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Preventive measures for alkali-silica reactions (binary and ternary systems)

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Abstract

Efforts to prevent alkali-silica reactions (ASR) in Virginia transportation facilities have focused on the selection of ASR-resistant cementitious materials. Initial evaluations of binary systems of ordinary portland cement (OPC) with pozzolans or slag in mortars with Pyrex glass aggregate suggested that high replacement levels of OPC with fly ash or slag could be necessary for ASR resistance. Concern that such high replacement levels could negatively impact early strengths prompted evaluations of concretes with construction aggregates. Concretes were produced with binary and ternary (OPC + silica fume + fly ash or slag) systems and evaluated for strength, transport properties, and ASR resistance. The results illustrate how ternary blends can be used to reduce transport properties or increase ASR resistance of concretes with low replacement levels of fly ash or slag and thus avoid low early strength problems.

Keywords: Alkali-aggregate reaction; Fly ash; Ground blast furnace slag; Silica fume

1. Introduction

Over the last 15 to 20 years, the Virginia Transportation Research Council (VTRC) has identified a number of structures and pavements exhibiting distress resulting from alkali-silica reaction (see Figs. 1–3) [1]. The reactive constituent in the affected aggregates, which include natural sands and gravels as well as crushed metamorphic rocks, is microcrystalline, strained or highly fractured quartz. Attempts to classify aggregates according to their potential for deleterious alkali-silica reactions (ASR) using ASTM C 227 and C 1260 (P214) were unsuccessful. Aggregates with known field histories of ASR have yielded 14-day expansions ranging from 0.07 to 0.4 percent in C 1260, while recommended criteria suggest that aggregates expanding less than 0.10% are innocuous. The focus of preventive measures consequently shifted to the cementitious materials.

The effectiveness of pozzolans and ground-granulated blast furnace slag in mitigating ASR have been discussed in the literature and these materials were readily available and in use for economic reasons. It was recognized that these materials were quite effective in producing concretes with low transport properties, and thus offered protection against chloride-induced corrosion of reinforcement as well. Hadley [2] and Ozol [3] have investigated field occurrences of ASR in which the overall alkali loading of the concretes did not seem to be high enough to trigger the distress exhibited. They attributed the observed problems to internal migration with resulting concentration of alkalies within the mass by severe wetting-drying cycles and stray electrical currents respectively. Xu and Hooton [4] experimentally demonstrated the migration and concentration of alkalies by moisture gradients and electrical potential differences. Consequently, matrices with low transport properties can be considered to have a positive effect on ASR resistance by reducing the potential for ionic ingress, migration, and concentration within the concrete mass.

Initial evaluation of materials was conducted using ASTM C 441 on ordinary portland cements (OPCs) with Class F fly ash, slag, or silica fume [5]. The results illustrated the effectiveness of the mineral admixtures in reducing ASR and established minimum amounts needed to mitigate cements of a given alkali level (see Fig. 4). With higher alkali cements, the minimum for fly ash (30%) and slag (50%) approached levels that might present construction difficulties with respect to early strength gain in cool weather. C 441 tests are conducted using crushed Pyrex glass no. 7740 as aggregate. This material is considerably more reactive than the reactive constituents present in Virginia aggregates. Consequently, tests were conducted on concretes containing a highly reactive Virginia aggregate

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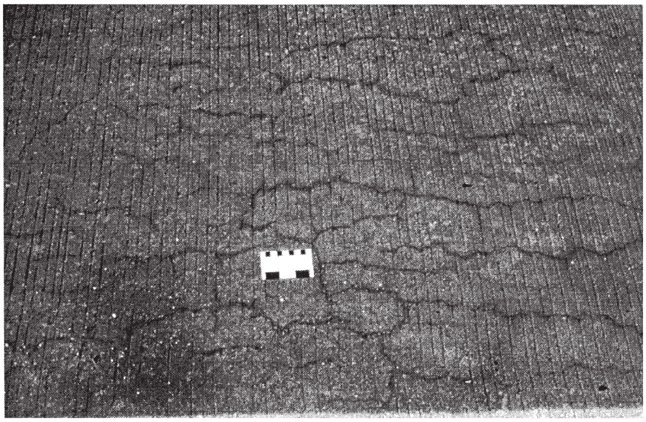

Fig. 1. Continuously reinforced concrete pavement exhibiting ASR distress. Coarse aggregate is Hylas crushed stone, fine aggregate is natural siliceous sand; both evidence reactivity.

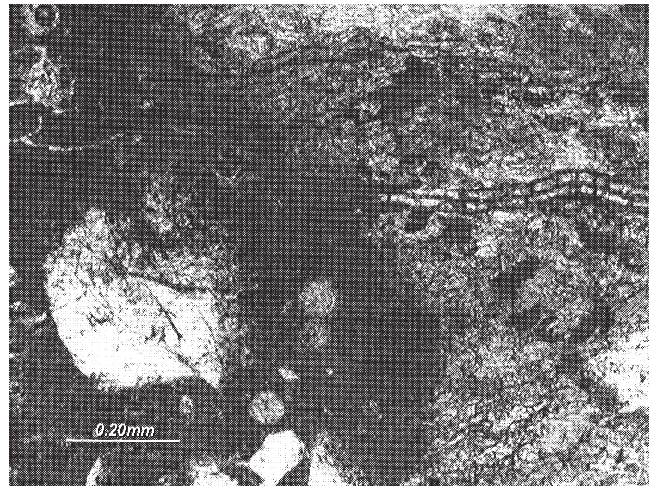

Fig. 3. Thin section of pavement shown in Fig. 1. The crack in Hylas particle is filled with reaction product and extends through the paste.

with the premise that such tests would provide a more realistic appraisal of the mitigative effects of cementitious materials. Tests were conducted on binary (OPC + fly ash, OPC + slag, OPC + silica fume) and ternary (OPC + fly ash + silica fume; OPC + slag + silica fume) cementitious blends. Properties evaluated include strength, permeability, and resistance to ASR.

2. Methods

Concretes were proportioned with a cementitious materials content of 377 kg/m^3, a water-to-cementitious materials ratio of 0.45 and an air content of 6.5 ± 1.5%. The coarse aggregate content was 1015 kg/m^3 and the fine aggregate content of the OPC concrete was 684 kg/m^3, with adjustments made in the fine aggregate content when pozzolans or slag were used. Pozzolans and slag were used in various mixtures to replace OPC on a percent by mass basis. Chemical parameters for the cementitious materials are shown in Table 1. The coarse aggregate used in the concretes is a crushed metarhyolite from Hylas; the fine aggregate is a natural siliceous sand from Richmond. Both aggregates have been associated with deleterious alkali-silica reactivity in concrete structures [1]. The metarhyolite yields C 1260 14-day expansions of 0.39% and the sand a value of 0.19%. The metarhyolite was selected for use in these tests because its C 1260 results are the highest encountered thus far in testing Virginia aggregates and consequently is presumed to be the one of the most highly alkali-silica reactive aggregates commonly used in Virginia.

2.1. Strength and electrical resistance

The compressive strength of mixtures was determined on 100 × 200-mm specimens moist-cured at 23°C for 3, 7, 28,

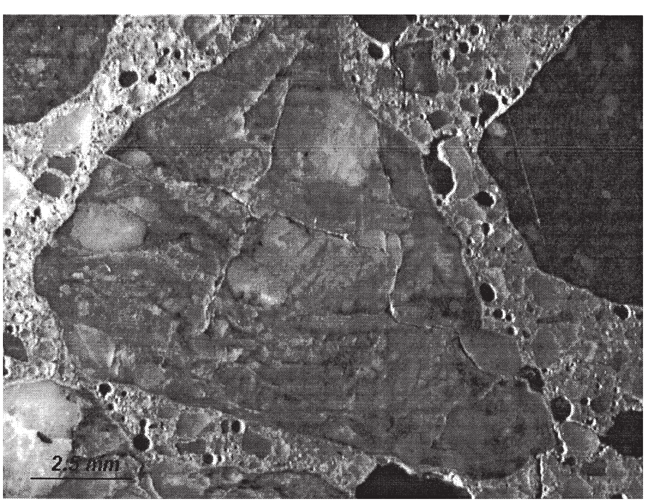

Fig. 2. Reacted Hylas particle in a lapped section from pavement shown in Fig. 1.

Table 1
Chemical analysis of cementitious materials

	OPC	Fly ash	Slag	Silica fume
SiO_2	20.4	53.0	37.6	94.6
Al_2O_3	4.9	31.3	3.3	0.3
Fe_2O_3	2.0	5.6	0.4	0.1
CaO	62.3	1.0	17.6	0.5
MgO	3.9	0.5	11.2	0.4
SO_3	3.32	0.54	1.94	–
Na_2O	0.24	0.22	0.22	0.15
K_2O	1.03	1.73	0.34	0.56
Na_2Oeq	0.92	1.35	0.44	0.25
C_3S	52.8	–	–	–
C_2S	18.8	–	–	–
C_3A	9.6	–	–	–
C_4AF	6.2	–	–	–
LOI	2.0	1.5	–	–
Blaine (m^2/kg)	403	–	540	–

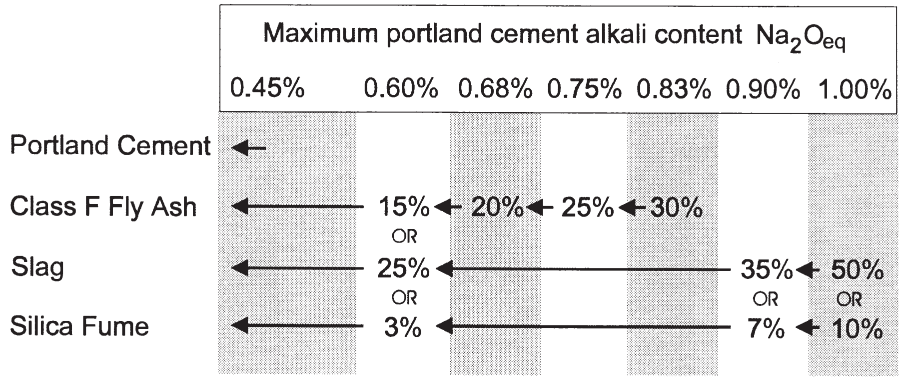

Fig. 4. Replacement levels of pozzolans or slag needed to meet 0.10% 56-day expansion limit in C 441 tests.

56 days, and 1 year. Electrical resistance of the concrete mixtures was determined on 100 × 100-mm specimens using the C 1202 test. High electrical resistance in this test is considered to indicate low transport properties of the concrete. Electrical resistance specimens were cured moist at 23°C and tested at 28 days and 1 year. An additional set of specimens was subjected to an accelerated curing used to indicate 1-year values at 28 days [6]. The accelerated curing consists of 7 days moist at 23°C followed by 21 days moist at 38°C.

2.2. ASR resistance

Concretes for evaluating ASR resistance were proportioned as above except that they were not air-entrained and a fixed amount of NaOH was introduced in the mixing water. The amount of NaOH added was that necessary to raise the alkali content of the OPC (0.90% Na_2Oeq) concrete to 4.7 kg/m^3, equivalent to using an OPC with an alkali content of 1.25% Na_2Oeq. The same amount of NaOH was added to each batch, regardless of actual OPC content.

Three 75 × 280-mm length change specimens were fabricated from each batch. Specimens were stored and measured following C 1293 procedures. Storage conditions were over water at 38°C and length change measurements were made at 3, 6, 12, 18, and 24 months.

3. Results and discussion

The compressive strength results are summarized in Fig. 5. The data illustrate that in binary systems, higher amounts of

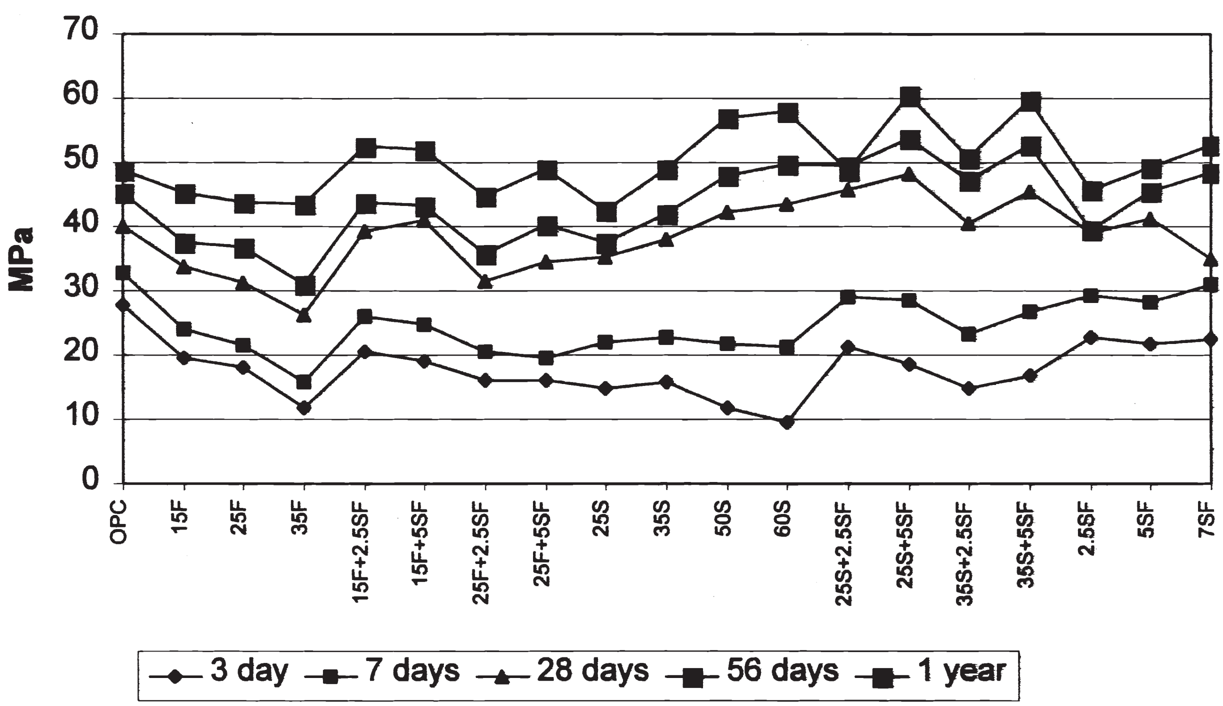

Fig. 5. Compressive strength of concretes.

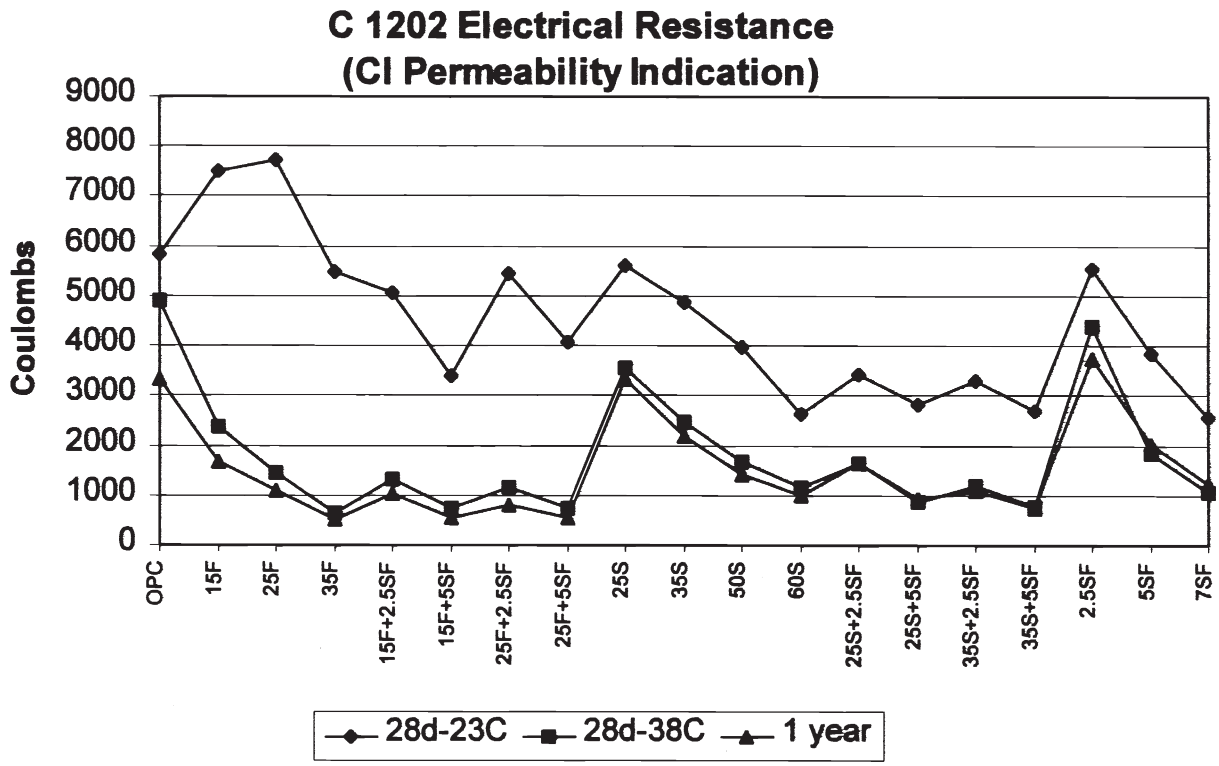

Fig. 6. Electrical resistance (C 1202) of concretes.

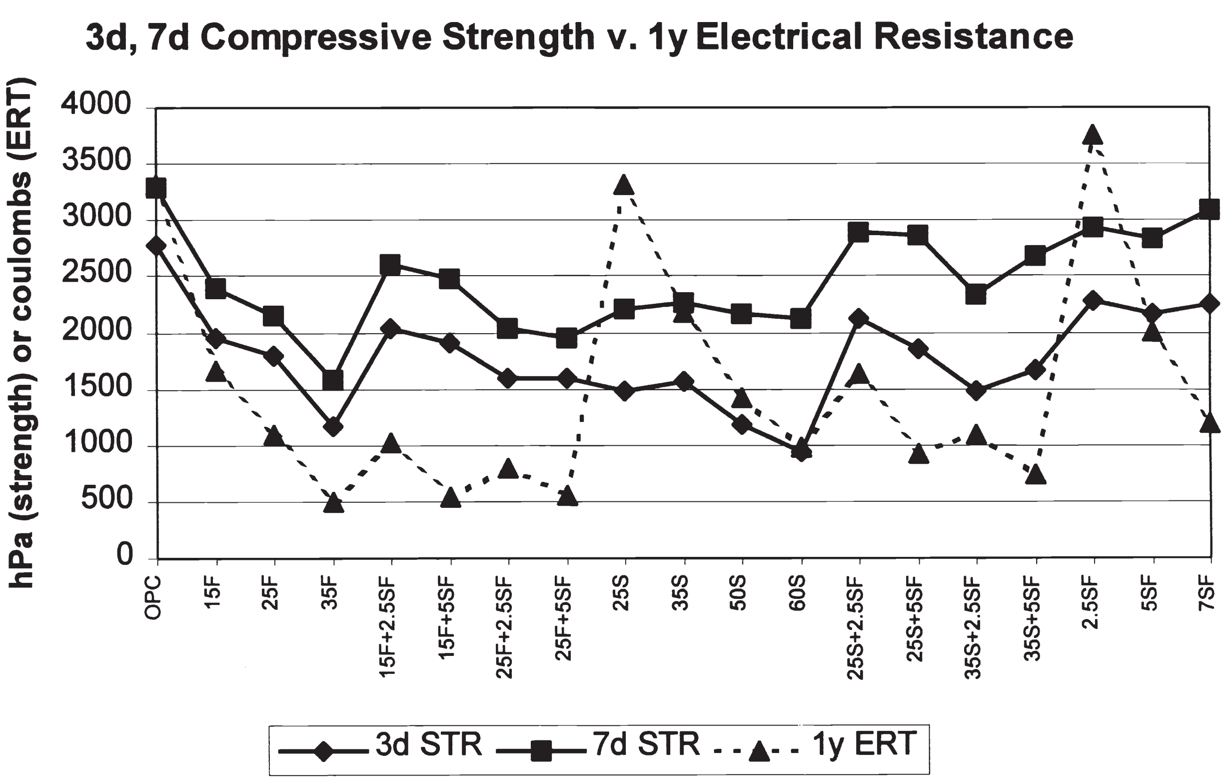

Fig. 7. Compressive strength (at 3 and 7 days) and electrical resistance (at 1 year) of concretes.

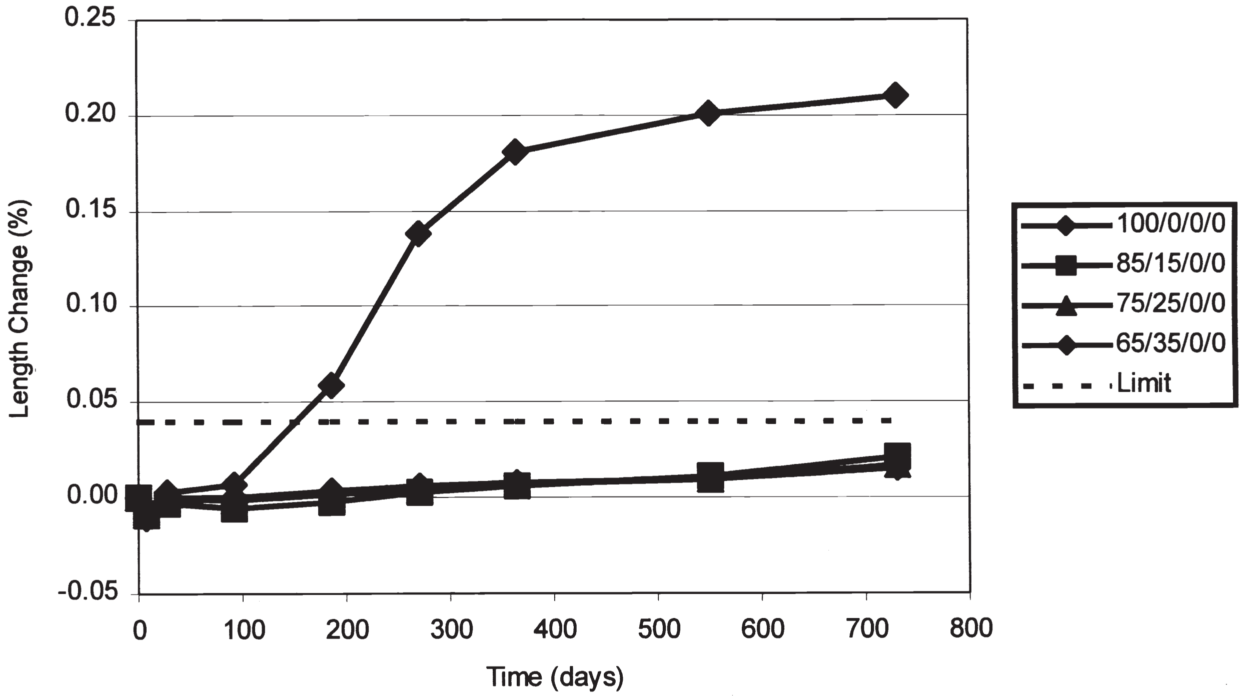

Fig. 8. ASR expansion results for fly ash-OPC concretes (OPC/fly ash/silica fume/slag).

fly ash or slag can result in decreased strengths at early ages. For the fly ash used in these tests, this adverse effect carried through 56 days as a consequence of the slow hydrating phases in the fly ash. However, by 1 year, the depression in strength level resulting from high amounts of fly ash had dissipated. In the slag concretes, early strength depression was overcome between 7 and 28 days.

Fig. 4 illustrates how the use of C 441 results with a particular criterion (0.10% expansion at 56 days) can require high replacement levels of fly ash or slag that can result in low early strengths. Concretes with such strength-gain characteristics can have an adverse impact on the construction process. Consequently, the concept of ternary blends (wherein small amounts of silica fume are used to augment the characteristics of concretes with lower amounts of fly ash or slag than would otherwise be needed) was developed.

Fig. 6 provides an indication of transport properties based on C 1202 electrical resistance measurements. The

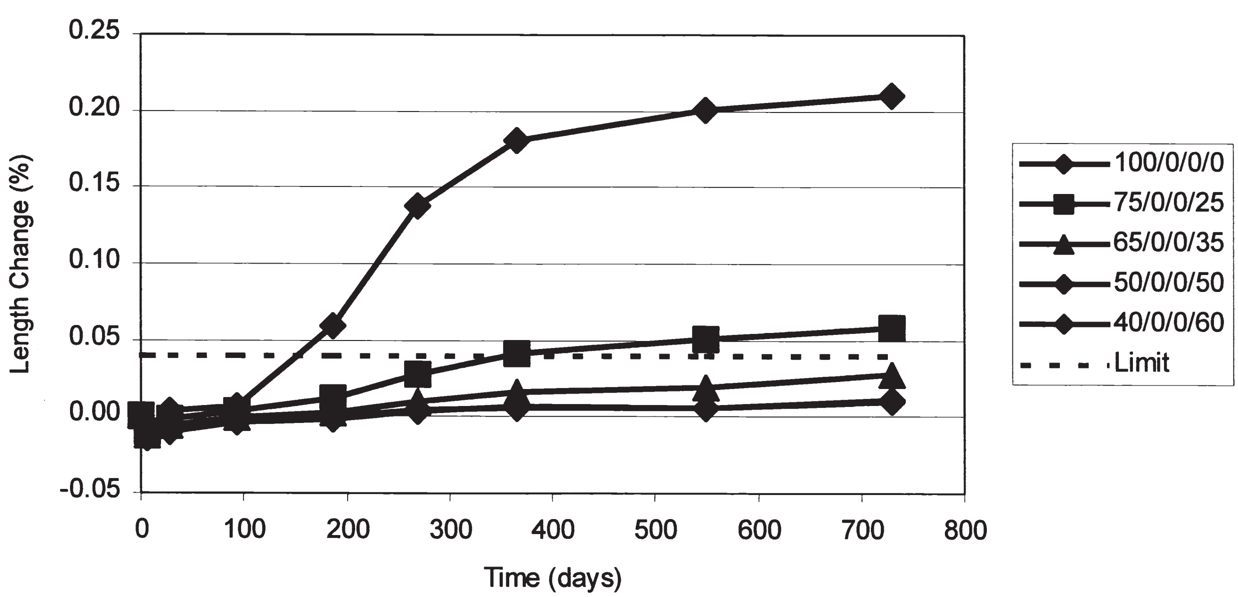

Fig. 9. ASR expansion results for slag-OPC concretes (OPC/fly ash/silica fume/slag).

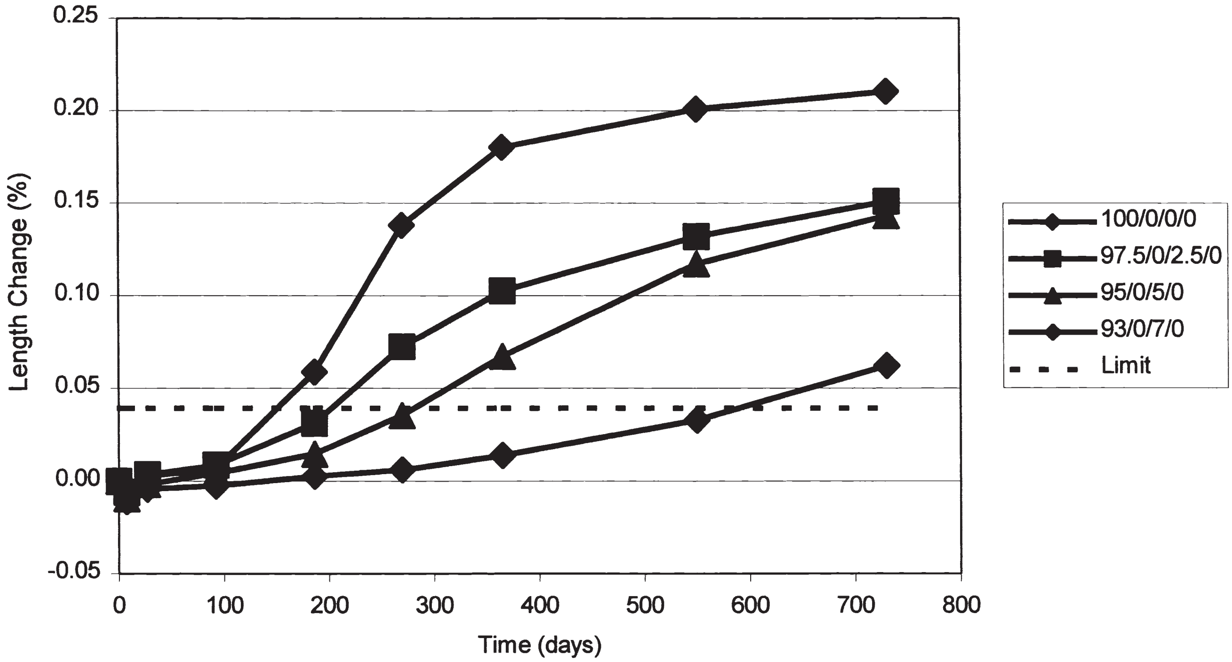

Fig. 10. ASR expansion results for silica fume-OPC concretes (OPC/fly ash/silica fume/slag).

figure illustrates that the accelerated curing procedure [6] provides a good indication of the later age transport properties at 28 days. The accelerated curing and 1-year results show that in the binary systems, increasing amounts of pozzolans or slag result in increasing electrical resistance. Electrical resistance equivalent to that obtained in binary systems with 35% fly ash or 60% slag can be obtained in ternary systems in which 5% silica fume is combined with 15% fly ash or 25% slag.

The relationship between early strength and later-age

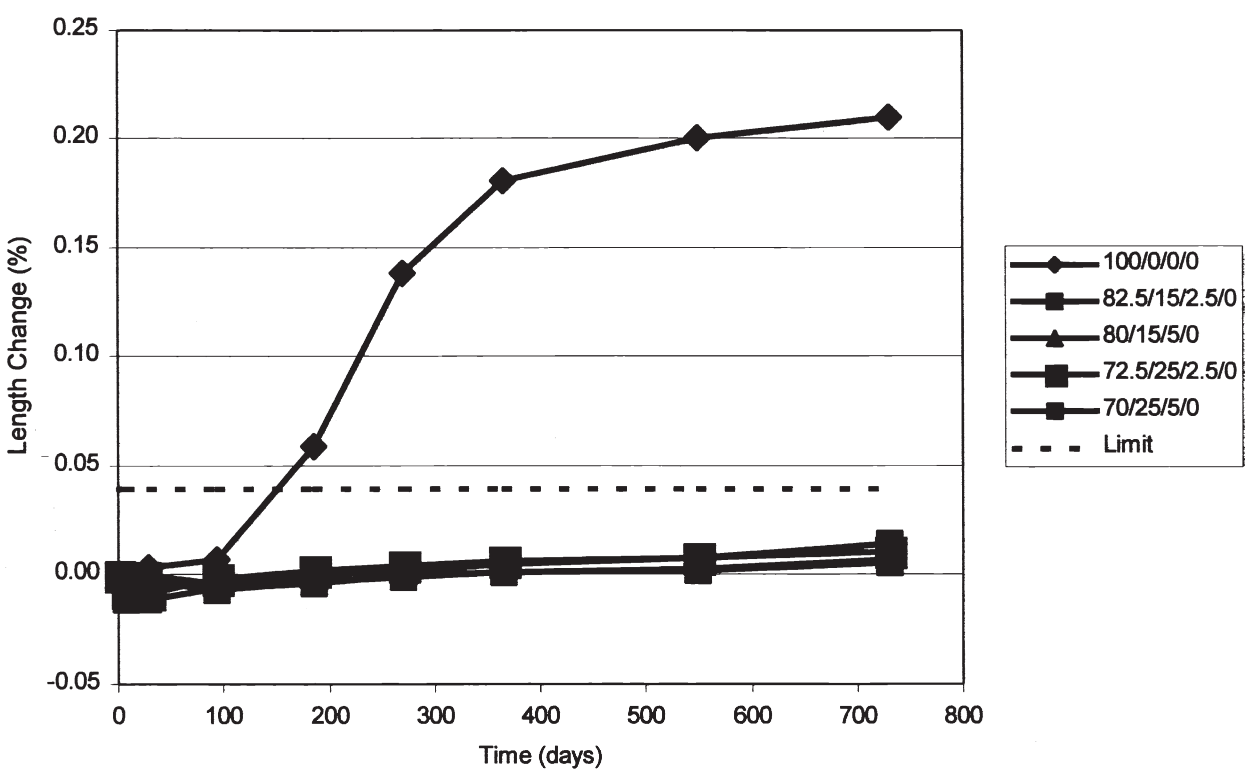

Fig. 11. ASR expansion results for ternary-blended fly ash concretes (OPC/fly ash/silica fume/slag).

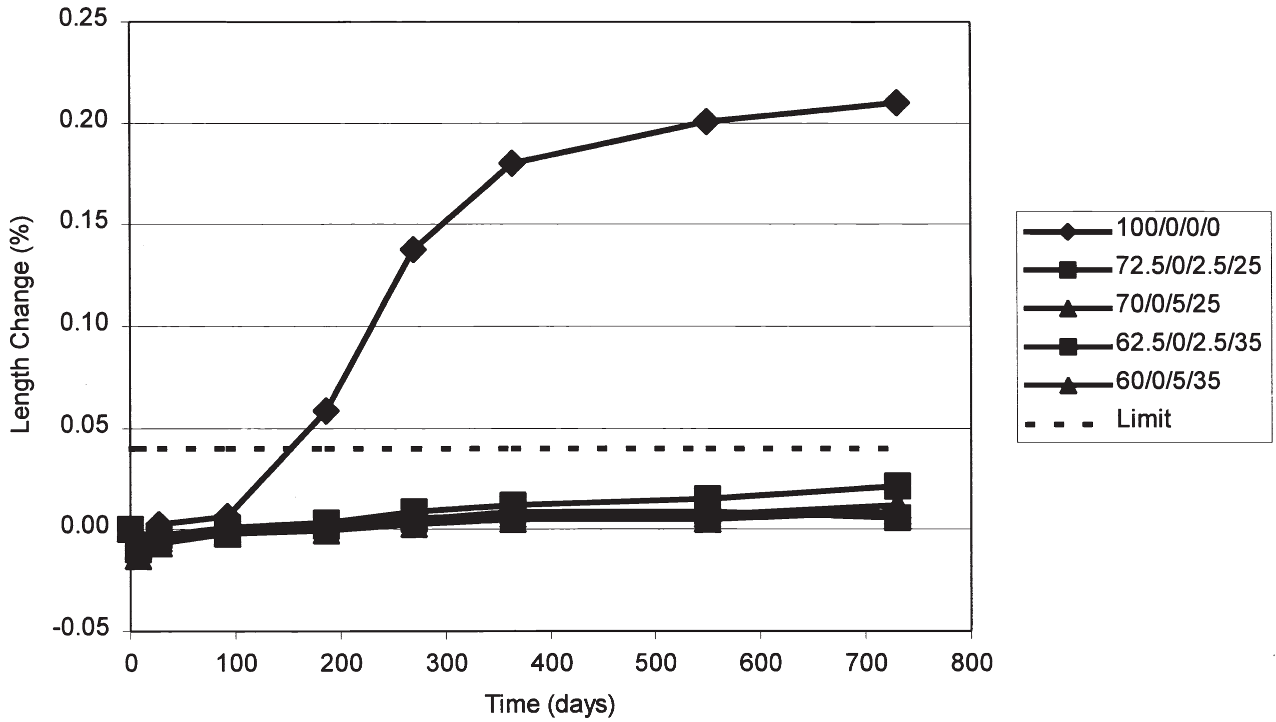

Fig. 12. ASR expansion results for ternary-blended slag concretes (OPC/fly ash/silica fume/slag).

electrical resistance of the concretes is shown in Fig. 7 in which 3- and 7-day strengths are plotted with 1-year electrical resistance. The ternary systems provide low transport properties without the negative impact of low early strength encountered in binary systems with fly ash or slag.

The C 1293 results for binary systems are shown in Figs. 8–10. Using a criterion of 0.04% maximum expansion [7] at 2 years, they indicate that 15% fly ash and 35% slag are the minimum amounts necessary in binary blends to control the reactivity of the aggregate. Silica fume at the maximum dosage of 7% was not effective in this test. These results suggest that lower amounts than are suggested by C 441 testing of fly ash or slag can effectively control the reactivity of Virginia aggregates. Conversely, silica fume did not perform as well in the C 1293 tests. The contrasting results obtained between the two tests may be reflective of differences in the method of acceleration used. C 441 relies on the rapidly reactive Pyrex glass, which may discount the effectiveness of slower hydrating fly ashes and slag, while C 1293 elevates alkali content with NaOH, which may overwhelm the small amount of silica fume used. Another consideration regarding the performance of the silica fume in binary blends is that no high range water-reducer was used, which may have resulted in insufficient dispersion of the particles for maximum effectiveness.

The C 441 approach may be considered to be conservative, and thus represents a minimal tolerance for potential reactivity. The C 1293 approach is perhaps more rational since it tests the aggregates proposed for use, but at this point the connection between test criterion and service prediction is not clearly defined.

The results of C 1293 tests on ternary systems are presented in Figs. 11 and 12. With sole respect to ASR resistance as measured by C 1293, little benefit is achieved from ternary blends containing fly ash. However, ternary-blended fly ash concretes containing small amounts of silica fume have increased electrical resistance and thus improved transport properties over binary blends with low fly ash contents. In the ternary slag concretes, 2.5 and 5% silica fume greatly improved the ASR resistance. As with the fly ash ternary blends, the ternary slag concretes had greatly reduced electrical resistance compared to binary blends with the same slag content; again with positive implications for improved durability.

4. Conclusions

Binary concretes with OPC and pozzolan or slag can be proportioned to provide resistance to ASR, but the specific proportions needed for a given situation depend on the evaluation method used. Using a conservative approach can require high replacement levels of fly ash or slag in binary systems. These high replacement levels produce concretes with very high electrical resistance, implying excellent overall durability, but at the cost of low early strength and potential construction problems. A more liberal approach suggests lower fly ash or slag contents can provide adequate ASR resistance, but such concretes posses lower electrical resistance than their higher replacement level counterparts. Incorporating small amounts of silica fume with OPC and fly ash or slag in ternary systems can be used to counterbalance the negative effect of high fly ash or slag replacement level on early strength and low replacement level on durability.

References

[1] D.S. Lane, Alkali-silica reactivity in Virginia, VTRC 94-R17, Charlottesville, VA, 1994.

[2] D.W. Hadley, Field and laboratory studies on the reactivity of sand-gravel aggregates, Journal of the PCA Research and Development Laboratories 10 (1968) 17–33.

[3] M.A. Ozol, Alkali silica reaction of concrete in electrical substation piers accelerated by electric current, STP 1061, Petrography Applied to Concrete and Concrete Aggregates, B. Erlin, D. Stark (Eds.), ASTM, 1990. pp. 106–120.

[4] Z. Xu, R.D. Hooton, Migration of alkali ions in mortar due to several mechanisms, Cem Concr Res 23 (1993) 951–961.

[5] D.S. Lane, C. Ozyildirim, Use of fly ash, slag, or silica fume to inhibit alkali-silica reactivity, VTRC 95-R21, Charlottesville, VA, 1995.

[6] C. Ozyildirim, Effects of temperature on the development of low permeability in concretes, VTRC 98-R14, Charlottesville, VA, 1998.

[7] M.D.A. Thomas, R.D. Hooton, C. Rogers, Prevention of damage due to alkali-aggregate reactions (AAR) in concrete construction—Canadian approach, Cement, Concrete, and Aggregates 19 (1) (1997) 26–30.