FINAL REPORT

COMBINATIONS OF POZZOLANS AND GROUND, GRANULATED, BLAST-FURNACE SLAG FOR DURABLE HYDRAULIC CEMENT CONCRETE

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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ABSTRACT

Hydraulic cement concretes were produced using pozzolans and ground, granulated, blast-furnace slag (slag) to investigate the effect of these materials on durability. The pozzolans used were an ASTM C 618 Class F fly ash with a low lime content and a dry, densified silica fume. The slag was an ASTM C 989 Grade 120 material. Concretes with a fixed cementitious materials content of 377 kg/m^3 and water-to-cementitious materials ratio (w/cm) were produced with an ASTM C 150 Type I/II cement and pozzolans or slag. The following replacement levels were used: fly ash: 0, 15, 25, and 35 percent; silica fume: 2.5, 5, and 7 percent; and slag: 25, 35, 50, and 60 percent. Concretes were also produced by combining small amounts of silica fume with small amounts of fly ash or slag.

The concretes were evaluated for strength, electrical resistance (ionic transport, permeability), drying shrinkage, resistance to freezing and thawing, and resistance to alkali-silica reaction (ASR)-related expansions. Early-age strengths and resistance to freezing and thawing were compromised by high replacement levels of fly ash or slag, although the use of a constant w/cm may have exaggerated these responses.

Concrete durability, as indicated by electrical resistance and resistance to ASR, was greatly improved by increasing the pozzolan or slag content. Use of ternary blends produced the desired property levels while maintaining the necessary durability characteristics.

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INTRODUCTION

Over the last 15 to 20 years, the Virginia Transportation Research Council has identified two primary mechanisms that have caused premature deterioration of concrete structures and pavements in Virginia. They are alkali-silica reaction (ASR) of aggregates (Lane, 1994) and chloride-induced corrosion of steel reinforcement. With regard to ASR, the reactive constituent in the affected aggregates is predominantly microcrystalline, strained, or highly fractured quartz. The affected rock types range from quartzose natural sands and gravels to a variety of crushed metamorphic rocks. Attempts to classify aggregates according to their potential for deleterious ASR using ASTM C 227 and C 1260 (P214) were unsuccessful; therefore, the focus of ASR preventive measures consequently shifted to the cementitious materials (Lane, 1994).

The effectiveness of pozzolans and ground granulated blast-furnace slag in mitigating ASR have been discussed in the literature (Thomas, 1996). These materials were readily available and in use for economic reasons. Because pozzolans and slag are also quite effective in producing concrete matrices with low ionic-transport properties, they also provide protection against chloride-induced corrosion of reinforcement. Concrete with low ionic-transport properties has direct relevance to ASR-resistance.

Hadley (1968) and Ozol (1990) have investigated field occurrences of ASR in structures 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 the internal concentration of alkalies. This phenomenon was attributed to severe wetting-drying cycles and stray electrical currents respectively. Xu and Hooton (1993) experimentally demonstrated that migration and concentration of alkalies can be caused 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.

The initial thrust by the Virginia Department of Transportation (VDOT) to require the use of pozzolans or slag in concrete was driven by the effort to prevent ASR. Specification revisions were based on an evaluation of materials conducted using ASTM Test Method C 441 on portland cements (PC) with Class F fly ash, slag, or silica fume (Lane and Ozyildirim, 1995). The results illustrate the effectiveness of the mineral admixtures in reducing ASR expansions and were used to establish minimum amounts needed to mitigate cements of a given alkali level. With higher alkali cements, the minima for fly ash (30%) and slag (50%) approached levels that might present construction difficulties with respect to early strength gain in cool weather or other durability problems such as scaling. However, C 441 tests are conducted using crushed Pyrex glass No. 7740, a material that is considerably more reactive than the reactive constituents present in Virginia aggregates. Consequently, a need arose to validate the new requirements on concretes containing a highly reactive Virginia aggregate and to conduct a more complete examination of the effects of pozzolans and slag on concrete properties pertaining to their performance and durability in Virginia's transportation system.

PURPOSE AND SCOPE

The purpose of this study was to examine the effects of pozzolans and slag on concrete properties and their influence on durability parameters related to performance with the intent of validating or revising recently adopted specifications requiring their use. Laboratory tests were conducted on binary [(PC) + fly ash, PC + slag, PC + silica fume] and ternary (PC + fly ash + silica fume; PC + slag + silica fume) cementitious blends. The properties evaluated include flexural and compressive strength, drying shrinkage, and electrical resistance (ionic-transport, permeability). The durability issues evaluated were resistance to freezing and thawing in the presence of deicing chemicals and resistance to ASR.

METHODS

The basic plan of this study was to compare the properties and resistance to certain deterioration mechanisms of concretes produced with pozzolans or slag to a control PC concrete. The chemical parameters of the cementitious materials are shown in Table 1. The fly ash tested was a low-lime content Class F material and the term "fly ash" as used in this report is meant to pertain only to materials of similar chemical and physical characteristics. The slag used was a Grade 120 material and the silica fume was in the dry-densified form.

Concretes were proportioned to meet VDOT Class 30 concrete (minimum 28-day compressive strength of 30 MPa) with a cementitious materials content of 377 kg/m^3, a water-to-cementitious materials ratio (w/cm) of 0.45, and an air content of 6.5 +/- 1.5 percent. The coarse aggregate content was 1109 kg/m^3 and the fine aggregate content of the PC concrete was 645 kg/m^3, with adjustments made in the fine aggregate content to maintain a constant concrete volume when pozzolans or slag were used.

Table 1. Chemical Analysis of Cementitious Materials (%)

Chemical	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	---

Table 2. Mixture Proportions (kg/m^3)

Batch	Mix (PC/FA/SF/SL)	Label	Cement	FA	SF	Slag	Fine Aggregate
1	100/0/0/0	PC	377	0	0	0	645
2	85/15/0/0	15F	320	57	0	0	627
3	75/25/0/0	25F	283	94	0	0	616
4	65/35/0/0	35F	245	132	0	0	604
5	82.5/15/2.5/0	15F + 2.5SF	311	57	9	0	624
6	80/15/5/0	15F + 5SF	301	57	19	0	621
7	72.5/25/2.5/0	25F + 2.5SF	273	94	9	0	613
8	70/25/5/0	25F + 5SF	264	94	19	0	610
9	75/0/0/25	25S	283	0	0	94	639
10	65/0/0/35	35S	245	0	0	132	637
11	50/0/0/50	50S	188	0	0	188	634
12	40/0/0/60	60S	151	0	0	226	631
13	72.5/0/2.5/25	25S + 2.5SF	273	0	9	94	636
14	70/0/5/25	25S + 5SF	264	0	19	94	633
15	62.5/0/2.5/35	35S + 2.5SF	236	0	9	132	634
16	60/0/5/35	35S + 5SF	226	0	19	132	631
17	97.5/0/2.5/0	2.5SF	367	0	9	0	642
18	95/0/5/0	5SF	358	0	19	0	639
19	93/0/7/0	7SF	350	0	26	0	637

The amounts of pozzolans and slag were varied over the ranges typically encountered in structural concretes and were used to replace PC on a percent-by-mass basis in the different mixtures. In addition to traditional binary blending of cementitious materials, ternary mixtures incorporating smaller amounts of fly ash plus silica fume or slag plus silica fume were included. The purpose of these mixtures was to investigate whether they could be used to overcome some of the expected negative aspects of mixtures with large amounts of fly ash or slag while providing the desired durability. The proportions of the mixtures are shown in Table 2.

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, (Lane, 1994) as exhibited in a 10-year old concrete pavement shown in Figures 1-3. The metarhyolite yields ASTM C 1260 14-day expansions of 0.39% and the sand a value of 0.19%. The C 1260 results for the metarhyolite aggregate are the highest encountered thus far in testing Virginia aggregates. Consequently, this aggregate is presumed to be the one of the most highly alkali-silica reactive aggregates commonly used in Virginia. This aggregate was selected for use in these tests under the premise that materials that control its susceptibility to ASR will also be effective with aggregates of lesser inherent reactive potential.

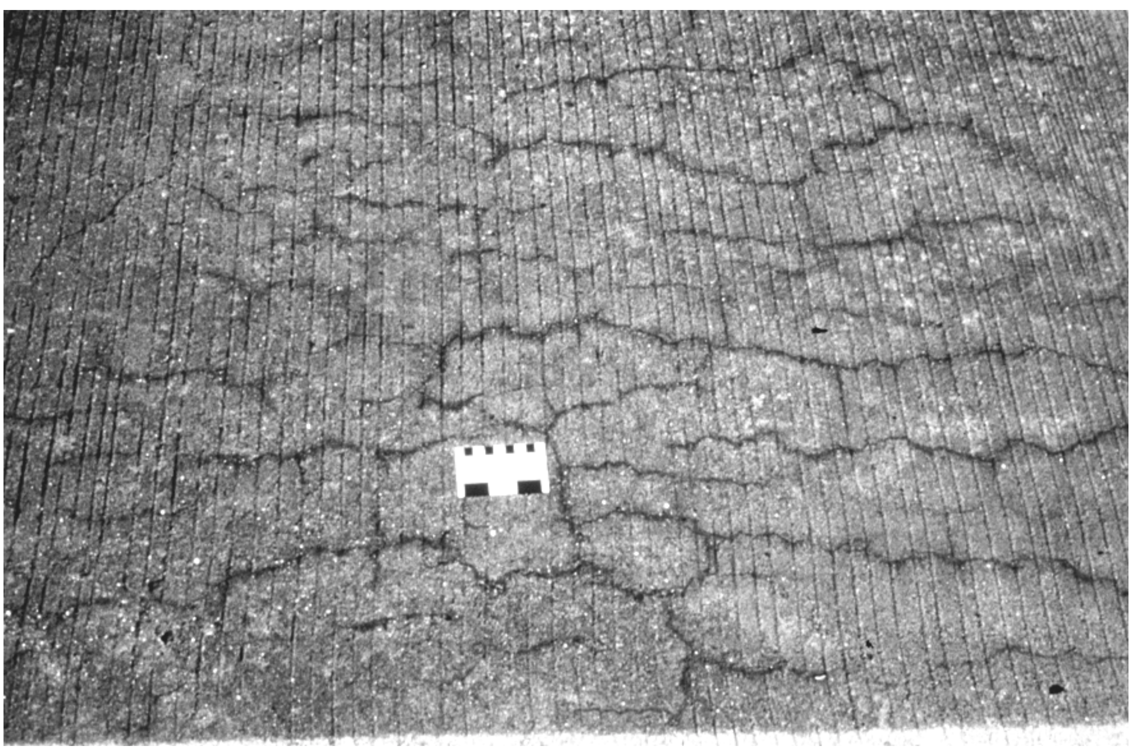

Figure 1. Condition of I295 Pavement Near Richmond 10 Years After Construction. (It Contains Metarhyolite Coarse Aggregate and Siliceous Fine Aggregate Showing ASR-Related Distress.)

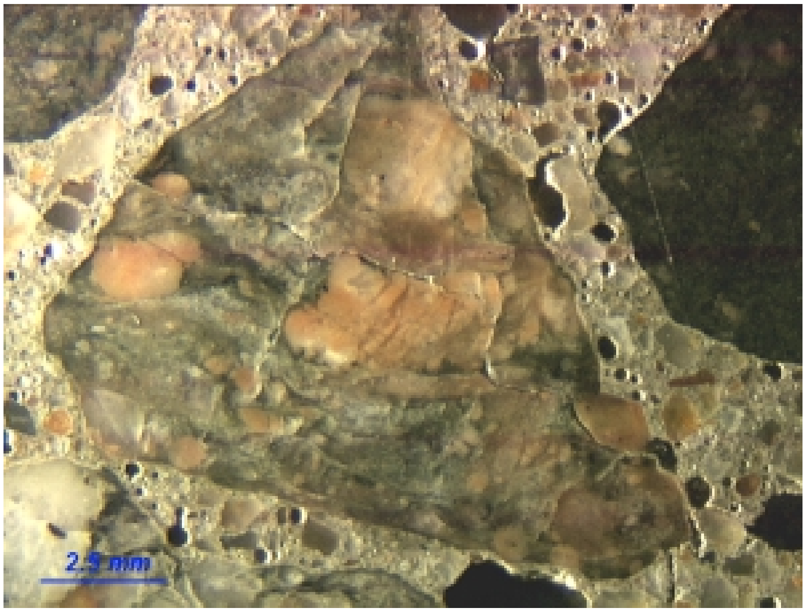

Figure 2. Polished Section From Pavement In Figure 1 Showing Distressed Aggregate Particle.

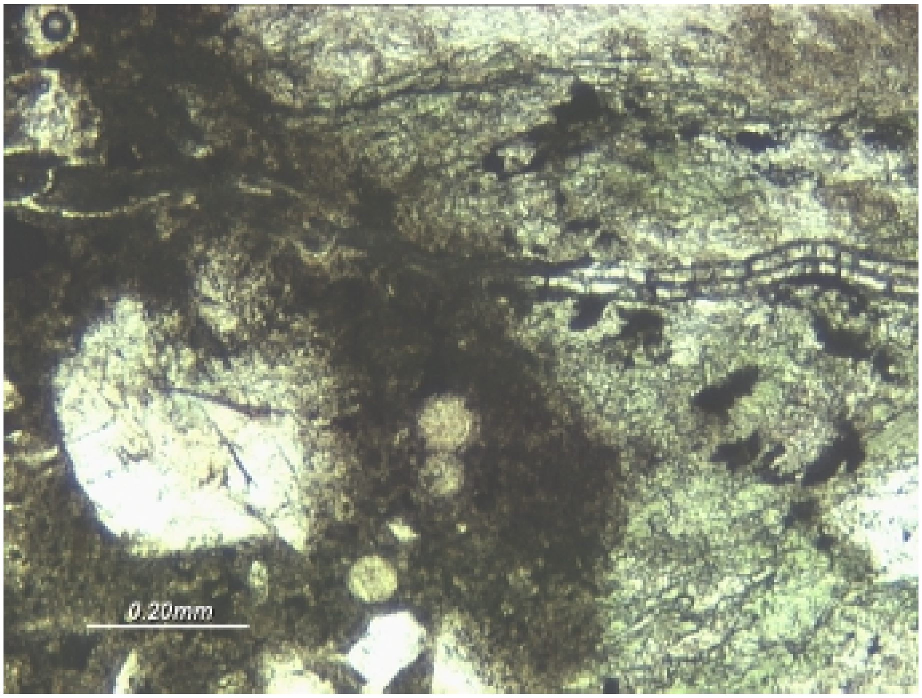

Figure 3. Thin Section of Concrete Pavement Shown in Figure 1. Crack In Aggregate Particle Is Filled With Reaction Product and Extends Through Paste.

No chemical admixtures (except an air-entraining admixture) were used in the concretes. The air-entrained concretes were mixed according to ASTM C 192 and sampled to determine the properties of the fresh concrete. After the fresh concrete tests were conducted, specimens were made for strength, electrical resistance, drying shrinkage, and freezing and thawing tests. Separate batches were mixed for the ASR tests because non-air-entrained concrete was desired for this test.

Strength

Specimens for determining strength were moist-cured at 23°C until the time of test. The compressive strength of mixtures was determined using ASTM C 39 on 100 x 200 mm specimens at 3, 7, 28, 56 days and 1 year. In lieu of sulfur-mortar capping, the compressive strength specimens were tested using neoprene pads in steel retaining rings because of the convenience afforded by this procedure. Flexural strength was determined using ASTM C 78 (third-point loading) on 75 x 75 x 280 mm specimens at 28 days and 1 year.

Electrical Resistance

Electrical resistance of the concrete mixtures was determined by testing 100 x 100 mm specimens using ASTM C 1202. The current passing through the specimen during the 6-hour test period is measured in coulombs. High electrical resistance in this test is considered to indicate low ionic-transport properties of the concrete. Electrical resistance specimens were moist-cured 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 (Ozyildirim, 1998). The accelerated curing consists of 7 days moist at 23°C, followed by 21 days moist at 38°C.

Drying Shrinkage

Drying shrinkage tests were conducted on 75 x 75 x 280 mm specimens. The specimens were moist-cured at 23°C for 28 days before being subjected to the drying (50 % relative humidity at 23°C) environment. Measurements were made according to ASTM C 157.

Resistance to Freezing and Thawing and Deicer Scaling

Freezing and thawing durability was evaluated by testing 75 x 100 x 405 mm specimens that were moist-cured for 14 days at 23°C. Freezing and thawing was performed following ASTM C 666 Procedure A (in water) with 2 % NaCl by mass added to the water. The dynamic modulus of elasticity and loss of mass were monitored during the testing period.

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. Adjustments were made in the fine aggregate content to account for the lack of entrained air. The amount of NaOH added was that necessary to raise the alkali content of the PC (0.92% Na_2Oeq) concrete to 4.7 kg/m^3, equivalent to using a PC with an alkali content of 1.25% Na_2Oeq. The same amount of NaOH was added to each batch, regardless of actual PC content. The alkali content of a field concrete with similar cement content placed in Virginia would typically be about 3.0 kg/m^3, assuming that the cement alkali content was 0.80%.

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

Table 3. Properties of Fresh Concrete

Batch	Mix (PC/FA/SF/SL)	Slump (mm)	Air (%)	Unit Weight (kg/m^3)
1	100/0/0/0	55	6.0	2326
2	85/15/0/0	115	6.9	2275
3	75/25/0/0	160	6.2	2275
4	65/35/0/0	180	6.0	2294
5	82.5/15/2.5/0	115	5.9	2307
6	80/15/5/0	75	6.7	2307
7	72.5/25/2.5/0	120	6.2	2288
8	70/25/5/0	110	6.0	2281
9	75/0/0/25	120	7.6	2268
10	65/0/0/35	140	6.4	2300
11	50/0/0/50	140	6.1	2307
12	40/0/0/60	135	5.8	2300
13	72.5/0/2.5/25	90	5.3	2333
14	70/0/5/25	55	5.0	2333
15	62.5/0/2.5/35	95	6.8	2262
16	60/0/5/35	75	5.6	2313
17	97.5/0/2.5/0	70	6.5	2288
18	95/0/5/0	55	6.1	2300
19	93/0/7/0	50	5.6	2313

RESULTS AND DISCUSSION

The properties of the fresh concrete are shown in Table 3. The air content for all batches was within the target range of 5 to 8 %. The slump of certain batches exceeded the target range of 50 to 100 mm. This occurred with the binary mixtures containing fly ash and slag, and three of four ternary blends of fly ash plus silica fume. The high slumps were obtained with the fly ash and slag mixtures as a result of the lower water demand of these materials. Consequently, the use of constant w/cm forced a higher water content for the fly ash and slag mixtures than was needed for workability. Had slump been held constant instead, it would be expected that the fly ash and slag concretes would exhibit improvements in most properties resulting from the reduced w/cm needed to achieve a targeted slump.

Strength

The compressive strength results are summarized in Figure 4. The data illustrate that in binary systems, the higher amounts of fly ash or slag found to be necessary to control ASR expansions in C 441 tests (Lane and Ozyildirim, 1995) 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 slowly hydrating phases in the fly ash. However, by 1 year, the depression in strength level resulting from high amounts of fly ash had dissipated, and the compressive strength of all mixtures greatly exceeded the design strength of 30 MPa. In the slag concretes, early strength depression was overcome between 7 and 28 days.

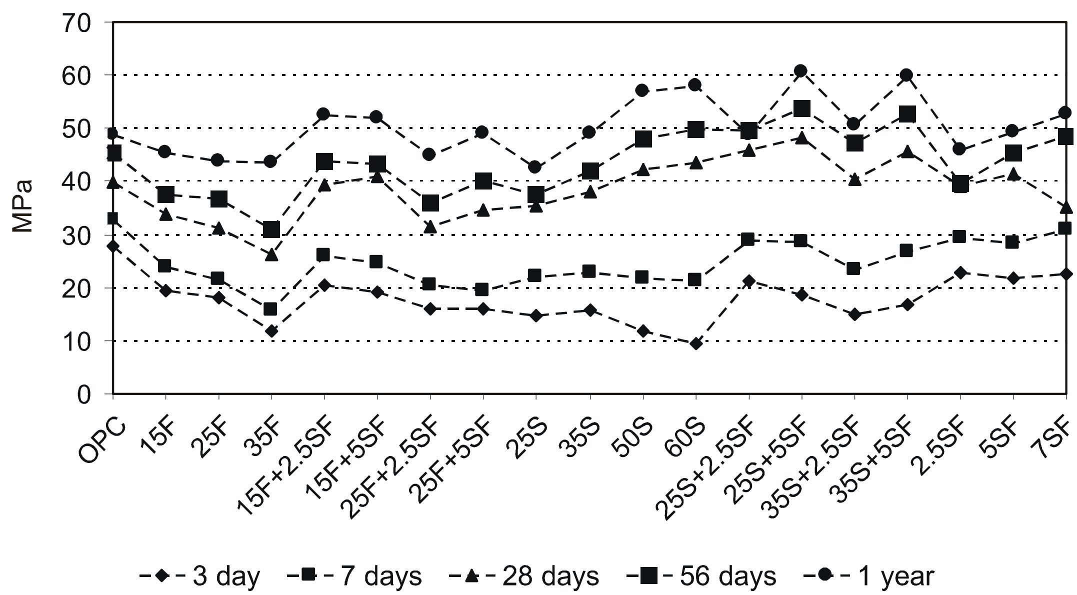

Figure 4. Compressive Strength Results.

Only one mixture, the binary blend with 35% fly ash, did not meet the 28-day design strength of 30 MPa. In Table 3, it can be seen that this mixture also exceeded the maximum slump; consequently, in actual application, a lower w/cm would be used, resulting in higher strength. This applies as well to other mixtures that exceeded the maximum slump value.

The ternary blends, wherein small amounts of silica fume are used to augment the characteristics of concretes with lower amounts of fly ash or slag, are shown to be generally effective in improving early strengths over high percentage binary blends. However, in actual application, the strength characteristics of the binary blends could be improved by reducing the w/cm as mentioned above or through the use of water-reducing admixtures.

The 28-day flexural strengths are presented in Figure 5. As expected, the trends and observations are similar to those discussed for compressive strength.

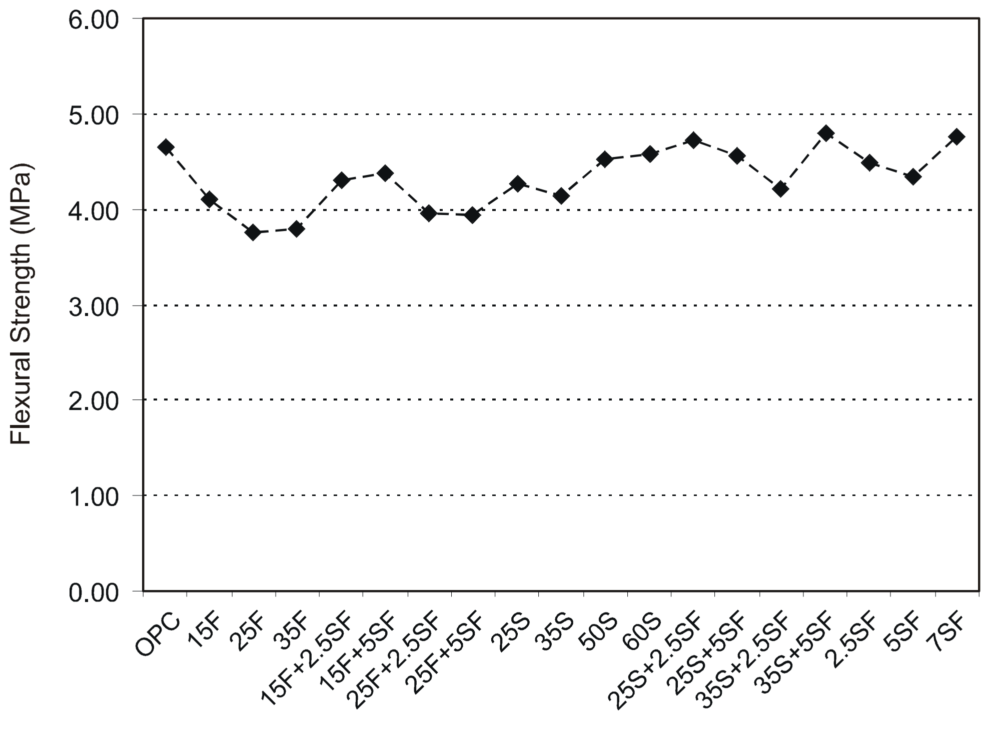

Figure 5. 28-day Flexural (Third-Point) Strength Data

Electrical Resistance

Figure 6 provides an indication of transport properties based on C 1202 electrical resistance measurements. The values reported are the charge passed in coulombs; therefore, low values correspond to high electrical resistance and indicate low transport properties. The figure illustrates that the accelerated curing procedure (Ozyildirim, 1998) provides a good indication of the later-age transport properties at 28 days. The accelerated curing and 1-year results show that the use of pozzolans in sufficient amounts significantly increases the electrical resistance of concrete with respect to the control. 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.

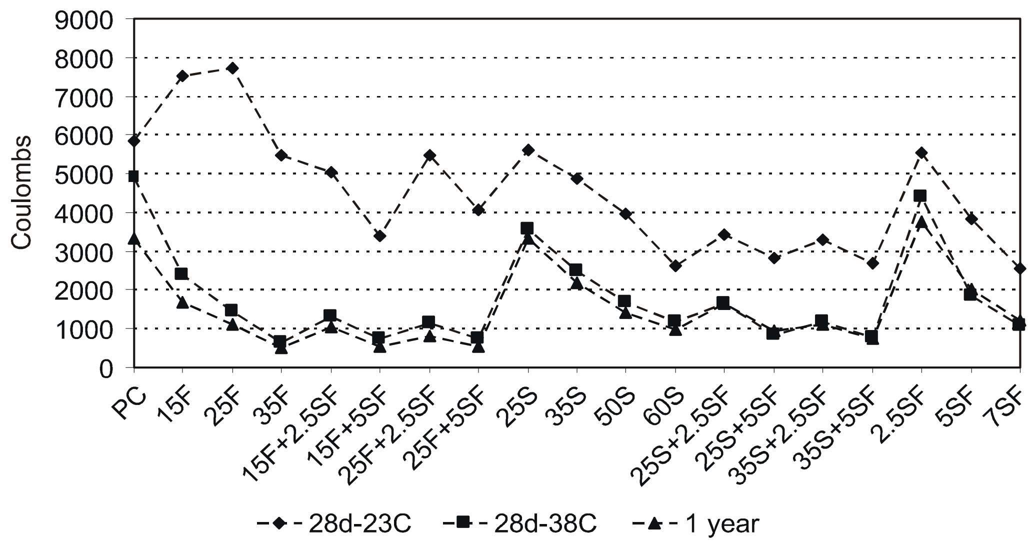

Figure 6. Electrical Resistance (Ionic Transport) Test Results

The relationship between early strength and later-age electrical resistance of the concretes is shown in Figure 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.

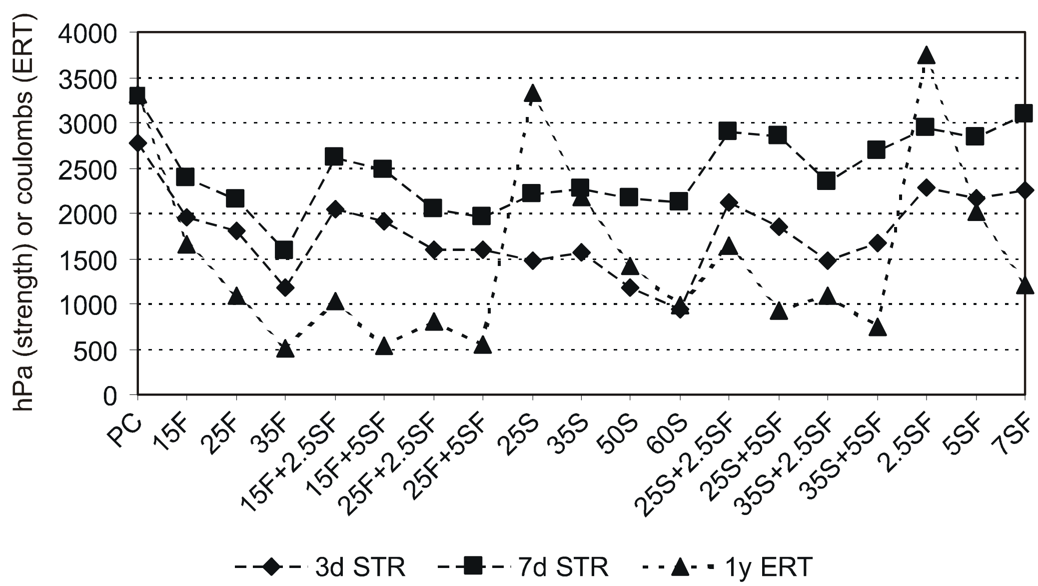

Figure 7. Comparison Of 3- And 7-Day Compressive Strengths With 1-Year Electrical Resistance (Ionic Transport)

Drying Shrinkage

The drying shrinkage results at 64 weeks are presented in Figure 8. Typical shrinkage values for unreinforced concretes fall in the range of 0.04 to 0.08% (Mehta, 1994). Only one mixture, the binary blend with 15% fly ash, fell slightly outside this range (0.083%). Binary mixtures with silica fume, higher amounts of fly ash, and 60% slag and the ternary mixtures yielded slightly lower shrinkage values than the other mixtures. This can be explained by increased consumption of water in hydrating the pozzolans (particularly silica fume) resulting in a lesser amount of evaporable water remaining in these concretes or because of the difficulty in removing water from these dense systems. In the binary fly ash and slag mixtures, shrinkage values are slightly exaggerated over what might be anticipated in field application because of the higher than necessary water content forced by the constant w/cm. However, the values for all mixtures are fairly similar, and it is not believed that the small differences observed would be reflected in actual field performance.

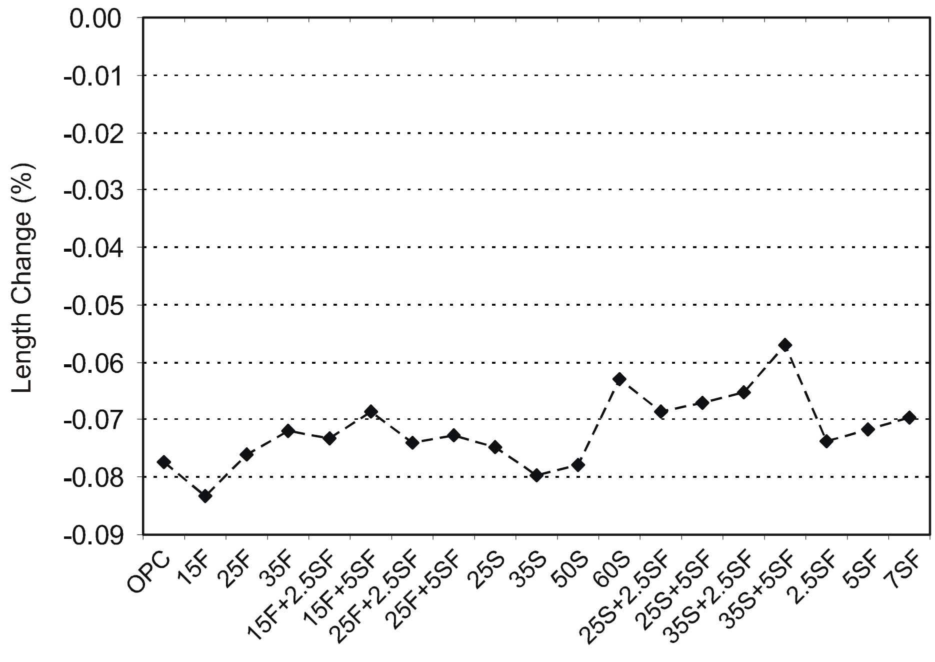

Figure 8. Results of Drying Shrinkage Tests

Freezing and Thawing

Results of the freezing and thawing testing after 300 cycles are shown in Figures 9 and 10. The durability factor data presented in Figure 9 is based on a comparison of initial and final dynamic modulus of elasticity measurements. Loss of modulus during this test is indicative of internal damage resulting from the freezing cycles. The minimum passing value after 300 cycles is a durability factor of 60. All mixtures showed excellent performance in this respect.

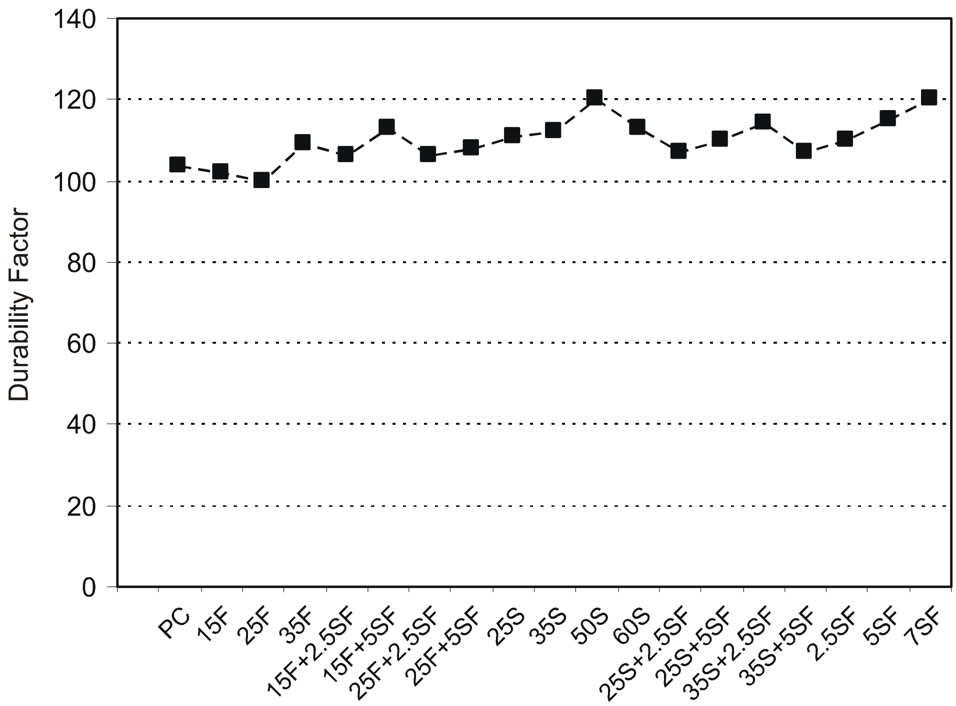

Figure 9. Durability Factors After 300 Cycles of Freezing and Thawing in 2% Nacl Solution

Loss of mass data is shown in Figure 10 and is a quantitative measure of surface scaling. A maximum loss of mass of 7.0 % is used by the Virginia Transportation Research Council to indicate satisfactory scaling resistance (Newlon, 1978). Only one mixture, the binary 60% slag blend (7.7%), exceeded this limit, with all other mixtures showing losses less than 5.0%. The best performance was exhibited by mixtures with a minimal replacement of PC. However, performance in this test for any given mixture is affected by w/cm; consequently, binary mixtures with fly ash and slag would be expected to perform better if advantage was taken of their lower water-demand. To the extent that scaling did occur, these tests suggest that it would be restricted to the top surface without any progressive internal damage. The end result expected from such a response would be some exposure of the coarse aggregate at the surface. Such scaling is not necessarily detrimental on riding surfaces (e.g., pavements and bridge decks), since exposure of the non-polishing coarse aggregate used in the concrete increases the macro-texture of the surface, thus maintaining a skid-resistant surface.

The nature of this test, in which specimens are continually immersed in 2% NaCl solution and cyclically frozen, is quite severe with respect to normal field conditions. Field concretes are generally more mature when first subjected to freezing-thawing cycles, freezing cycles in the field are much less intense than the test cycles, and the saturation level of field concrete is frequently below the critical level. Considering all of these factors, as suggested by Newlon and Mitchell (1994), it is expected that the mixtures evaluated in this program will provide good performance in field applications under ordinary circumstances.

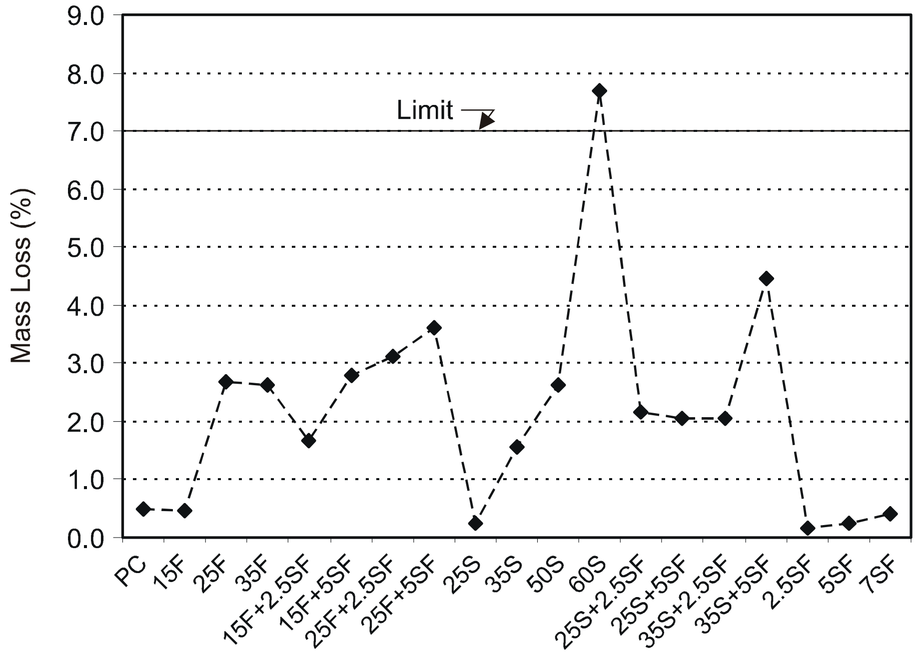

Figure 10. Mass Loss (%) After 300 Cycles of Freezing and Thawing in 2% Nacl Solution

Alkali-Silica Reactivity

The C 1293 results are shown in Figures 11-13. Using a criterion of 0.04% maximum expansion (Thomas et al., 1997) at 2 years, these results indicate that 15% fly ash (Figure 11) and 35% slag (Figure 12) are minimum amounts needed in binary blends to control the reactivity of the aggregate combination. Silica fume (Figure 13), at the maximum dosage of 7%, was not effective in this test. These results suggest that fly ash or slag are effective in controlling the reactivity of Virginia aggregates in smaller amounts than are suggested by C 441 testing (Lane and Ozyildirim, 1995). Conversely, silica fume was not as effective in the C 1293 tests as it was in the C 441 testing. The contrasting results obtained between the two tests with the different materials may result from 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. However, at this point, the connection between test criterion and service prediction is not yet clearly defined.

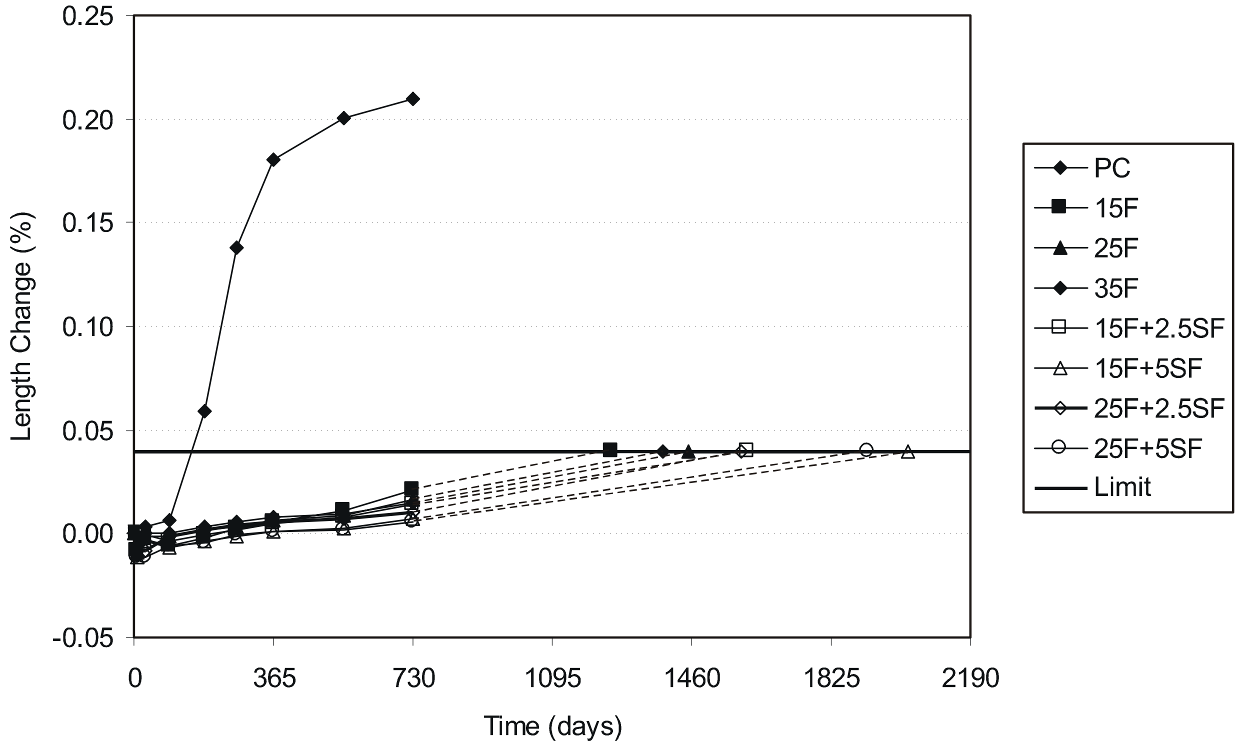

Figure 11. ASR Test Results For Binary and Ternary Mixtures Containing Fly Ash. (Measured Values Are Connected By Solid Lines; Dashed Lines Are Straight-Line Projections to the 0.04% Expansion Limit.)

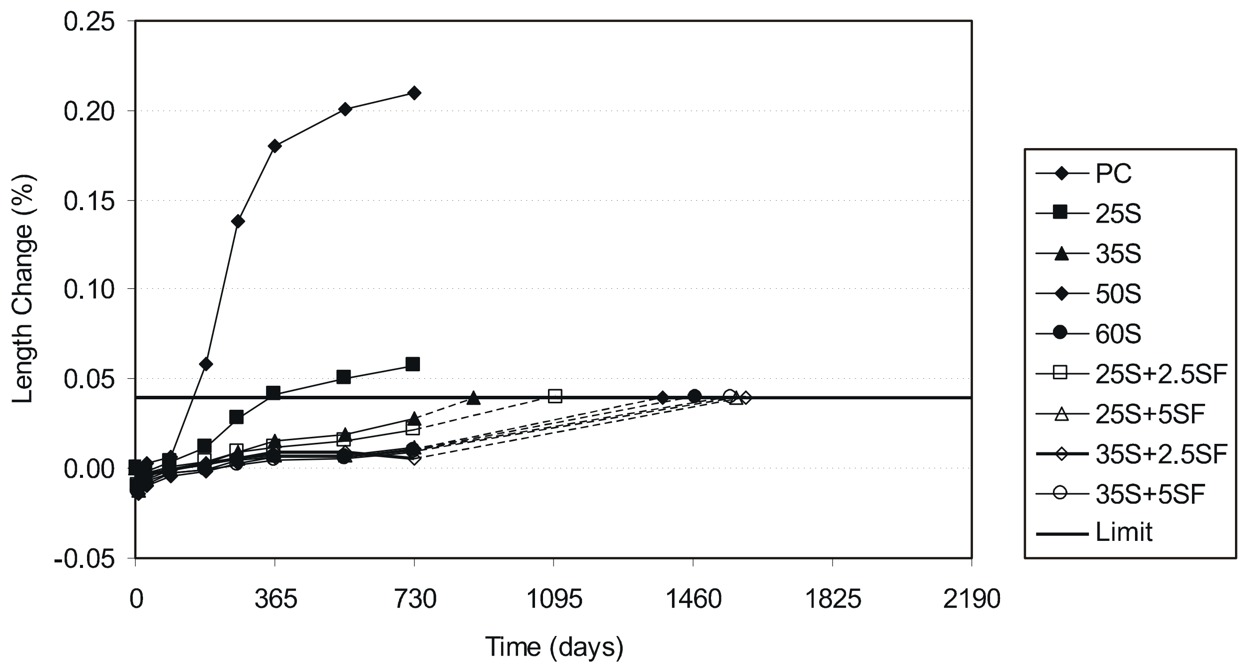

Figure 12. ASR Test Results For Binary and Ternary Mixtures Containing Slag. (Measured Values Are Connected By Solid Lines; Dashed Limes Are Straight-Line Projections to the 0.04% Expansion Limit.)

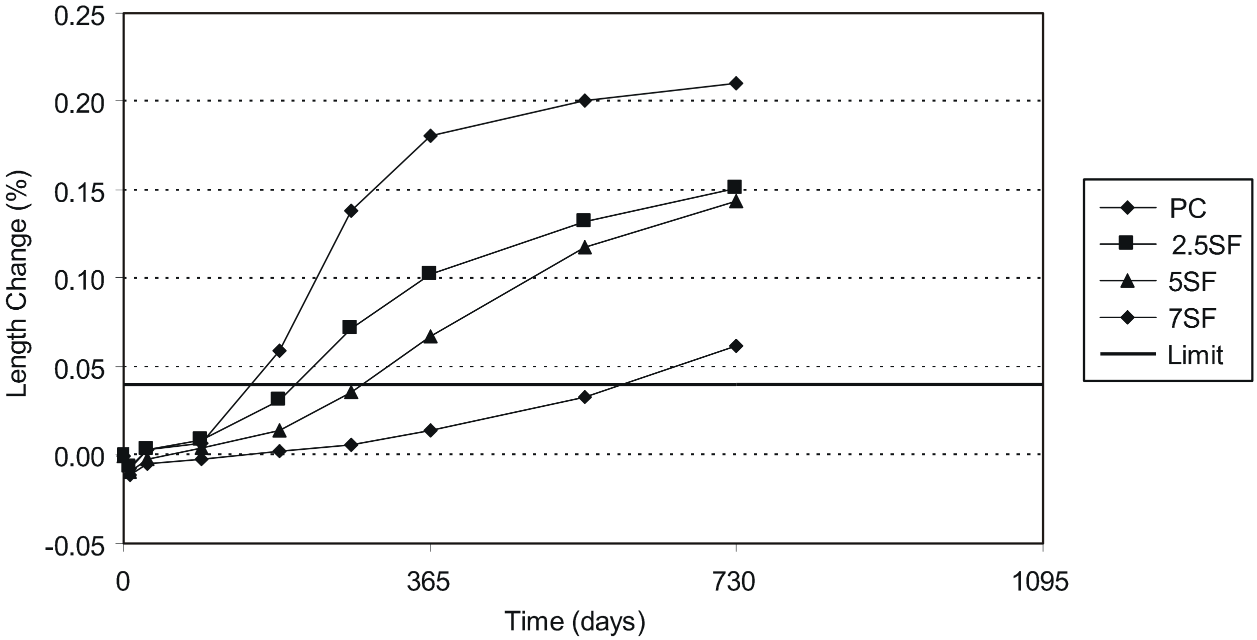

Figure 13. ASR Test Results For Binary Mixtures Containing Silica Fume.

The results of C 1293 tests on ternary systems with fly ash and slag are presented in Figures 11 and 12 respectively. With respect solely to keeping expansion below 0.04%, 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. The ternary blends also offer much improvement over the performance of binary silica fume concretes in this test.

Although the C 1293 results are typically used in a pass/fail manner, it is worth speculating on how the data might be used to predict the service-life of concrete mixtures. The basis for this predictive model is a comparison of the time-to-failure of the control concrete in the test to the time-to-cracking of field concrete. A ratio of test-years to service-life-years is thus obtained (e.g., X test-years is equivalent to Y service-life-years). Having established this ratio, it can be applied to the time-to-failure (or projected time-to-failure) of test mixtures to predict a time-to-cracking in field applications.

In this study, the control (PC) concrete exceeded 0.04% expansion at about 0.5 year. Assuming the field concrete in which the aggregate combination exhibiting ASR would have reached a deleterious state at 5 years, the 2-year test period might reasonably be considered to reflect a 20-year field service—in other words, a 1:10 year, test to service-life relationship. In addition to the actual test results shown connected by solid lines in Figures 11 and 12, the data are projected to an expansion of 0.04% by a straight-line method to provide the time-to-failure for the test mixtures. The straight-line projection is thought to be somewhat conservative since the general tendency is for expansion rate to decrease with time. From the fly ash results (Figure 11), the 25% and 35% replacement levels project to 0.04% expansion at approximately 3.75 years, thus predicting nearly 40 years service until the initiation of cracking based on the 1:10 year relationship. Given that many structures remain serviceable for a considerable period after initial cracking, a lengthy service life can be predicted for these fly ash concretes. In Figures 11 and 12, it also can be seen that small additions of silica fume to fly ash or slag concretes greatly extend the predicted time to 0.04% expansion. This prediction of potential service life from C 1293 results is still quite tentative and requires considerably more grounding through comparison with field performance evaluation of concretes containing pozzolans or slag and reactive aggregates. However, the results do lend strong support to the use of these materials to prevent damage resulting from ASR.

SUMMARY AND CONCLUSIONS

Overall, the pozzolan and slag concretes performed very well in these evaluations. Later-age strengths and drying shrinkage were equivalent to or better than the control. Some negative impact of fly ash and slag was noted with higher percentage replacements on early (3- and 7-day) strengths and scaling resistance. The testing plan used exaggerates these negatives to some degree because the use of constant w/cm results in a higher water content than needed for workability with these materials. In application, the ability to reduce w/cm with these materials can result in improvements across the board. The use of ternary blends incorporating small amounts of silica fume with smaller amounts of fly ash or slag was shown to be a viable approach to counteract the negative impact of higher replacement levels of fly ash and slag on early strength, while maintaining the excellent durability characteristics associated with high-level replacements of cement with these materials.

Although early strength-gain characteristics can be important to construction costs in the short-term, the most significant cost item in transportation systems is in dealing with premature deterioration of structures and pavements. The primary causes of early distress in hydraulic cement concretes encountered in Virginia have been chloride-induced corrosion of reinforcing steel and ASR. Concretes with high ionic-transport properties are more susceptible to both of these deterioration mechanisms; and, in fact, to other deterioration mechanisms such as sulfate attack, carbonation, and leaching, in which a fundamental role is played by the chemical activity of the system.

The electrical resistance test serves as an indicator of the ionic-transport properties and the results clearly indicate the improvement imparted with increasing pozzolan or slag content. Likewise, resistance to ASR-related expansion was greatly improved with increasing content of these materials. The synergistic effect of combining silica fume with fly ash or slag in ternary blends was illustrated by the fact that these combinations yielded the longest time to projected failure in the ASR tests and were needed to achieve satisfactory results with silica fume. These beneficial effects were also shown by the comparison of early strength to a 1-year ionic transport.

The pozzolan and slag concretes evaluated in this study provide significantly improved characteristics with respect to the primary causes of concrete deterioration over the control concrete. Ternary blending of materials offers flexibility to tailor concrete properties for specific construction situations. In application, the slight potential drawbacks that may be encountered when using high amounts of fly ash or slag can be avoided by appropriate mixture proportioning, the use of chemical admixtures, and proper construction practices.

RECOMMENDATIONS

1. The required use of pozzolans or slag in hydraulic cement concretes should be continued because these materials significantly enhance the durability of concrete.

2. Ternary blends of cementitious materials should be permitted since they offer flexibility in achieving the desired properties for specific applications while providing the desired durability characteristics. Ternary mixtures should be approved for use in bridge deck overlay concretes.

3. The current procedures for assuring ASR-resistance of concretes should be reevaluated to determine if an approach more specific to construction aggregates would be beneficial to VDOT's interests. One means of accomplishing this would be by increasing the 56-day C 441 expansion from 0.10% to 0.15%. This would have the effect of reducing the required percentage of fly ash to levels that were found to be effective in the C 1293 testing reported in this study.

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