compresive strength, concrete, paving, Spratt aggregate.

Reference: Detwiler, Rachel J., *Substitution of Fly Ash for Cement or Aggregate in Concrete: Strength Development and Suppression of ASR*, RD127, Portland Cement Association, Skokie, Illinois 2002, 28 pages.

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Cover Photos:
(top) Fly ash particles as viewed through an electron microscope (54048); (bottom left) compressive strength gain over time; (right) ASTM C 1293 specimens (see Fig. 6 of report) (70032).

RD127 PCA R&D Serial No. 2146

Substitution of Fly Ash for Cement or Aggregate in Concrete: Strength Development and Suppression of ASR

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Construction Technology Laboratories, Inc.

Research and Development Bulletin RD127

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INTRODUCTION

The objective of this work was to determine whether the substitution of fly ash for part of the sand (without reducing the cement content) would produce acceptable strength gain in concrete in cold weather while still providing adequate control of deleterious expansions due to alkali-silica reactivity.

Review of Previous Research

Gaze and Nixon (1983) studied the effect of fly ash on the expansion of mortar bars containing Beltane opal, a standard reactive aggregate, stored at 38°C. One series of specimens was made using low-alkali cement and 10, 20, or 30% fly ash (replacement). Potassium sulfate was added to keep the alkali level constant at 1.2% equivalent Na_2O in order to eliminate the effect of dilution of the alkalis. Their results showed that even when the alkali content was kept constant, the fly ash reduced the expansion of the mortar, with very little expansion for the 20% and 30% fly ash mortars. In the second series the equivalent alkali content of plain cement mortars was varied from 0.9 to 1.2% by adding potassium sulfate in order to simulate the effect of diluting a high-alkali cement with up to 30% fly ash. They found that dilution of the alkalis also reduced expansions, but by less than was achieved by the substitution of fly ash for part of the cement when the alkali content was kept constant. Thus the effect of fly ash on expansion due to alkali-silica reaction cannot be attributed to dilution alone.

Thomas et al. (1991) examined concrete specimens of equivalent 28-day strength and workability but made with different levels of fly ash. Prisms 75 x 75 x 200 mm were stored at 100% R.H. at either 20°C or 38°C. Length changes were monitored for two years. Companion prisms and beams 100 x 100 x 500 mm were cured in water at 20°C for 28 days, after which they were placed at an outdoor exposure site for 7 years. The specimens containing either no fly ash or 5% fly ash suffered significant expansion and cracking due to alkali-silica reaction, with a consequent degradation of engineering properties. However, specimens with 20% or 30% of a high-alkali fly ash substituted for the cement exhibited little expansion and no cracking. Petrographic examination of these specimens showed no evidence of damaging alkali-silica reaction. Alkali-silica gel was found in isolated locations not associated with cracking. The authors pointed out that if the fly ash were acting only as an inert diluent of the cement alkalis (or available alkalis), one would expect a reduction in alkali-silica reaction. However, the results indicated that the effect of fly ash is more than simply the dilution of alkalis. In concretes having similar cement contents and equal quantities of reactive sand, the concrete with 20% fly ash (addition) suffered no damage, while the concrete without fly ash experienced considerable expansion and cracking.

Using a fly ash with a high total alkali content, Nixon et al. (1985) found that at early ages the fly ash made a net contribution to the alkali content of the pore solution. After about 28 days, however, the fly ash reduced the alkalinity of the pore solution below that produced by dilution with an inert material. However, with very low alkali cements, the fly ash contributed to the alkalinity at ages up to one year.

Bhatty and Greening (1978) studied the ability of calcium silicate hydrates to retain different types of alkalis. They found that hydrates having low CaO/SiO_2 ratios are more effective in binding alkalis. For example, the hydrate with a CaO/SiO_2 ratio of 0.97 retained twice the amount of alkali as the hydrate with a CaO/SiO_2 ratio of 1.25. They also found that calcium silicate hydrate in equilibrium with 1 N NaOH solution has a maximum CaO/SiO_2 ratio between 1.25 and 1.32, while the CaO/SiO_2 ratio of calcium silicate hydrate formed on the hydration of cement is about 1.5. The addition of a pozzolan to the cement reduces the CaO/SiO_2 ratio, thus reducing the soluble alkali. Later, Bhatty (1985) extended and modified this work using C_3S and finely ground opal as the reactants in water or 1 N NaOH solution. By comparing the alkali concentration in the original solution with the filtrates obtained after different reaction times, Bhatty was able to determine the amount of alkali retained by the hydrates. He concluded that the amount of SiO_2 needed to prevent deleterious expansions due to alkali-aggregate reaction should be such that the CaO/SiO_2 ratio does not exceed about 1.5. Some of the silica may be supplied by the aggregate itself.

The effect of fly ash on the pore structure of concrete may also help to reduce expansions due to alkali-silica reaction. The silica in fly ash reacts with the calcium hydroxide produced by the hydration of the cement to form calcium silicate hydrate. Since calcium silicate hydrate takes up more space than the calcium hydroxide it replaces, this reaction results in a finer, less continuous pore system. In field exposures, where water and additional alkalis may enter the concrete from the environment, this tightening of the pore structure limits their availability to participate in the generation and swelling of alkali-silica gel.

Thus one may consider three mechanisms by which fly ash controls expansion due to alkali-silica reaction:

1. dilution of the cement alkalis by a fly ash with a lower alkali content, or at least a lower available alkali content.
2. removal of some of the alkalis from the pore solution by binding them into the low CaO/SiO_2 ratio hydration products.
3. reduction of concrete permeability and diffusivity due to the pozzolanic reaction of the fly ash with the calcium hydroxide produced by the hydration of the cement.

If the cement content is not reduced (that is, if fly ash is added), then the first mechanism does not apply; however, the other two could still play a role. Essentially this test program examines the effectiveness of these two mechanisms in controlling expansion due to alkali-silica reaction.

Overview of This Project

Two good-quality Class F fly ashes were selected. Both had low alkali contents and could otherwise be expected to be effective in controlling expansion due to alkali-silica reactivity. A highly reactive coarse aggregate and a non-reactive fine aggregate were used in all mixes. The mix design for the control concrete had a 0.45 water/ cement ratio and contained 330 kg/m^3 of a 1% alkali cement. For each fly ash, 20% and 30% fly ash concretes were made in three ways: (1) by substitution for an equal mass of cement, (2) by substitution for an equal mass of sand, and (3) by substitution for half cement and half sand. Thus for the 20% fly ash concretes the cement content was reduced by 20%, 10%, or not at all. The concrete prism test (ASTM C 1293) was used to determine the expansions due to alkali-silica reaction Length changes were monitored for three years.

Companion 100 x 200 mm cylinders were also cast. All of them were cured in their plastic molds at 23°C for the first 24 hours. After demolding, half were transferred to the 23°C, 100% R.H. moist room, while the remainder were placed in saturated lime water at 4°C to simulate cold weather curing conditions. Compressive strengths of both sets of specimens were tested at 3, 7, 28, and 90 days.

EXPERIMENTAL PROGRAM

Materials

All of the concrete mixes were made using Spratt coarse aggregate, which is known to be highly reactive with alkalis in cement and is used as a standard material in Canada. Spratt aggregate is crushed siliceous limestone and dolomitic limestone. Petrographic examination of this aggregate showed a chalcedony content exceeding the 3% allowed by the PCA *Guide Specification for Concrete Subject to Alkali-Silica Reactions*, as can be seen from Table 1. A few of the rock fragments in the 4.75 mm sieve fraction and in the pan consisted entirely of chalcedony. Table 1 also shows that by the other two criteria in the *Guide Specification*, ASTM C 1260 and ASTM C 1293, the aggregate is considered reactive.

The fine aggregate was Eau Claire sand. The selected mix designs contained constant quantities of reactive coarse aggregate and varying quantities of fine aggregate. In order to maintain a constant quantity of reactive aggregate in the concretes, it was necessary to use a nonreactive fine aggregate. Eau Claire sand has proven to be nonreactive over many years of experimental work. It has a bulk specific gravity of 2.64, absorption of 0.90%, and a fineness modulus of 2.87.

The cement had an alkali content of 0.96% Na_2O equivalent. The complete oxide analysis is given in Table 2. The two fly ashes conform to ASTM C 618-96 for Class F fly ash, including the optional limit of 1.5% on the content of available alkalis. As can be seen from Table 2, the fly ashes have different CaO and total alkali contents and different finenesses. However, both would be expected to be effective in controlling alkali-silica reactivity.

Table 1. Guide Specification Tests of Spratt Aggregate

Test	Result	Failure criteria (PCA IS415)
ASTM C 295	3% chalcedony	> 5.0% strained quartz > 3.0% chert or chalcedony > 1.0% tridymite > 0.5% opal > 3.0% volcanic glass
ASTM C 1260 (constant water)	14-day expansion 0.32%	14-day expansion > 0.10%
ASTM C 1293	12-month expansion 0.20%	12-month expansion > 0.04%

Table 2. Analyses of Cement and Fly Ashes, % by Mass

Analyte	Cement	Fly Ash A	Fly Ash B
SiO_2	19.48	62.33	48.26
Al_2O_3	5.72	22.96	25.34
Fe_2O_3	2.69	5.43	19.78
CaO	62.84	3.51	1.07
MgO	2.26	1.24	0.70
SO_3	4.17	0.14	0.10
Na_2O	0.35	1.44	0.17
K_2O	0.92	1.31	2.05
TiO_2	0.29	1.16	1.40
P_2O_5	0.12	0.04	0.13
Mn_2O_3	0.21	0.03	0.03
SrO	0.08	0.10	0.07
LOI	1.24	0.11	0.47
Total alkalis (Na_2O equivalent)	0.96	2.30	1.52
Available alkalis		0.51	0.51
SiO_2+Al_2O_3+Fe_2O_3		90.73	93.38
Surface area, cm^2/g	3084	3149	2175
Calculated Bogue Compounds, %			
C_3S	51		
C_2S	17		
C_3A	12		
C_4AF	8		

If the aggregate is determined to be potentially reactive, the *Guide Specification* gives three options for controlling the reactivity: (A) use of a pozzolan or slag with portland cement or blended cement, (B) use of a blended cement without additional pozzolan or slag, or (C) use of a low-alkali cement. Fly ashes used for Option A must conform to ASTM C 618.

The effectiveness of a blended cement or combination of cement and pozzolan or slag may be evaluated by either of two options: (A) by ASTM C 1260, in which case the 14-day expansion must not exceed 0.10%, or (B) by ASTM C 441, in which case the expansion is not to exceed that of control mortars made with a low (0.50-0.60%) alkali cement. In each case, the dosages of fly ash to be used on the job are to be used in the test. For this work we used 20% and 30% replacement of cement. As Tables 3 and 4 show, both fly ashes are effective in controlling ASR by both criteria. The failure criteria are as shown in the table captions.

Table 3. Evaluation of Fly Ash/Cement Combinations by ASTM C 1260 Maximum Allowable Expansion: 0.10%

Fly Ash	20%	30%
A	0.03%	0.02%
B	0.05%	0.03%

Table 4. Evaluation of Fly Ash/Cement Combinations by ASTM C 441 Expansion of Control Made With Low-Alkali Cement: 0.21%

Fly Ash	20%	30%
A	0.11%	0.05%
B	0.12%	0.06%

Mix Designs

The mix designs for the compressive strength tests are typical of those used in pavements. The control mix had a water/cement ratio of 0.45 and contained 332 kg/m³ of cement. The water reducer was kept to a relatively low dosage. The fly ash mix designs were all based on the control mix. The test program included both 20% and 30% dosages of fly ash by mass of cement. In some mixes the fly ash replaced an equal mass of cement (mixes designated "S" for substitution), in other mixes an equal mass of sand (mixes designated "A" for addition), and in others half sand and half cement (mixes designated "P" for partial substitution). The amount of water reducer was kept constant for all mixes and the amount of water adjusted as needed to maintain a slump of 25 to 50 mm. Table 5 shows all of the mix quantities (SSD basis) as batched. It is clear that Fly Ash B had a greater water demand than Fly Ash A.

All of the specimens were mixed and cast at room temperature (23°C). The coarse aggregates were soaked in water for approximately 24 hours and drained just before mixing. The excess water was weighed and the mix water reduced by the amount of water retained by the aggregate. The fine and coarse aggregates were placed in the pan

Table 5a. (Metric) Concrete Mixes as Fabricated, kg/m³, SSD Basis

Mix	Water	Cement	Fly ash	Coarse aggregate	Fine aggregate
Control	150	332	0	971	947
Fly Ash A 20% S*	145	266	66	972	949
Fly Ash A 20% P	158	299	66	971	915
Fly Ash A 20% A	159	332	66	971	880
Fly Ash A 30% S	150	230	99	962	939
Fly Ash A 30% P	151	280	99	962	890
Fly Ash A 30% A	157	328	98	959	837
Fly Ash B 20% S	163	255	65	949	926
Fly Ash B 20% P	168	293	65	952	897
Fly Ash B 20% A	174	327	65	957	869
Fly Ash B 30% S	163	231	99	963	939
Fly Ash B 30% P	159	282	100	971	897
Fly Ash B 30% A	161	330	99	964	841

* S = substitution of cement with fly ash, P = partial substitution of cement and sand with fly ash, A = addition of fly ash.

Table 5b. (Inch-Pound Units) Concrete Mixes as Fabricated, lb/yd³, SSD Basis

Mix	Water	Cement	Fly ash	Coarse aggregate	Fine aggregate
Control	253	560	0	1637	1596
Fly Ash A 20% S*	244	448	111	1638	1600
Fly Ash A 20% P	266	504	111	1637	1542
Fly Ash A 20% A	268	560	111	1637	1483
Fly Ash A 30% S	253	388	167	1622	1583
Fly Ash A 30% P	255	472	167	1622	1500
Fly Ash A 30% A	265	553	165	1616	1411
Fly Ash B 20% S	275	430	110	1600	1561
Fly Ash B 20% P	283	494	110	1605	1512
Fly Ash B 20% A	293	551	110	1613	1465
Fly Ash B 30% S	275	389	167	1623	1583
Fly Ash B 30% P	268	475	169	1637	1512
Fly Ash B 30% A	271	556	167	1625	1418

* S = substitution of cement with fly ash, P = partial substitution of cement and sand with fly ash, A = addition of fly ash.

mixer. The water reducing admixture was mixed with some of the mix water before being added, along with the cement, to the mixer. The concrete was mixed for three minutes, allowed to rest for three minutes, and then mixed for an additional two minutes. During the second mixing, additional water was added to bring the slump to within the specified range. Both slump and unit weight were measured immediately after mixing. The specimens were cast in two layers and consolidated by external vibration. They remained in the 23°C mixing room for 24 hours before being demolded and placed in the appropriate curing environments.

Compressive Strength Tests

For each mix a total of twenty-four 100 x 200 mm cylinders were cast. After the initial 24 hours at 23°C they were removed from their molds and placed in one of two curing environments: the standard 23°C moist room or saturated lime water kept at 4°C. The latter curing regime is a simulation of winter curing conditions. Compressive strengths were determined in accordance with ASTM C 39 for these specimens at 3, 7, 28, and 90 days. The reported strength is the average of three replicates, except where one measurement deviated from the others by 10% or more. Any such measurement was omitted from the calculation. Figures 1 and 2 show the strength gain data.

The presence of fly ash as a substitution for cement retarded the early-age strength gain. For Fly Ash B, some of this effect may be attributed to increased water demand. The concretes containing 30% fly ash appear to have been most negatively affected by the reduced curing temperature (Figure 1b). However, greater dosages of water reducer would allow for a lower water/cementitious materials ratio to be used, thus compensating for the effect of fly ash substitution on strength gain. Fly ash additions and partial substitutions resulted in strength gains similar to that of the portland cement control concrete.

Expansions Due to Alkali-Silica Reaction

The length change due to alkali-silica reaction was determined by ASTM C 1293, which is based on a Canadian standard test (CSA A23.2-14A). For each mix, three 75 x 75 x 285 mm prisms were cast with pins in each end for the length change measurements. After demolding (at 24 hours), these prisms were conditioned for 30 ± 5 minutes in 23°C water before the initial length measurements. They were then placed in sealed containers over water in a 38°C room.

According to the Canadian Standards Association (1994), the concrete prism test (CSA A23.2-14A) may be used to evaluate the effect of the use of supplementary cementing materials. Appendix B on alkali-aggregate reaction states:

> At present, the most suitable method for assessing the efficacy of supplementary cementing materials in reducing expansion is the concrete prism expansion test. Most agencies currently use a modified version of CSA Test Method A23.2-14A. When conducting this test, it is recommended that the cement be replaced at the level proposed for construction and that additional alkali be added, in the form of NaOH, to bring the cement alkali content to 1.25% Na_2O equivalent for acceleration purposes. Current experience is that a testing period of 2 years is sufficient for the evaluation of concretes containing fly ash or slag but *particular attention should be paid to the rate of expansion toward the end of the testing period*…[emphasis added]

Figures 3 through 5 show the ASTM C 1293 expansion data for three years' exposure. Figure 3 shows the data for all of the concretes. The expansion of the control concrete shows that the Spratt aggregate is highly reactive. These specimens appear to have reached their maximum expansion at approximately one year. The remaining curves show that all of the fly ash combinations have been effective in suppressing expansion to a considerable degree, although not all met the criterion of less than 0.04% expansion in two years.

Figure 4 shows the expansion data for the Fly Ash A concretes in greater detail. All of the combinations containing Fly Ash A suppressed the expansion to less than 0.04% in two years except the 20% addition, while the 20% partial substitution was close to the failure criterion. The best results were attained by the concretes containing 30% fly ash by substitution or partial substitution. The concrete with 20% fly ash by substitution also performed very well. Figure 5 is a similar plot showing the expansion data for the Fly Ash B concretes. All of the combinations containing Fly Ash B suppressed the expansion to less than 0.04% in two years. By the end of three years, the expansions appear to have stopped increasing. For this fly ash, the concretes containing 20% or 30% fly ash by substitution or partial substitution performed best. It should be noted that the Spratt aggregate used in this test program is highly reactive and that expansions would be expected to be much less for mildly or moderately reactive aggregates. Such aggregates may not require the same quantities of fly ash for control of the expansion of the concrete.

It is clear from these plots that the CSA's recommendation to pay particular attention to the expansion rate at the end of the two-year test period is appropriate. The fly ashes seem to have delayed expansion for almost a year and then suppressed it but not prevented it entirely. In some cases the expansion leveled off at the end of two years, while in others it did not.

Figure 6 shows a control specimen (#1) and specimens containing 20% of Fly Ash A by substitution (#5), partial substitution (#8), and addition (#12). The crack pattern characteristic of alkali-silica reaction can be seen on all four specimens. Of the three specimens containing fly ash, the one with the most severe cracking had the fly ash added to the cement, while that with the least severe cracking had the fly ash substituted for the cement.

SUMMARY AND CONCLUSIONS

The original purpose of this work was to evaluate the effectiveness of fly ash as an addition to, rather than a substitute for, cement in concrete containing alkali-reactive aggregate. The highly reactive Spratt aggregate was used as the coarse aggregate, while a nonreactive sand was used as the fine aggregate. Two ASTM C 618 Class F fly ashes were used at 20% and 30% of the cement as substitution, partial substitution, and addition to the cement.

The findings show that the use of fly ash in concretes retards the strength gain at early ages, particularly when the concrete is cured at low temperatures. Maintaining rather than reducing the cement content mitigated this effect. If greater strength at early ages is desired, a reduction in the water/cementitious materials ratio would be necessary.

The control of expansion due to alkali-silica reaction has been attributed to three mechanisms:

1. dilution of the cement alkalis by a fly ash with a lower alkali content, or at least a lower available alkali content.
2. removal of some of the alkalis from the pore solution by binding into the low CaO/SiO_2 ratio hydration products.
3. reduction of concrete permeability and diffusivity due to the pozzolanic reaction of the fly ash with calcium hydroxide from the hydration of the cement.

Where the cement content is not reduced, the first mechanism does not come into play. However, the other two mechanisms have been demonstrated in this work, as in previous studies, to have significant effects.

The limits given in CSA Test Method A23.2-14A, which is the basis for ASTM C 1293, may be used for evaluating the effectiveness of supplementary cementing materials in controlling alkali-silica reaction. For fly ash and slag concretes, the test is continued for two years. At the end of the test, both the expansion and the rate of expansion are considered in evaluating the effectiveness of the supplementary cementing material in controlling expansions.

Examination of the expansion data for the concrete prisms over two years shows that all of the combinations of cement and fly ash (addition, substitution, or partial substitution at levels of 20% and 30% of the cement) controlled expansion due to alkali-silica reaction to a considerable degree. However, some combinations were more effective than others. For a given dosage of fly ash, addition (maintaining the cement content) was less effective than substitution or partial substitution of fly ash for cement. This indicates that dilution of the alkalis in the cement is a significant factor in the control of expansions due to alkali-silica reaction. Overall, the least effective combination reduced the expansion by 65%, while the most effective combination reduced the expansion by 90%.

It should be noted that Spratt aggregate is highly reactive. It far exceeded all three criteria given by the Portland Cement Association's *Guide Specification for Concrete Subject to Alkali-Silica Reactions* to identify an aggregate as reactive. In Canada, it is used as a standard reference material for alkali-silica reactivity testing, not in structural concrete. For this aggregate and these fly ashes, at least a partial substitution of the cement is needed to control expansion. If the resulting reduction in strength at early ages and/or in late-season concreting is unacceptable, it would be necessary to reduce the water/cementitious materials ratio accordingly. This would also increase the overall durability of the concrete. With a moderately reactive aggregate, it is likely that adequate control of expansions could be achieved by addition of sufficient quantities of a suitable fly ash. If so, it would also be easier to achieve the desired strength gain characteristics while also controlling expansions. However, the specific concrete mix designs should be tested to ensure that they will perform acceptably in the field.

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FIGURES AND ADDITIONAL TABLES

Table 6a. (Metric) Compressive Strengths for Concretes Cured at 23°C for the First 24 Hours Followed by Curing at 4°C to Age Shown, MPa

Mix/Age, days	3	7	28	90
Control 4°C	31.4	35.9	41.8	50.0
Control 23°C	34.8	39.7	47.2	52.0
20% S Fly Ash A	25.3	32.3	39.8	54.6
20% P Fly Ash A	26.8	34.0	41.4	55.2
20% A Fly Ash A	29.6	34.6	42.1	57.0
30% S Fly Ash A	24.7	29.9	34.1	43.0
30% P Fly Ash A	30.1	33.9	40.4	45.8
30% A Fly Ash A	32.2	34.2	40.9	47.4
20% S Fly Ash B	26.7	29.4	38.4	42.9
20% P Fly Ash B	28.0	30.9	39.6	43.3
20% A Fly Ash B	30.0	33.1	40.9	45.9
30% S Fly Ash B	22.3	25.3	34.2	38.5
30% P Fly Ash B	27.3	30.9	39.8	44.3
30% A Fly Ash B	31.9	33.7	38.5	47.9

* S = substitution of cement with fly ash, P = partial substitution of cement and sand with fly ash,
A = addition of fly ash

Table 6b. (Inch-Pound Units) Compressive Strengths for Concretes Cured at 73°F for the First 24 hours Followed by Curing at 39°F to Age Shown, psi

Mix/Age, days	3	7	28	90
Control 39°F	4550	5210	6070	7250
Control 73°F	5040	5760	6840	7540
20% S Fly Ash A*	3670	4690	5770	7920
20% P Fly Ash A	3890	4930	6000	8000
20% A Fly Ash A	4300	5020	6110	8260
30% S Fly Ash A	3580	4340	4940	6240
30% P Fly Ash A	4360	4920	5860	6640
30% A Fly Ash A	4670	4960	5930	6870
20% S Fly Ash B	3870	4270	5570	6230
20% P Fly Ash B	4060	4480	5740	6280
20% A Fly Ash B	4340	4800	5930	6660
30% S Fly Ash B	3240	3680	4960	5590
30% P Fly Ash B	3960	4480	5770	6420
30% A Fly Ash B	4630	4890	5580	6940

* S = substitution of cement with fly ash, P = partial substitution of cement and sand with fly ash,
A = addition of fly ash

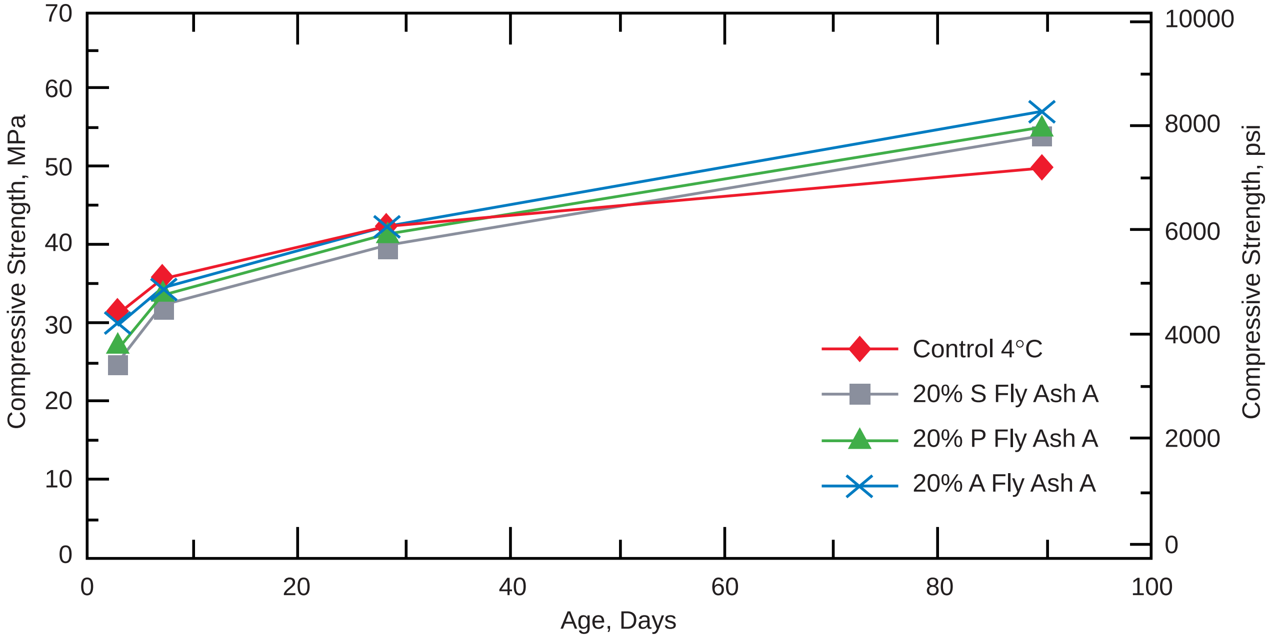

Figure 1a. Compressive strengths for the 20% Fly Ash A concretes cured at 4°C after the first 24 hours. By age 28 days, the strengths of all concretes except the one with the lowest cement content are comparable; by age 90 days, all of the fly ash concretes are stronger than the control. “S” indicates substitution, “P” indicates partial substitution, and “A” indicates addition of fly ash.

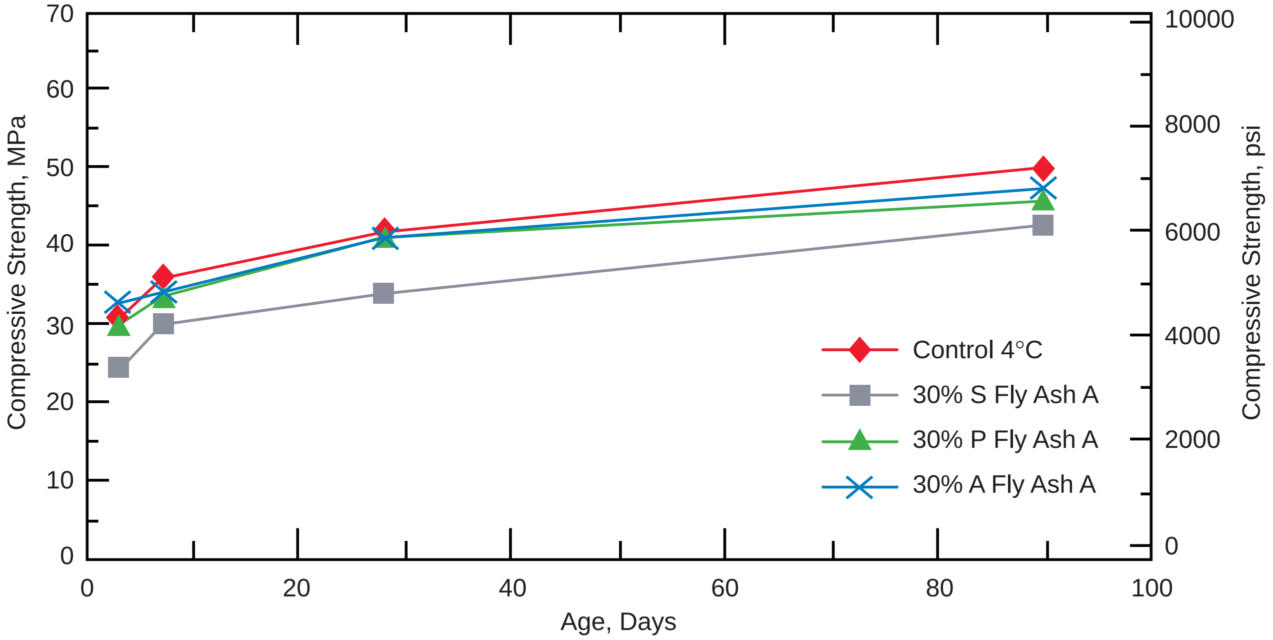

Figure 1b. Compressive strengths for the 30% Fly Ash A concretes cured at 4°C after the first 24 hours. Except for the concrete with the lowest cement content, the strengths are comparable at all ages. “S” indicates substitution, “P” indicates partial substitution, and “A” indicates addition of fly ash.

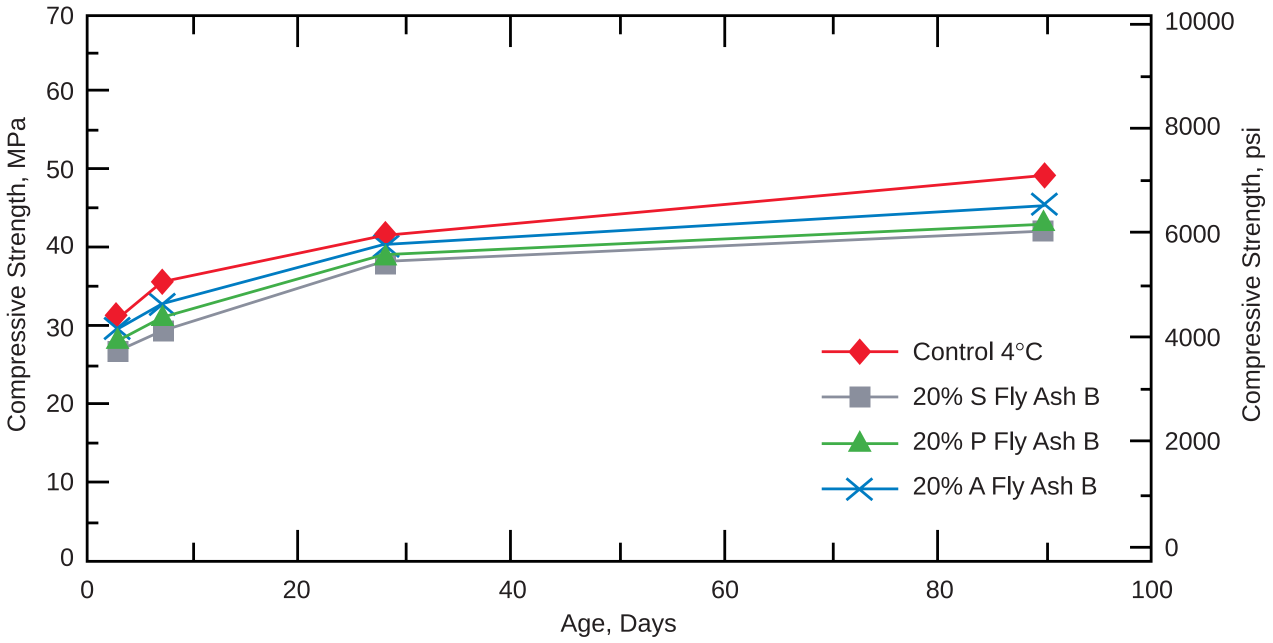

Figure 1c. Compressive strengths for the 20% Fly Ash B concretes cured at 4°C after the first 24 hours. The higher water demand of this fly ash has a slight negative effect on the strength of the concrete. However, this effect could be compensated for by reducing the water/cementitious materials ratio accordingly. "S" indicates substitution, "P" indicates partial substitution, and "A" indicates addition of fly ash.

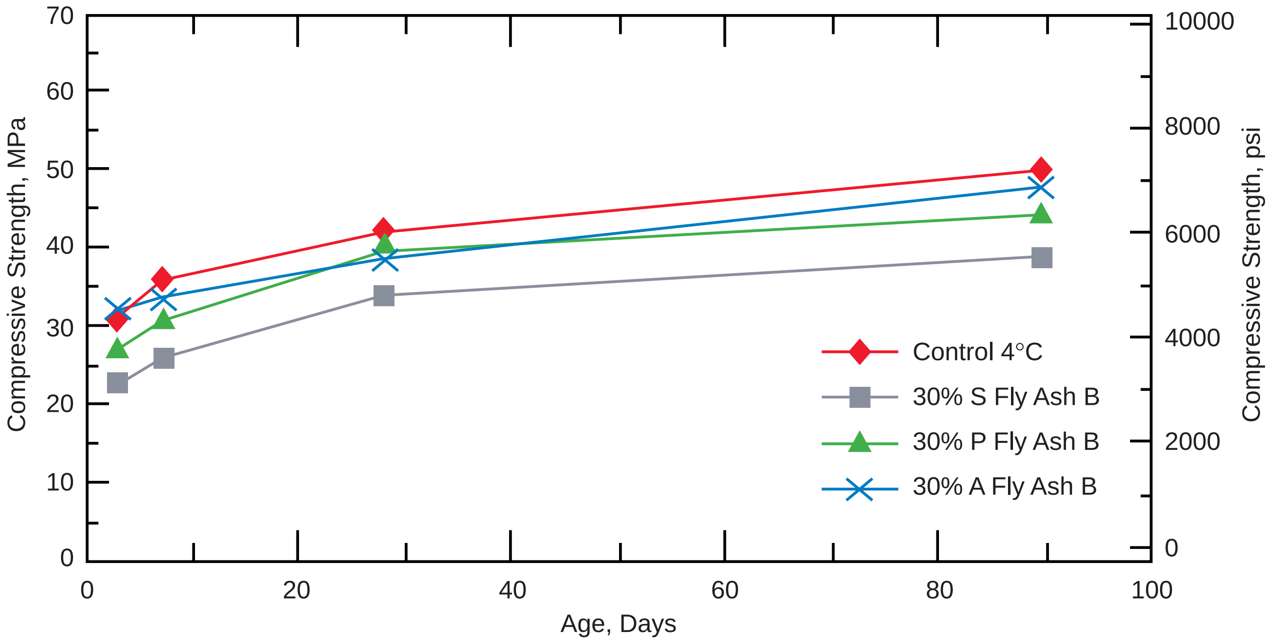

Figure 1d. Compressive strengths for the 30% Fly Ash B concretes cured at 4°C after the first 24 hours. Here the reduced cement content and increased water/cementitious materials ratio reduced the strengths of the concretes in which fly ash was substituted for some or all of the cement. "S" indicates substitution, "P" partial substitution, and "A" addition of fly ash.

Table 7a. (Metric) Compressive Strengths for Concretes Cured at 23°C, MPa

Mix	3 days	7 days	28 days	90 days
Control 23°C	34.8	39.7	47.1	52.0
20% S Fly Ash A	30.4	36.0	46.7	57.5
20% P Fly Ash A	30.7	37.3	46.8	59.6
20% A Fly Ash A	33.2	38.8	47.2	58.9
30% S Fly Ash A	27.4	33.5	41.1	54.2
30% P Fly Ash A	30.3	36.8	43.5	60.3
30% A Fly Ash A	31.9	37.9	45.7	58.9
20% S Fly Ash B	28.2	34.7	42.8	50.4
20% P Fly Ash B	29.5	36.0	45.5	50.2
20% A Fly Ash B	30.4	37.8	46.0	51.8
30% S Fly Ash B	24.5	32.1	40.6	49.7
30% P Fly Ash B	29.4	35.9	46.0	55.5
30% A Fly Ash B	31.8	37.4	45.5	56.8

* S = substitution of cement with fly ash, P = partial substitution of cement and sand with fly ash,
A = addition of fly ash

Table 7b. (Inch-Pound Units) Compressive Strengths for Concretes Cured at 73°F, psi

Mix	3 days	7 days	28 days	90 days
Control 73°F	5040	5760	6840	7540
20% S Fly Ash A	4400	5220	6780	8340
20% P Fly Ash A	4460	5410	6790	8650
20% A Fly Ash A	4810	5630	6840	8550
30% S Fly Ash A	3980	4860	5960	7860
30% P Fly Ash A	4390	5340	6310	8750
30% A Fly Ash A	4630	5490	6620	8550
20% S Fly Ash B	4090	5030	6200	7320
20% P Fly Ash B	4290	5230	6590	7280
20% A Fly Ash B	4400	5480	6670	7510
30% S Fly Ash B	3560	4650	5890	7210
30% P Fly Ash B	4260	5210	6670	8050
30% A Fly Ash B	4620	5430	6590	8240

* S = substitution of cement with fly ash, P = partial substitution of cement and sand with fly ash,
A = addition of fly ash

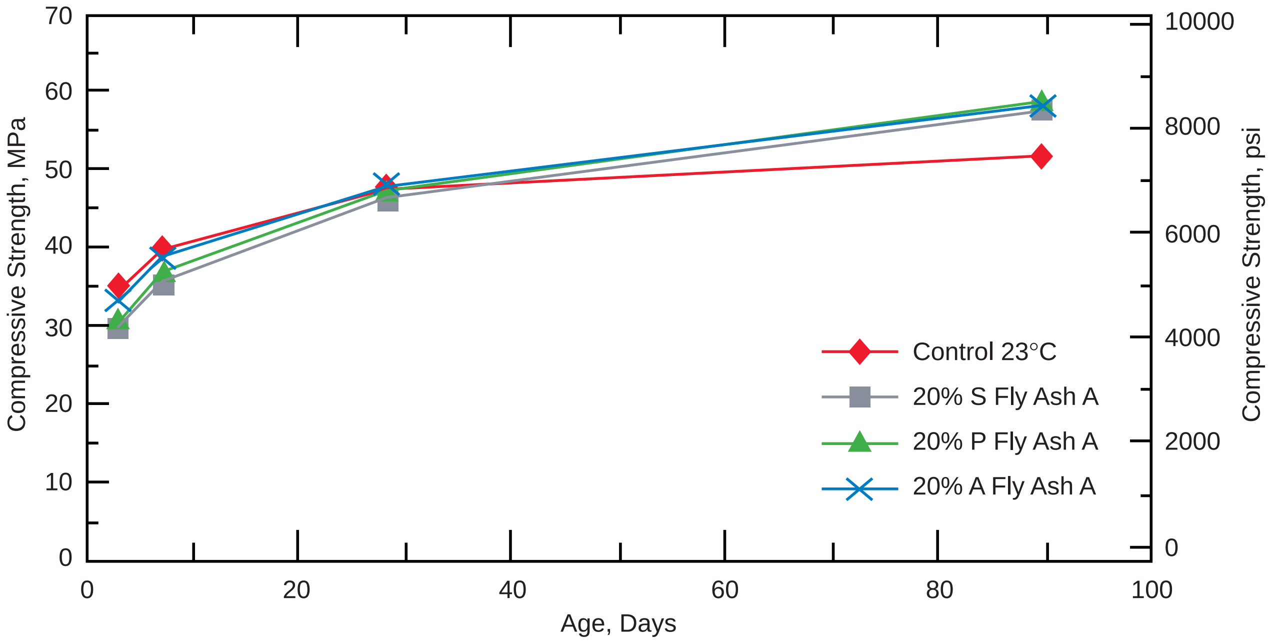

Figure 2a. Compressive strengths for 20% Fly Ash A concretes cured at 23°C. By 28 days, the strengths of the fly ash concretes are equal to that of the control; at age 90 days they exceed it. “S” indicates substitution, “P” indicates partial substitution, and “A” indicates addition of fly ash.

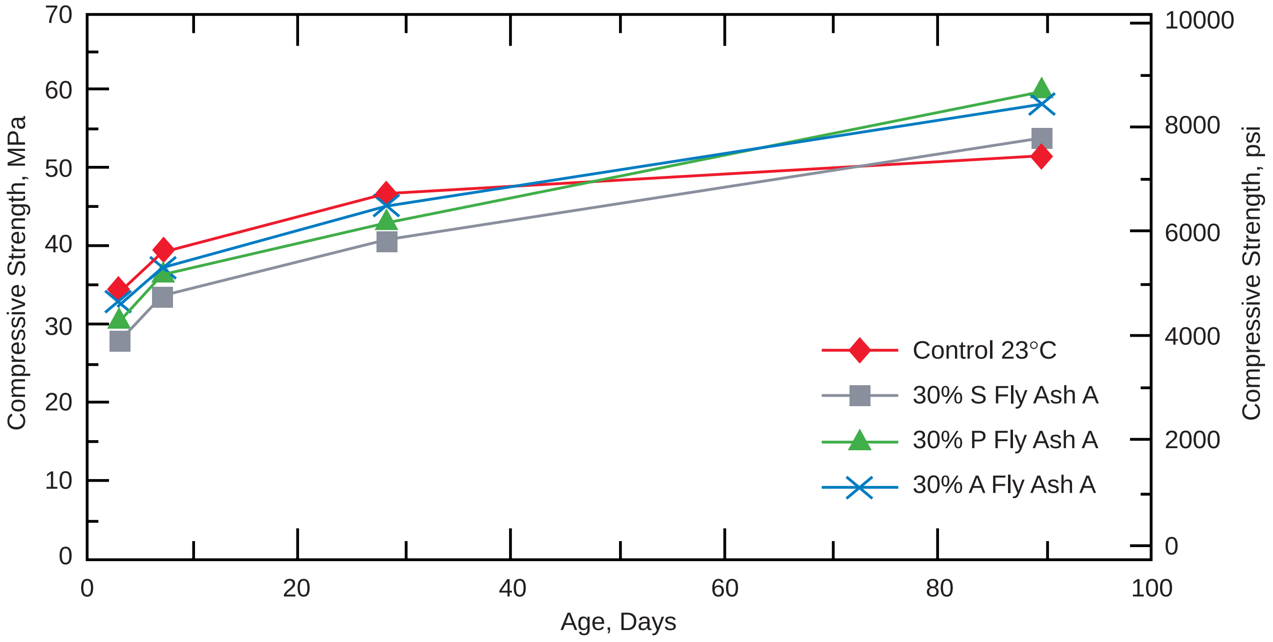

Figure 2b. Compressive strengths for 30% Fly Ash A concretes cured at 23°C. The retarding effect of the fly ash on strength gain is apparent through age 28 days, although when the cement content remains constant (fly ash is added), the effect of the fly ash on strength is minimal. By age 90 days the strengths of the fly ash concretes exceed that of the control. “S” indicates substitution, “P” indicates partial substitution, and “A” indicates addition of fly ash.

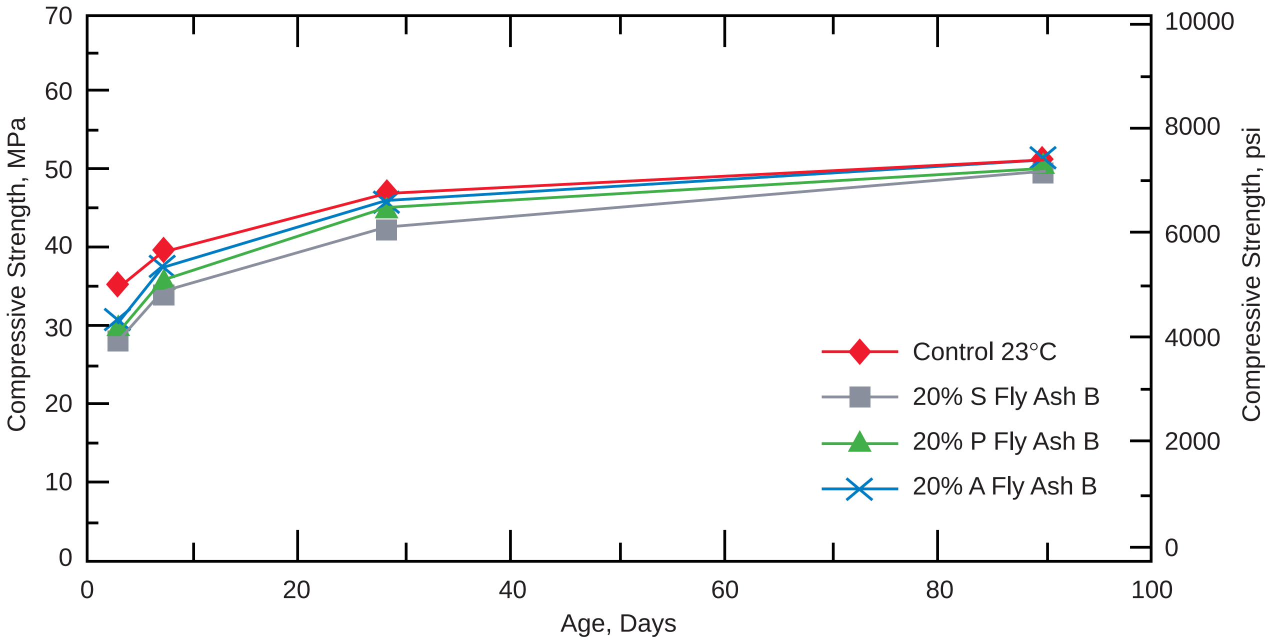

Figure 2c. Compressive strengths for 20% Fly Ash B concretes cured at 23°C. The presence of the fly ash (with the resulting increased water demand) reduces the strength of the concrete at all ages, but by 90 days the effect is negligible. "S" indicates substitution, "P" indicates partial substitution, and "A" indicates addition of fly ash.

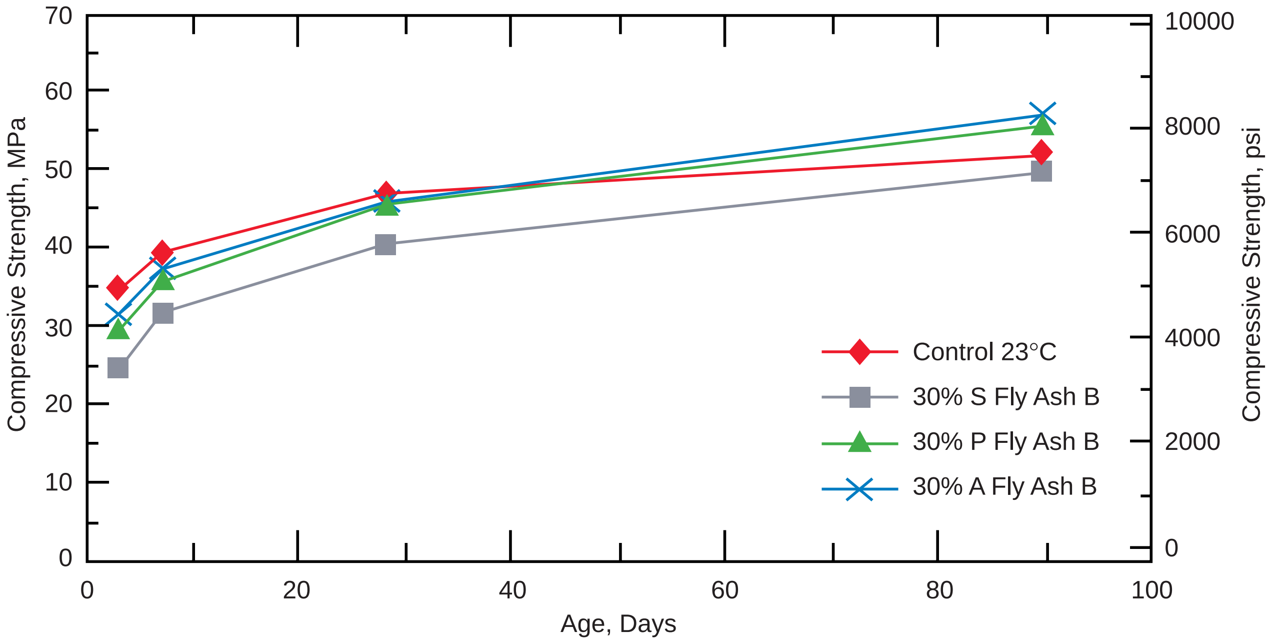

Figure 2d. Compressive strengths for 30% Fly Ash B concretes cured at 23°C. The effect of substituting fly ash for cement reduced the strength at all ages. For the concretes in which fly ash was added or only partially substituted for cement, the retarding effect was negligible at 28 days. By 90 days, these concretes were stronger than the control. "S" indicates substitution, "P" indicates partial substitution, and "A" indicates addition of fly ash.

Table 8. ASTM C 1293 Expansion for 20% Fly Ash A by Substitution

Age, days	Expansion %, of Individual Prisms 1	2	3	Mean Expansion, %
7	0.000	0.001	0.000	0.000
14	0.002	0.004	0.001	0.002
28	0.003	0.001	0.001	0.002
56	0.002	0.004	0.002	0.003
91	-0.002	0.003	0.000	0.000
181	-0.003	0.003	0.000	0.000
273	0.001	0.004	0.004	0.003
364	0.014	0.008	0.012	0.011
413	0.019	0.011	0.017	0.016
490	0.024	0.017	0.021	0.021
558	0.020	0.017	0.018	0.018
623	0.027	0.022	0.024	0.024
704	0.031	0.027	0.027	0.028
775	0.031	0.028	0.026	0.028
819	0.033	0.029	0.029	0.030
900	0.036	0.035	0.030	0.034
963	0.038	0.033	0.032	0.034
1047	0.034	0.032	0.030	0.032
1102	0.036	0.036	0.034	0.035

Table 9. ASTM C 1293 Expansion for 20% Fly Ash A by Partial Substitution

Age, days	Expansion %, of Individual Prisms 1	2	3	Mean Expansion, %
7	0.003	0.002	0.001	0.002
14	0.005	0.003	0.003	0.004
28	0.004	0.002	0.001	0.002
56	0.002	0.000	0.000	0.001
91	-0.001	0.001	0.000	0.000
181	-0.002	0.001	-0.007	-0.003
273	0.000	0.004	-0.004	0.000
364	0.012	0.018	0.011	0.014
413	0.026	0.031	0.022	0.026
490	0.026	0.035	0.026	0.029
558	0.031	0.037	0.027	0.032
623	0.039	0.042	0.032	0.038
704	0.034	0.046	0.036	0.039
775	0.042	0.048	0.036	0.042
819	0.041	0.052	0.039	0.044
900	0.044	0.052	0.039	0.045
963	0.048	0.056	0.044	0.049
1047	0.047	0.055	0.044	0.049
1102	0.049	0.056	0.046	0.050

Table 10. ASTM C 1293 Expansion for 20% Fly Ash A by Addition

Age, days	Expansion %, of Individual Prisms			Mean Expansion, %
	1	2	3	
7	0.002	0.004	0.003	0.003
14	0.004	0.005	0.005	0.005
28	0.002	0.001	0.002	0.002
56	-0.001	-0.002	0.000	-0.001
91	0.001	0.002	-0.001	0.001
181	-0.001	0.004	-0.001	0.001
273	0.002	0.005	0.001	0.003
364	0.039	0.039	0.036	0.038
413	0.044	0.039	0.043	0.042
490	0.054	0.049	0.048	0.050
558	0.053	0.055	0.055	0.054
623	0.060	0.057	0.060	0.059
704	0.060	0.062	0.064	0.062
775	0.063	0.063	0.065	0.064
819	0.067	0.067	0.070	0.068
900	0.072	0.068	0.073	0.071
963	0.077	0.075	0.082	0.078
1047	0.078	0.072	0.075	0.075
1102	0.077	0.072	0.075	0.075

Table 11. ASTM C 1293 Expansion for 30% Fly Ash A by Substitution

Age, days	Expansion %, of Individual Prisms			Mean Expansion, %
	1	2	3	
7	0.002	0.001	0.001	0.001
14	0.003	0.003	0.001	0.002
28	0.002	0.001	0.000	0.001
56	-0.003	-0.001	-0.007	-0.004
91	-0.005	-0.001	-0.010	-0.005
181	-0.008	-0.001	-0.011	-0.007
273	-0.006	0.001	-0.010	-0.005
364	-0.004	0.011	0.000	0.002
413	-0.003	0.009	0.000	0.002
490	-0.002	0.014	0.002	0.005
558	0.001	0.018	0.005	0.008
623	0.001	0.019	0.009	0.010
704	0.003	0.021	0.011	0.012
775	0.005	0.025	0.014	0.015
819	0.006	0.024	0.016	0.015
900	0.008	0.026	0.019	0.018
963	0.009	0.025	0.022	0.019
1047	0.008	0.027	0.021	0.019
1102	0.010	0.029	0.023	0.021

Table 12. ASTM C 1293 Expansion for 30% Fly Ash A by Partial Substitution

Age, days	Expansion %, of Individual Prisms 1	2	3	Mean Expansion, %
7	-0.001	0.000	-0.001	-0.001
14	0.001	0.001	-0.003	0.000
28	0.001	0.002	-0.002	0.000
56	-0.007	-0.005	-0.010	-0.007
91	-0.003	-0.002	-0.003	-0.003
181	-0.004	0.006	-0.002	0.000
273	-0.002	0.008	0.003	0.003
364	0.001	0.011	0.017	0.010
413	0.003	0.012	0.009	0.008
490	0.003	0.014	0.014	0.010
558	0.011	0.015	0.021	0.016
623	0.009	0.016	0.021	0.015
704	0.007	0.018	0.019	0.015
775	0.011	0.021	0.025	0.019
819	0.011	0.021	0.025	0.019
900	0.011	0.023	0.027	0.020
963	0.014	0.025	0.035	0.025
1047	0.013	0.026	0.025	0.021
1102	0.014	0.030	0.028	0.024

Table 13. ASTM C 1293 Expansion for 30% Fly Ash A by Addition

Age, days	Expansion %, of Individual Prisms 1	2	3	Mean Expansion, %
7	0.001	0.000	0.001	0.001
14	0.002	0.002	0.002	0.002
28	0.001	0.000	0.001	0.001
56	-0.003	-0.006	-0.002	-0.004
91	-0.004	-0.006	-0.004	-0.005
181	-0.003	-0.006	-0.004	-0.004
273	-0.001	-0.002	0.000	-0.001
364	0.007	0.013	0.015	0.012
413	0.010	0.016	0.022	0.016
490	0.016	0.020	0.026	0.021
558	0.019	0.022	0.026	0.022
623	0.019	0.024	0.030	0.024
704	0.026	0.031	0.038	0.032
775	0.029	0.033	0.041	0.034
819	0.029	0.033	0.042	0.035
900	0.032	0.034	0.042	0.036
963	0.041	0.044	0.045	0.043
1047	0.036	0.035	0.040	0.037
1102	0.045	0.043	0.041	0.043

Table 14. ASTM C 1293 Expansion for 20% Fly Ash B by Substitution

Age, days	Expansion %, of Individual Prisms			Mean Expansion, %
	1	2	3	
7	0.003	0.001	0.004	0.003
14	0.006	0.003	0.007	0.005
28	0.002	0.001	0.003	0.002
56	-0.004	0.001	-0.005	-0.003
91	-0.010	-0.006	-0.015	-0.010
181	-0.008	-0.010	-0.013	-0.010
273	-0.004	-0.008	-0.011	-0.008
364	-0.002	-0.002	-0.008	-0.004
413	0.005	0.002	-0.002	0.002
490	0.005	0.005	-0.002	0.003
558	0.007	0.006	-0.001	0.004
623	0.010	0.007	0.003	0.007
704	0.014	0.011	0.005	0.010
775	0.015	0.011	0.005	0.010
819	0.016	0.014	0.006	0.012
900	0.018	0.014	0.009	0.014
963	0.020	0.015	0.011	0.015
1047	0.014	0.009	0.008	0.010
1102	0.017	0.014	0.011	0.014

Table 15. ASTM C 1293 Expansion for 20% Fly Ash B by Partial Substitution

Age, days	Expansion %, of Individual Prisms			Mean Expansion, %
	1	2	3	
7	0.003	0.005	0.003	0.004
14	0.005	0.008	0.005	0.006
28	0.003	0.003	0.002	0.003
56	0.005	0.000	0.000	0.002
91	0.003	-0.002	-0.002	0.000
181	0.000	-0.003	-0.003	-0.002
273	-0.003	0.000	-0.001	-0.001
364	-0.002	0.004	0.006	0.003
413	0.001	0.012	0.012	0.008
490	0.002	0.015	0.015	0.011
558	0.003	0.015	0.016	0.011
623	0.006	0.016	0.017	0.013
704	0.006	0.021	0.020	0.016
775	0.007	0.017	0.023	0.016
819	0.007	0.019	0.025	0.017
900	0.009	0.020	0.026	0.018
963	0.011	0.024	0.030	0.022
1047	0.002	0.023	0.024	0.016
1102	0.013	0.023	0.032	0.023

Table 16. ASTM C 1293 Expansion for 20% Fly Ash B by Addition

Age, days	Expansion %, of Individual Prisms			Mean Expansion, %
	1	2	3	
7	0.005	0.005	0.004	0.005
14	0.008	0.008	0.008	0.008
28	0.008	0.007	0.006	0.007
56	0.002	0.002	-0.002	0.001
91	0.001	0.002	-0.003	0.000
181	0.001	0.002	-0.004	0.000
273	0.000	0.001	-0.003	-0.001
364	0.022	0.025	0.002	0.016
413	0.027	0.029	0.007	0.021
490	0.031	0.031	0.008	0.023
558	0.032	0.032	0.009	0.024
623	0.035	0.037	0.012	0.028
704	0.042	0.038	0.018	0.033
775	0.040	0.038	0.018	0.032
819	0.041	0.039	0.021	0.034
900	0.044	0.039	0.018	0.034
963	0.046	0.041	0.022	0.036
1047	0.042	0.038	0.017	0.032
1102	0.044	0.043	0.021	0.036

Table 17. ASTM C 1293 Expansion for 30% Fly Ash B by Substitution

Age, days	Expansion %, of Individual Prisms			Mean Expansion, %
	1	2	3	
7	0.000	-0.001	0.002	0.000
14	0.002	0.000	0.004	0.002
28	0.000	-0.001	0.002	0.000
56	-0.002	-0.003	-0.001	-0.002
91	-0.003	-0.003	-0.001	-0.002
181	-0.003	0.001	-0.001	-0.001
273	0.000	0.005	0.003	0.003
364	0.004	0.003	0.011	0.006
413	0.009	0.009	0.013	0.010
490	0.012	0.013	0.015	0.013
558	0.012	0.013	0.015	0.013
623	0.012	0.014	0.015	0.014
704	0.020	0.018	0.023	0.020
775	0.016	0.017	0.020	0.018
819	0.019	0.018	0.020	0.019
900	0.020	0.019	0.018	0.019
963	0.020	0.024	0.022	0.022
1047	0.019	0.020	0.022	0.020
1102	0.022	0.020	0.023	0.022

Table 18. ASTM C 1293 Expansion for 30% Fly Ash B by Partial Substitution

Age, days	Expansion %, of Individual Prisms 1	2	3	Mean Expansion, %
7	0.002	0.000	0.001	0.001
14	0.004	0.002	0.003	0.003
28	0.002	0.000	0.000	0.001
56	0.000	-0.001	-0.015	-0.005
91	-0.001	-0.003	-0.019	-0.008
181	-0.001	-0.004	-0.019	-0.008
273	0.001	-0.003	-0.020	-0.007
364	0.014	0.012	-0.013	0.004
413	0.014	0.015	-0.014	0.005
490	0.020	0.017	-0.007	0.010
558	0.022	0.017	-0.007	0.011
623	0.023	0.017	-0.004	0.012
704	0.024	0.020	0.002	0.015
775	0.024	0.020	0.005	0.016
819	0.025	0.022	0.002	0.016
900	0.023	0.019	0.003	0.015
963	0.029	0.023	0.010	0.021
1047	0.028	0.023	0.007	0.019
1102	0.029	0.024	0.006	0.020

Table 19. ASTM C 1293 Expansion for 30% Fly Ash B by Addition

Age, days	Expansion %, of Individual Prisms 1	2	3	Mean Expansion, %
7	-0.001	0.001	0.001	0.000
14	0.001	0.004	0.003	0.003
28	-0.001	0.001	0.001	0.000
56	-0.002	-0.002	-0.003	-0.002
91	-0.001	-0.003	-0.003	-0.002
181	-0.001	0.002	-0.003	-0.001
273	0.003	0.008	0.001	0.004
364	0.024	0.020	0.015	0.020
413	0.026	0.023	0.021	0.023
490	0.031	0.024	0.026	0.027
558	0.034	0.029	0.031	0.031
623	0.038	0.029	0.030	0.032
704	0.043	0.031	0.035	0.036
775	0.040	0.036	0.032	0.036
819	0.039	0.042	0.038	0.040
900	0.040	0.038	0.037	0.038
963	0.047	0.041	0.042	0.043
1047	0.038	0.034	0.033	0.035
1102	0.040	0.040	0.035	0.038

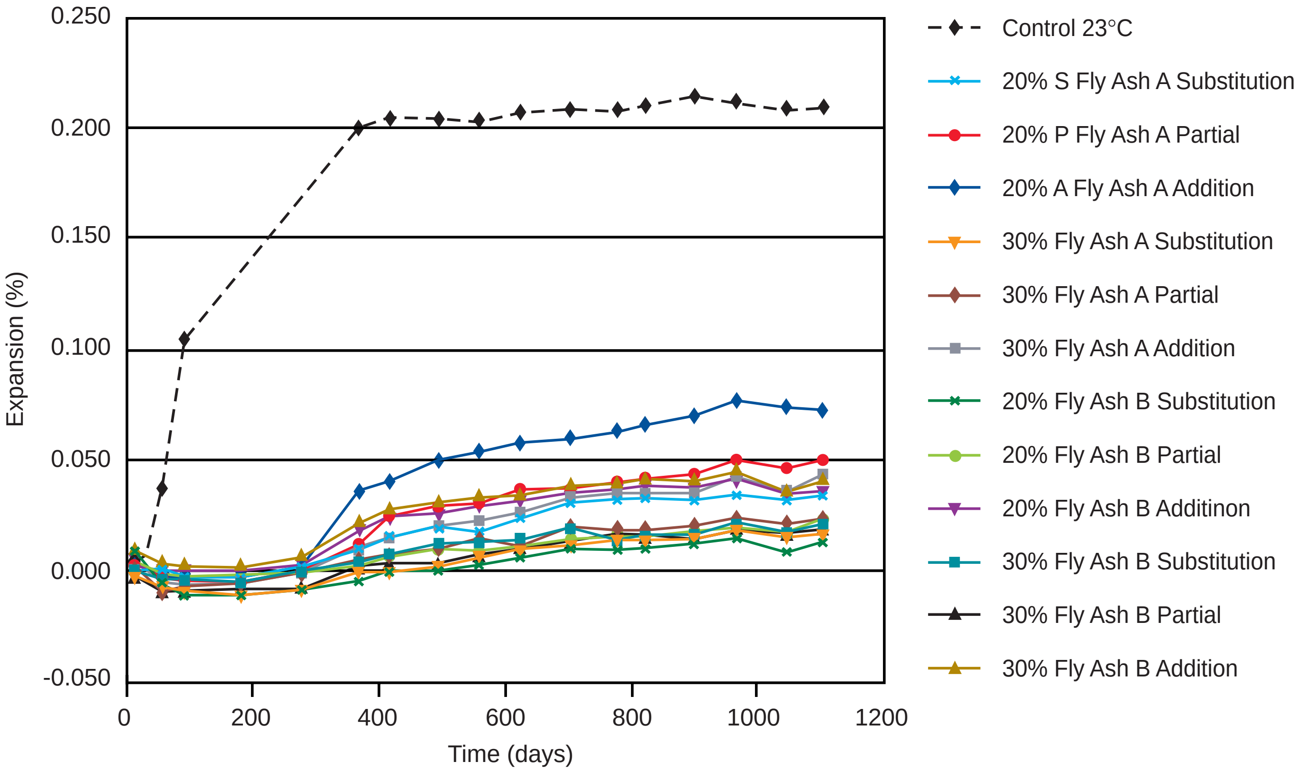

Figure 3. ASTM C 1293 expansion data for all of the concretes. While all fly ash combinations reduced the expansion due to the reactivity of the Spratt aggregate by between 65 and 90%, not all met the criterion of 0.04% expansion in two years.

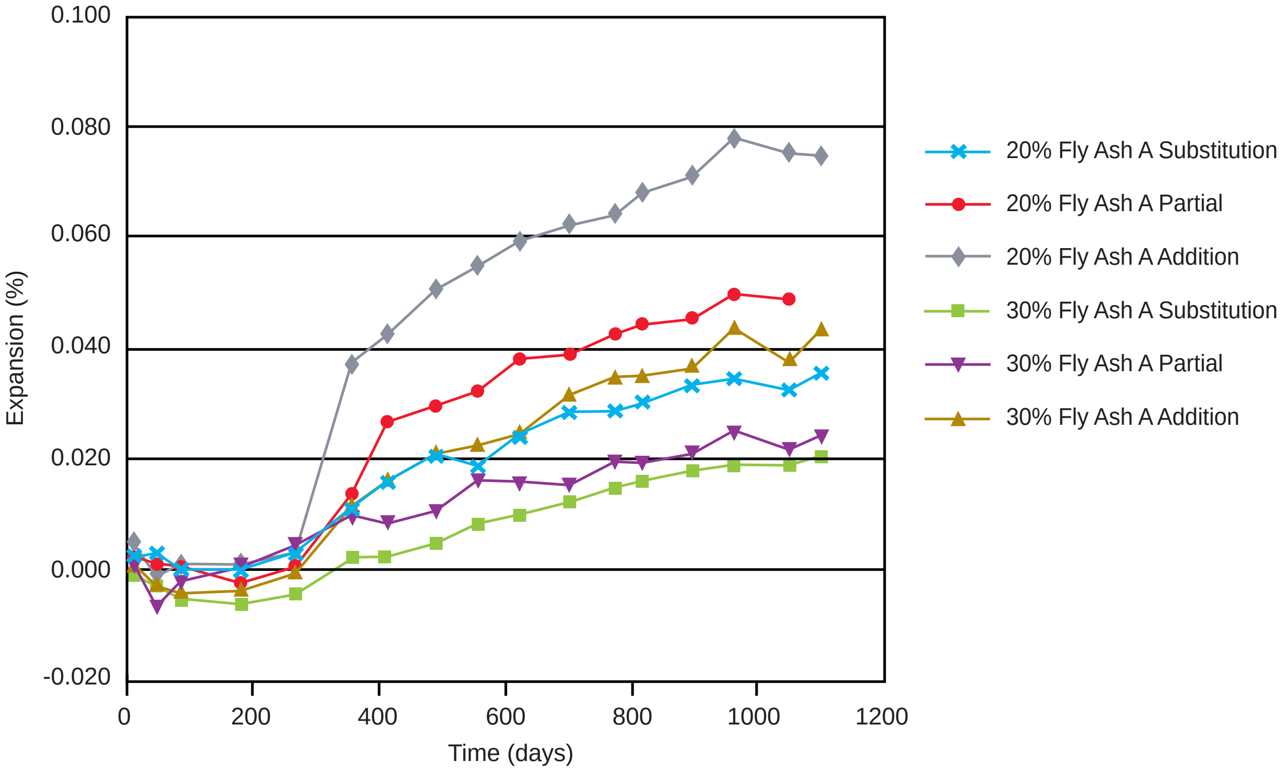

Figure 4. ASTM C 1293 expansion data for Fly Ash A concretes. All of the combinations containing Fly Ash A suppressed the expansion to less than 0.04% in two years except the 20% addition. However, the expansion for the 20% partial substitution had not levelled off by then, indicating that this combination may not be entirely acceptable either. The best results were attained by the concretes containing 30% fly ash by substitution or partial substitution. The concrete with 20% fly ash by substitution also performed well.

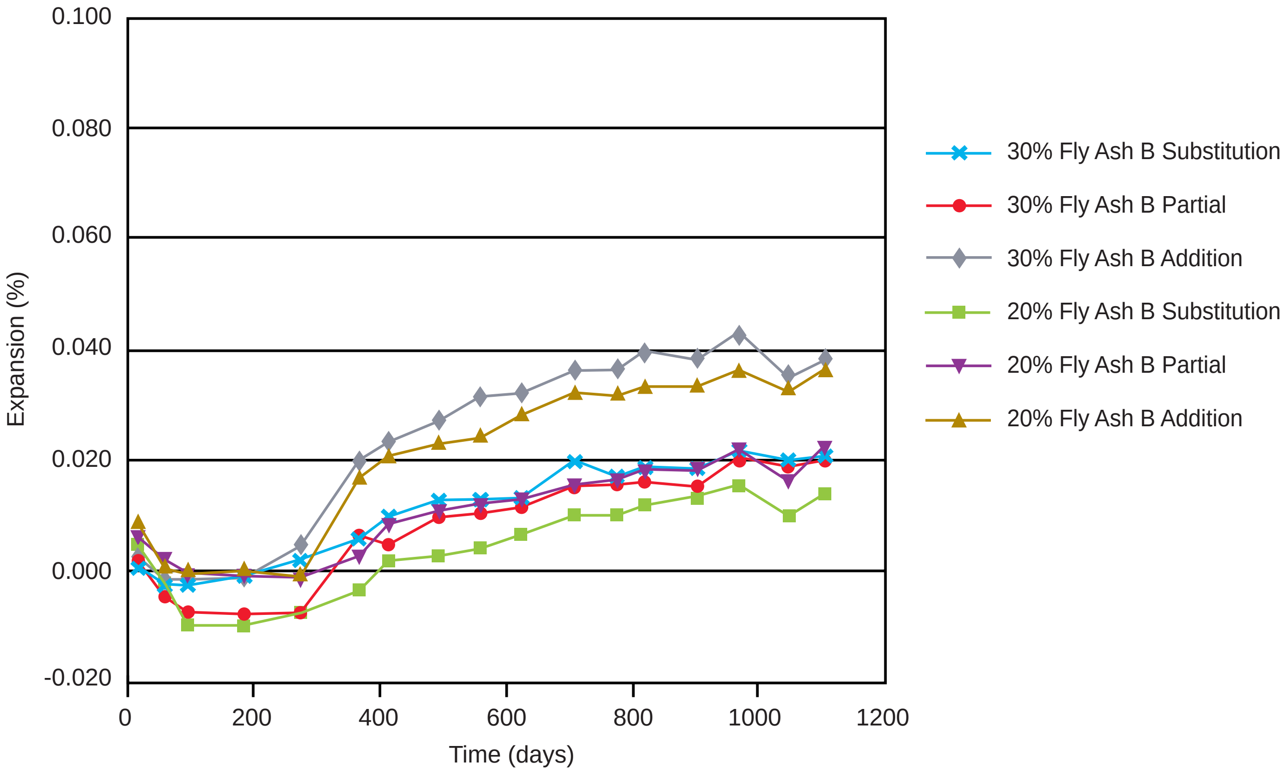

Figure 5. ASTM C 1293 expansion data for Fly Ash B concretes. All of the combinations containing Fly Ash B suppressed the expansion to less than 0.04% in two years. By the end of three years, the expansions appear to have stopped increasing. For this fly ash, the concretes containing 20% or 30% fly ash by substitution or partial substitution performed the best. Note that Fly Ash B increased the water demand of the concrete.

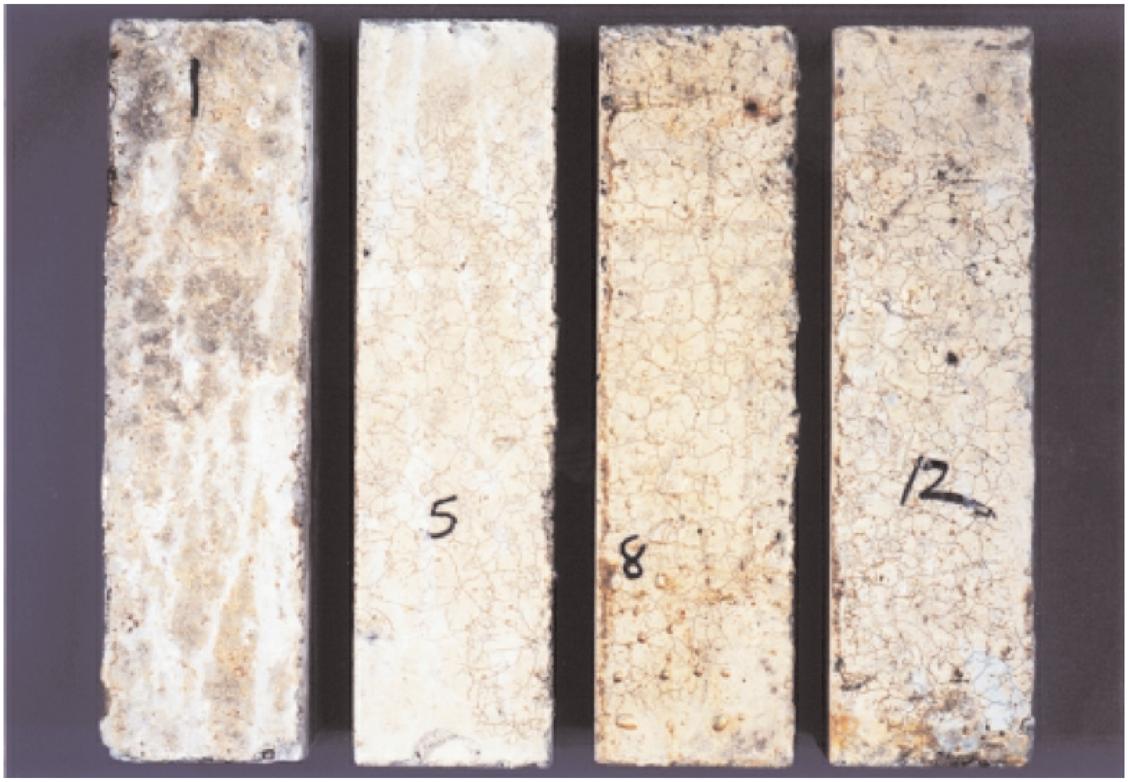

Figure 6. The control specimen (#1) and specimens containing 20% Fly Ash A by substitution (#5), partial substitution (#8), and addition (#12) after three years' testing all show the cracking characteristic of alkali-silica reaction.

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