DURABILITY OF TERNARY BLEND CONCRETE WITH SILICA FUME AND BLAST-FURNACE SLAG: LABORATORY AND OUTDOOR EXPOSURE SITE STUDIES

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Abstract
In 1998, seven outdoor exposure pavement slabs were constructed using a highly reactive siliceous limestone. Ternary concrete mixtures silica fume, blast-furnace slag, and high-alkali Portland cement concrete mixtures were included. Cores were taken after 2 and 6 years to assess alkali-silica reaction, and ingress of chlorides. Significant expansion and visible cracking due to alkali-silica reaction occurred in the field concrete made with the high-alkali Portland cement control mixture, but not in any of the slag, silica fume or ternary mixtures. Expansion, tensile strength and Damage Rating Index testing also confirm the ASR condition observations. Inspection of the field slabs after 6 years showed little sign of salt scaling damage with the exception of the 50% slag mixture which is experiencing light scaling. Rapid chloride penetration tests, chloride bulk diffusion tests, and chloride profiles of cores taken from the field indicate that ternary blends are very resistant to chloride ingress.

Keywords: concrete; ternary blend; silica fume; blast-furnace slag; durability; outdoor exposure; field trials; alkali-silica reaction; salt scaling; chloride penetration.

1 INTRODUCTION

The replacement level of a single supplementary cementing material (SCM) needed to prevent expansion due to alkali-silica reaction (ASR) may create other problems or concerns. The incorporation of 50% slag [1,2,3] or greater than 20% fly ash [2,4,5] needed to ensure adequate protection against ASR may lead to poor resistance to deicer salt scaling under some circumstances. In fact, the Ontario Provincial Standards and Specifications [6] have imposed maximum limits on the use of slag (BFS) and fly ash (FA) to 25% and 10% of the total mass of cementitious materials respectively, except when the contractor provides an extended warranty on the concrete. These maximum limits are too low to consistently prevent expansion due to ASR, especially in Ontario, where most Portland cements (PC) have high alkalis. In such cases, a policy of using non-reactive aggregates has been instituted, however these are not always locally available. Also, when silica fume (SF) is used at levels greater than 10% by mass of cement as sometimes necessary to prevent ASR expansion [7], it can potentially lead to problems with the workability of the fresh concrete as well as potential difficulties in adequately dispersing the silica fume [8].

A solution that has become more common is to use a high-performance ternary blend concrete that uses moderate levels (15% to 35%) of blast-furnace slag (or fly ash) in combination with silica fume at lower than typical levels (<7% by mass). The use of appropriately proportioned ternary blends allows the effects of one SCM to compensate for the inherent shortcomings of another. Such concretes have been found to exhibit excellent fresh and mechanical properties. For example, the addition of an ultra-fine pozzolan, such as silica fume, to a mixture containing blast-furnace slag can prevent excessive bleeding problems. In a PC/SF/FA system, a synergistic rheological effect was observed by Thomas et al [9] in which the fly ash content offset the increased water demand typically associated with silica fume use. This was also observed for silica fume plus slag ternary mixtures by Bickley [10] during the construction of the Scotia Plaza Tower in Toronto, Canada. Ternary blended concrete with SF and either slag or fly ash required reduced dosages of superplasticizers to obtain satisfactory workability. Afrani and Rogers [11] found that a blend of 25% ground granulated blast-furnace slag and 3.8% silica fume required a lower water to cementitious materials ratio (W/CM) for a given slump than a 100% PC mixture, without the need for superplasticizer.

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Despite recent interest in ternary blend concretes and a few published studies on their use, little is known about their actual durability performance. McGrath and Hooton [12] determined that SF and fly ash, and SF and slag mixtures yield less permeable concretes than concretes with SF alone and this was also found for heat cured concrete by Titherington and Hooton [13]. Comparative studies between PC, binary, and ternary cementitious systems conducted by Khatri [14] in Australia concluded that the most significant improvements of ternary concretes are associated with durability aspects related to a marine environment. Furthermore, ternary mixtures containing PC, silica fume and either blast-furnace slag or fly ash yielded an optimum balance between mechanical and durability properties.

The Canadian Standards Association [15] concrete standard provides advice on the use of ternary blends to mitigate deleterious expansion due to ASR. Results from our current research program were used, in part, to form the advice given in the new standard. The standard, entitled "CAN/CSA-A23.2-27A - Standard Practice to Identify Degree of Alkali-Reactivity of Aggregates and to Identify Measures to Avoid Deleterious Expansion in Concrete" states the following: *"When two or more SCM's are used together to control ASR, the minimum replacement levels […] for the individual SCM's may be partially reduced provided that the sum of the parts of each SCM is greater than, or equal to, one."*

2 OUTDOOR EXPOSURE SITE

2.1 Description

As reported in a previous paper [16] in September of 1998, a field investigation assessing the durability performance of ternary blend concretes was initiated by an academic-government-industry consortium consisting of the University of Toronto, the National Science and Engineering Research Council, and four cement companies (Essroc-Italcementi, Lafarge Canada, St. Lawrence Cement and St Marys Cement). Seven different concretes were cast in the field to assess durability performance in an outdoor exposure setting as well as with standard laboratory tests. In addition to strength, resistance to alkali-silica reactivity, chloride ion ingress, and deicer salt scaling were measured.

The field-trial site was the replacement of a severely damaged service roadway at the Essroc cement plant in Picton, Ontario, Canada (roughly halfway between Toronto and Montreal). This site is frequently trafficked by heavy industrial trucks, receives frequent deicer salt applications in the winter, and undergoes numerous freeze-thaw cycles a year.

A known alkali-silica reactive siliceous crushed limestone (Spratt) was used as the coarse aggregate (20mm) in all concrete mixtures. The degree of reactivity was assessed using the Accelerated Mortar Bar Test (CAN/CSA-A23.2-25A, similar to ASTM C1260). An expansion level of 0.493% (greater than the CSA 0.15% limit) was observed after 14-days of immersion in 1M NaOH at 80°C.

Cementitious materials used were a high-alkali CSA Type GU (ASTM Type I) cement, a blended CSA GUb-8SF silica fume cement with 8% silica fume and ground granulated blast-furnace slag. Refer to Table 1 for the chemical analyses of cementitious materials. Batching took place at a commercial ready-mix concrete plant in Belleville (~35 km away). The cementitious material content was 420-kg/m^3 yielding a range in the total alkali content from 1.98 to 4.07-kg/m^3. Batching was done at a water to cementitious materials ratio (w/cm) of 0.42, in conjunction with a water reducer admixture. Adjustments to workability were achieved by dosing with an alkali-free, naphthalene sulfonate-based high-range water reducer on site.

Seven 250-mm thick slabs-on-grade were cast with no steel reinforcement. Three mixtures contained a single SCM, three ternary blend mixtures (silica fume and slag), and a control mixture with no SCM's and high-alkali Portland cement. Details of the concrete mixtures, including air content, slump, and 28-day compressive strengths are provided in Table 2.

As the casting procedure has an impact on the durability performance of a mixture, details of environment, casting, timing and curing are provided. The outdoor air temperature on the day of casting was 22ºC ± 2ºC with a relative humidity of 74% ± 6%. At time of casting, the concrete temperature was 24-27ºC. Each placement was started 70 ± 10 minutes after mixing in the plant, and it took ~20 minutes to cast each slab-on-grade. After a rough rake level, a vibrating screed was used to achieve a final level. An evaporation retarder was applied immediately following screeding. A final finish was achieved using a magnesium float followed by a broom for texture. A membrane-forming compound, was used for curing, and was applied 60 ± 20 minutes after the broom finish, with the exception of two mixtures (50% slag and 8% silica fume), where it was applied 10 minutes after the broom finish. Laboratory specimens were cast 10 minutes after the start of the slabs-on-grade.

2.2 Evaluation of Performance

Durability performance was evaluated by in-situ performance and laboratory studies. Laboratory testing was conducted on specimens (slabs, prisms and cylinders) cast during the site construction (referred to as "initial" specimens), as well as specimens cored from the slabs at 2 and 6-years. Evaluation of the various durability properties was achieved as described below.

2.2.1 ASR Expansion and Visual Assessment

To assess control of ASR expansion, concrete prisms were cast with measuring studs and stored at 38˚C and 100% relative humidity (as per CSA A23.2-14A with the exception that field mixtures were used here). Field observations have also been conducted yearly for typical signs of ASR; such as differential movements and pattern cracking of unreinforced concrete. Damage Rating Index (DRI) measurements were made on polished surfaces from slices of cores extracted from the field concretes after 6-years exposure. The Damage Rating Index method of evaluation, developed by Dunbar and Grattan-Bellew [17] is based on numeric and weighted observations of ASR-related defects such as cracks and gel, with a higher number indicating more damage.

2.2.2 Chloride Penetration Resistance

Assessment of the resistance to chloride ion ingress was evaluated both in the laboratory and in the field. Laboratory testing involved the Rapid Chloride Penetration Test (RCPT – ASTM C1202), the Nordtest NT Build 492 Rapid Migration test, and the Chloride Ponding test (bulk diffusion – Nordtest NT Build 443). As well, cores were removed from the slabs after 2 and 6-years, then profile-ground to different depths to determine the quantity of chloride ions that penetrated the surface as a result of the periodic application of deicing salts in the field.

2.2.3 De-icer Scaling Resistance

Salt scaling resistance assessed by laboratory testing according to MTO LS-412 (similar to ASTM C672, but using a 3% NaCl solution and monitoring surface scaling by measuring mass loss) of both finished and formed surfaces of test slabs, were presented previously [16]. Visual field surveys looking for any evidence of scaling have been conducted yearly up to 8 years.

2.2.4 Modified Stiffness Damage Test

The Stiffness Damage Test was originally developed by Chrisp et al. [18,19] and involves measuring the hysteresis of the stress-strain curve of cylinders or cores tested in compression; the hysteresis increases with increasing damage due to ASR. In this study, the modified test developed by Smaoui et al [20] was used. In the modified approach, cylindrical samples are loaded in uniaxial compression up to a maximum load of 10 MPa and then unloaded. The cycle is repeated 4 more times and the stress-strain curve plotted for the five cycles. The parameters calculated from the resulting stress-strain curve are: (i) the static modulus during the first loading, (ii) the area of the hysteresis loop during the first load/unload cycle and (iii) the total plastic strain after all 5 cycles. It has been shown that a reliable relationship exists between the expansion of the concrete and both the energy dissipated during the first load/unload cycle (area of hysteresis loop) and the plastic strain.

2.2.5 Gas-Pressure Tensile Test

The gas-pressure tensile test was developed by Clayton [21] and involves the application of gas pressure to the curved surface of a saturated cylinder, while the flat ends of the cylinder remain open to atmospheric pressure. This results in 3-dimensional tensile stresses being developed within the cylinder and eventual tensile failure on a plane perpendicular to the axis. In the tests conducted here the gas (N_2) pressure was increased at a rate of 1 MPa/minute until failure.

3 RESULTS

3.1 Visual Evaluation and Damage-Rating Index

Slabs were power washed to remove debris and the slabs were examined as the water evaporated to look for cracks. After 6 years, the only field-exposed slabs exhibiting visual pattern cracking were those from the high-alkali portland cement control mixture (Figure 1). In terms of de-icer salt scaling, there was only evidence of minor scaling or abrasion on the 50% slag slabs (Figure 2).

Damage Rating Indices are given in Table 3. The only one with an extremely high DRI was the Portland cement concrete with a value of 211. Several others were in the 35-60 range (8%SF, 35% slag, 4%SF+25% slag), while the rest were <10 (50% slag, 6% SF+25% slag, and 5%SF+ 35% slag).

3.2 Concrete Prism Expansions

Table 4 shows the average expansion of concrete prisms cast during construction and stored in the laboratory at 38˚C and 100% relative humidity. After two years, the high-alkali control mixture with Spratt aggregate (100% OPC) expanded to 0.238%. Significant expansion was observed at 2-years in mixtures with only single SCM's, notably the 8% silica fume (0.048%) [16]. Monitoring was continued to 8.75-years, as shown in Table 6, and no other mixtures have exceeded 0.04% expansion.

3.3 Stiffness Damage and Gas-Pressure Tensile Strength

The results of the modified stiffness damage test and the gas-pressure tensile test are presented in Table 5.

3.4 Rapid Chloride Penetration Testing

Table 6 shows the average RCPT results (tested in duplicate) on cores taken at 6 years as well as on laboratory-cured cylinders tested at 28 days and 2 years. The three ternary blends exhibit the least penetrable concrete. They all fall in the "very low" category (100-1000 coulombs) as defined by ASTM C1202. The 5.2% SF and 35% slag mixture yielded the best results, and the 6% SF and 25% slag mixture was a close second, especially at later ages. It is interesting to note that the 8% SF mixture shows a slight increase in conductivity with age. The additional use of blast-furnace slag along with silica fume appears to prevent this increase in charge passed with time.

3.5 Rapid Migration Testing

The Nordtest NT Build 492 Rapid Migration Test was used to evaluate concrete sliced from cores after 6-years exposure. Duplicate samples were tested. As shown in Table 6, all concretes with SCMs exhibited much lower non-steady state migration coefficients than the Portland cement control.

3.6 Resistivity Testing

As also shown in Table 6, all concretes with SCMs exhibited much higher values of resistivity relative to the Portland cement control.

3.7 Chloride Bulk Diffusion

Bulk diffusion was tested on concrete specimens of 50-mm thick by 100-mm in diameter. Saw-cut cylinders were used for the initial (0-year) measurements, whereas saw-cut field cores were used for 2-year and 6-year tests. Samples were vacuum-saturated; the sides were sealed with epoxy paste, then submerged in 3M NaCl at 23°C for either 40 or 120-days, and then ground in 1-mm layers on a milling machine using a 50-mm diameter diamond-tipped bit. Powder samples from selected layers were digested in nitric acid (similar to ASTM C114), filtered, and analyzed for total chloride content by potentiometric titration using 0.01-mol/L silver nitrate and a silver billet electrode. This procedure yields concentration profiles of chloride ion penetration from the exposed surface.

A numerical solution to Fick's second law of diffusion was fitted to the data using least-squares non-linear regression analysis to determine the apparent diffusion coefficient (D_A) and the extrapolated surface concentration (C_S) along with the coefficient of determination (r^2). These values are reported in Table 7 for different ages and ponding durations. After 40-days of ponding, the three ternary blends showed an increased resistance to chloride ion ingress especially at early ages. The least penetrable mixture contained 5.2% SF and 35% slag.

It is apparent that there is little difference in diffusion coefficients of laboratory cylinders for the control mixture (100% OPC) between 28-days and 2-years. However, the 6-year values for the control mixture based on cores taken from the site are much higher, likely due to chloride penetrating the ASR-induced cracks. Concrete mixtures containing blast-furnace slag exhibited decreases in chloride ingress as the concrete matured, whereas the 8% silica fume shows an increase in chloride concentration with maturity, which is consistent with the increase in the charge passed in the ASTM C1260 test. The ternary blends show a relatively similar performance to each other at both ages, suggesting that they achieve a greater resistance to chloride ingress at an earlier age than mixtures with only a single SCM. It is noted that results for all of the 6-year cores from the binary and ternary concrete mixtures are slightly higher than those for the cores tested at 2 years. These small differences are mostly within the precision of the test, with the exception of the 8% silica fume mixture which had the second highest damage rating index after that of the control.

3.8 Surface Chloride Profile Grinding of Field Samples

After two and six winters of deicer salt applications, cores were removed from the field slabs and the surfaces were profile-ground to determine the in-situ chloride concentration profile of the various mixtures. It should be noted that these results do not reflect the effects of diffusion alone. Other transport mechanisms (such as absorption, wetting/drying cycles, chemical binding) are also factors affecting the chloride profile.

In an effort to minimize the effects of these other mechanisms, any data points within the 3-mm surface skin have been neglected in the non-linear regression analysis. It should be noted that although a numeric solution to Fick's second law of diffusion has been fitted to the data to provide apparent diffusion coefficients (D_A) and surface concentration values (C_S), these values are for comparative purposes only and are not meant to represent an accurate model. To simplify calculations, it was assumed that D_A does not change with time, and the time duration was either 2 years or 6 years. Allowances have not been made for material property changes with continued hydration, periods where no salt was applied, periods of freezing, or other factors that vary with time. Table 8 details results from the regression analysis.

A relatively low coefficient of determination (r^2) was obtained for the control mixture due to the scatter of the data even beyond the first 3-mm. While changes between 2 and 6 years exposure in calculated diffusion coefficients were small, results at both ages show that the ternary blends are performing as well or better than the single SCM mixtures. Reductions in the apparent diffusion coefficient of 73% to 82% were observed with respect to the control mixture after 2 years, with reductions of 82% to 93% after 6 years.

3.9 De-Icer Salt-Scaling

The results from the laboratory slab scaling tests were reported previously [16]. Briefly, only the mixture containing 50% blast-furnace slag exceeded the scaling limit, while the 8% silica fume mixture exhibited the least scaling. All three ternary mixtures passed this test, but exhibited a small increase in scaling mass over the control mixture.

Site visual inspection at 6-years showed that none of the ternary blend mixtures exhibited scaling in excess of the control. Some of the damage seen is due to abrasion; there was a lot of grit on the slabs and it was heavily trafficked. There was some minor scaling on the slabs containing blast-furnace slag (Figure 2), with increased scaling with greater replacement levels. The ternary blends and the silica fume mixture are performing as well as the control mixture, but are not exhibiting any ASR-related damage (Figure 1).

4. DISCUSSION

4.1 Effect of Ternary Blends on Expansion due to Alkali-Silica Reaction

Taken collectively, the effect of ASR on the mechanical properties is apparent, with the control mix, which exhibits ASR cracking in the field, showing much reduced stiffness and tensile strength. The mixes with 8% silica fume or 35% slag show some reduction in mechanical properties compared to the other SCM mixes, despite the absence of visible cracking in the field. This could result from the lower SCM contents of these mixes resulting in reduced long-term mechanical properties compared to the other mixes with SCM, but it may also result, at least partially, from some small level of ASR that has not yet manifested itself as visible cracking.

After 8.75-years, expansion values (Table 4) indicate that the ternary blend concretes tested continue to effectively control the expansion due to alkali-silica reaction. Mixtures with 35 and 50% blast-furnace slag were also capable of limiting expansion to below the CSA threshold of 0.04% at 2-years. The GUb-8SF mixture (8% SF) did not suppress expansion to below the 0.04% threshold level at 2-years, but did not expand much more after 8.75-years (but perhaps in part due to alkali leaching from the prisms). Higher levels of replacement than 8% would be necessary using this type of silica fume alone.

The Damage Rating Index of the control mixture was high with a value of 211. The only other concretes with DRI >50 were the ones with (a) 8% silica fume and (b) 35% slag, which is consistent with the observed reduction in mechanical properties. DRI values well below 50 are considered to be insignificant.

The static modulus of elasticity on 6-year cores ranges from 26.1 GPa to 46.9 GPa for the seven concrete mixtures (Table 5). The lowest value was observed for the control mix without SCM and this low value is clearly an indication that some level of deterioration has occurred. The energy dissipated during the first load/unload cycle and the plastic strain remaining after 5 cycles are significantly higher for the control mix compared to the other mixes. The first of these parameters (energy dissipated) has been shown to have the most reliable correlation with expansion for concretes containing the same reactive aggregate [20]. The energy data in Table 4 can be divided into three groups with the energy dissipated being the highest for the control mix and the lowest for the ternary mixes and the mix with 50% slag, and intermediate values being observed for the mixes with 8% silica fume or 35% slag. A similar trend can be seen for the gas-pressure tensile strength data, with the control mix having the lowest strength and the ternary mixes and the mix with 50% slag having the highest strength. However, in this case, only the silica fume mix can be considered as having an intermediate value as the strength of the mix with 35% is not significantly different from the group with the higher values. In Figure 3, although the data points are not well distributed, there appears to be a linear relation between the energy dissipated in the stiffness damage test and the DRI values determined petrographically.

4.2 Resistance to the Ingress of Chloride Ions

The Rapid Chloride Permeability Test (RCPT) provides a useful comparative measure of the transport properties of concrete by measuring the amount of charge passed via electrochemical means. This test indicated greater resistance to chloride ion ingress by the ternary blend concretes, with the 5.2% silica fume and 35% slag mixture performing the best at all ages tested. Similarly, results for MTO's outdoor exposure site in Kingston [23] showed that a blend of 3.8% silica fume and 25% slag caused greater than 70% reduction in the coulombs passed, outperforming the 50% slag mixture.

A comparison of the average diffusion coefficients for all series of tests indicate that the ternary blend concretes are more resistant to chloride ingress than the mixtures with only a single SCM. The mixture with 5.2% silica fume and 35% slag exhibited the lowest diffusion rate.

The evolution of the concentration profiles and diffusion coefficients show that the added presence of the silica fume reduces the higher diffusion rates typically found in the early-age slag mixtures. In turn, the presence of blast-furnace slag helps in providing a later-age decrease in the diffusion coefficient of silica fume mixtures. The ternary blend concretes exhibited diffusion rates that started low and consistently stayed low.

4.3 Salt Scaling Resistance

Previous laboratory work by other researchers have shown that concretes containing either blast-furnace slag or fly ash typically have lower resistances to deicer salt scaling than Portland cement concretes [24-32]. However, reported field observations, including results from the Picton site, have shown satisfactory performance of concretes containing slag despite poor laboratory results [3,11,33]. This highlights the difference in durability performance predicted by laboratory testing versus field exposure. Therefore, interpretation of laboratory scaling data should be done with care, and where possible verified by documented field performance.

5 CONCLUSIONS

The following conclusions can be made from the 6-year tests on the outdoor exposure site:

1. The incorporation of blast-furnace slag into concrete made with silica fume blended cement reduced the water demand (or high-range water reducer dose for equal workability).
2. The combination of silica fume and blast-furnace slag offers increased resistance to ASR expansion and chloride ingress than the use of either of these materials alone.
3. After 6 years, the only concrete exhibiting visual ASR cracking, loss of tensile strength, increased stiffness damage, as well as a high Damage Rating Index (DRI) was the one made with high-alkali Portland cement. The 8% silica fume mix, while not visually cracked is starting to show microstructural indications of ASR problems, based on the DRI and stiffness damage.
4. While, with the exception of the 8% silica fume mixture, the results of laboratory scaling tests indicated that the concretes produced with blended cement had inferior performance compared to plain Portland cement concrete, especially at higher levels of slag, visual observations indicate similar field scaling performance; except for the concrete with 50% slag, which suffered slightly increased scaling.
5. Considering physical properties and durability to ASR, Chloride ingress, and deicer salt scaling, the three ternary blends exhibit superior performance than mixtures with only one SCM or the control.
6. The ASR and chloride resistance durability performance tests conducted in the laboratory appear to be useful for prediction of long-term field performance. The ASTM deicer scaling

test, as modified to measure scaling mass loss appears to be too severe relative to field performance.

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TABLE 1: Chemical analyses of cementitious materials.

Oxide	*Portland Cement (GU)*	*Blended Cement (GUb-8SF)*	*Blast-furnace Slag*
SiO_2	19.59	25.42	35.28
Al_2O_3	5.11	4.84	9.71
Fe_2O_3	2.29	2.28	0.56
CaO	62.66	56.74	40.47
MgO	1.93	1.68	8.76
SO_3	4.19	3.96	3.79
Na_2O	0.27	0.33	0.41
K_2O	1.02	0.98	0.45
Na_2Oe	0.94	0.97	0.71
LOI	2.77	2.96	0.00

TABLE 2: Concrete mixtures and properties (w/cm = 0.42).

Mixture		*OPC*	*SF*	*Slag*	*Na_2O_e*	*Air Content*	*Slump*	*28-Day Comp. Strength (MPa)*
Label	*Code*	*(%)*	*(%)*	*(%)*	*(kg/m³)*	*(%)*	*(mm)*	
100 PC	0/0	100	0	0	3.95	5.3	125	59.9
8SF	8/0	92	8	0	4.07	5.5	120	67.7
35Slag	0/35	65	0	35	2.57	7.2	155	54.1
50Slag	0/50	50	0	50	1.97	5.6	170	43.6
4SF/25Slag	4/25	71	4	25	3.02	5.8	155	68.3
6SF/25Slag	6/25	69	6	25	3.05	5.0	130	63.1
5SF/35Slag	5.2/35	59.8	5.2	35	2.65	5.2	170	68.3

TABLE 3: Damage Ratings of 6-year old Concrete Cores from the Exposure Site.

Mix	Damage Rating Inputs								Damage Rating Index (DRI)
	C. Agg Fracture	C. Agg Crack With Gel	C. Agg Open Crack	C. Agg Debonded	C. Agg Rims	Paste Crack	Paste Crack With Gel	Air void Gel	
100 OPC	48.3	123.1	11.3	0	0	12.1	11.3	4.9	211
8SF	22.7	1.7	1.7	0	0	31.1	0	0.2	57.4
35Slag	40.6	4.8	0	0	0	4.8	0	0	50.1
50Slag	4.9	0	0	0	0	0	0	0.6	4.9
4SF/25Slag	31.9	0	0	0	0.4	3.5	0	0	35.9
6SF/25Slag	2.2	0	1.7	0	0	0	0	0	3.9
5SF/35Slag	5.3	0	1.6	0	0.8	0	0	0	7.6

TABLE 4: Concrete Prism Expansions at 38°C.

% SF / % Slag	*Control*	*Binary*			*Ternary*		
	0/0	*8/0*	*0/35*	*0/50*	*4/25*	*6/25*	*5.2/35*
1 year %	0.231	0.018	0.013	0.007	0.007	0.008	0.008
2 year %	0.238	0.048	0.019	0.006	0.006	0.007	0.007
8.75 year %	0.263	0.046	0.036	0.024	0.024	0.028	0.026

TABLE 5: Results of Stiffness Damage Test and Gas-Pressure Tensile Strength Test.

Mix	*Stiffness Damage Test*			*Gas-Pressure Tensile Strength (MPa)*
	Modulus (GPa)	*Energy dissipated (J/m³)*	*Plastic strain (μm/m)*	
100 OPC	26.1	8.1×10^{-4}	95	2.7
8% SF	39.3	2.0×10^{-4}	11	4.6
35% Slag	36.9	1.6×10^{-4}	15	5.9
50% Slag	42.1	7.5×10^{-5}	8.1	6.1
4% SF & 25% Slag	43.8	6.4×10^{-5}	6.3	6.8
6% SF & 25% Slag	44.1	8.9×10^{-5}	4.8	6.9
5% SF & 35% Slag	46.9	4.9×10^{-5}	21*	5.9

*High result due to "sudden" deformation in last (5th) cycle probably as a result of load platen reseating (plastic strain after 4 cycles only 5.0 μm/m).

TABLE 6: Picton Mixtures: 6-Year Rapid Chloride Index Tests of Field Concretes.

Age	*Specimens*	*Control*	*Binary Mixes*			*Ternary Mixes*		
		0/0	*8/0*	*0/35*	*0/50*	*4/25*	*6/25*	*5.2/35*
NT 492 RMT (10^{-12} m²/s) 6 y	Field core	13.4	5.1	3.4	2.1	3.7	2.0	1.7
ASTM C 1202 18 d	Lab cylinder	4500	420	1170	970	470	390	290
2 y	Lab cylinder	2290	450	470	370	290	240	230
6 y	Field core	2580	580	370	280	270	220	180
Resistivity (ohm-cm)	Field core	24,300	56,700	69,200	91,000	112,400	120,900	141,000

TABLE 7: Picton Mixtures: Results from Laboratory Tests on Chloride Diffusion.

Age & Ponding Time	*Coefficients and Statistics*	*Mixtures (Silica Fume/Slag)*						
		0/0	*8/0*	*0/35*	*0/50*	*4/25*	*6/25*	*5.2/35*
28-Days	D_A (10^{-12} m²/s)	8.5	1.0	2.0	2.5	1.5	1.0	0.8
40-Day	C_S (% mass)	0.94	0.92	1.07	1.26	0.83	0.71	0.64
Ponding	r^2	0.996	0.988	0.997	0.990	0.992	0.985	0.992
2-Years	D_A (10^{-12} m²/s)	8.4	2.9	1.8	1.1	1.0	1.3	0.9
40-Day	C_S (% mass)	1.00	0.90	1.67	1.46	1.27	1.31	1.46
Ponding	r^2	0.981	0.996	0.996	0.998	0.996	0.996	0.990
2-Years	D_A (10^{-12} m²/s)	4.8	1.4	1.3	0.6	0.6	0.7	0.8
120-Day	C_S (% mass)	0.97	1.03	1.32	2.20	1.56	1.46	1.30
Ponding	r^2	0.987	0.986	0.981	0.997	0.990	0.987	0.963
6-Years	D_A (10^{-12} m²/s)	15.4	4.3	2.1	1.3	1.6	1.0	2.0
42-day	C_S (% mass)	0.91	1.05	0.82	0.91	0.99	1.35	0.62
Ponding	r^2	0.99	0.99	1.00	0.98	0.99	0.99	0.97

TABLE 8: Picton Mixtures: Chloride Profiles of Field Concretes.

Age	*Coefficients and Statistics*	*Mixtures (Silica Fume/Slag)*						
		0/0	*8/0*	*0/35*	*0/50*	*4/25*	*6/25*	*5.2/35*
2-Years	D_A (10^{-12} m²/s)	1.1	0.3	0.2	0.2	0.3	0.2	0.2
Field Exposure	C_S (% mass)	0.23	0.38	0.47	0.61	0.33	0.54	0.53
	r^2	0.845	0.999	0.968	0.970	0.977	0.996	0.997
6-Years	D_A (10^{-12}m²/s)	1.38	0.24	0.17	0.25	0.16	0.14	0.12
Field	C_S (% mass)	0.23	0.44	0.45	0.43	0.40	0.47	0.47
Exposure	r^2	0.955	0.95	0.98	0.965	0.98	0.98	0.985
% decrease	@ 2-Years	0%	73%	82%	82%	73%	82%	82%
wrt control	@ 6-Years	0%	83%	88%	82%	88%	90%	93%

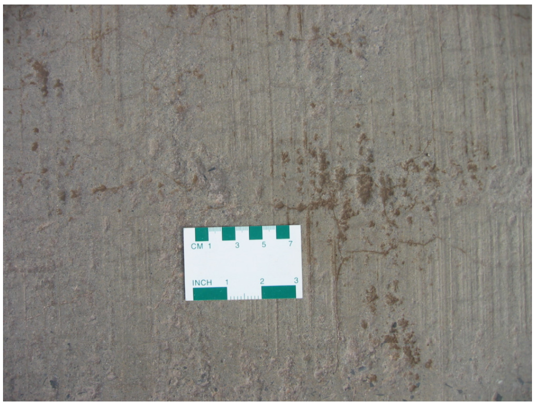

Figure 1: Fine map cracking on 100% PC concrete slab in 2004 at 6 years.

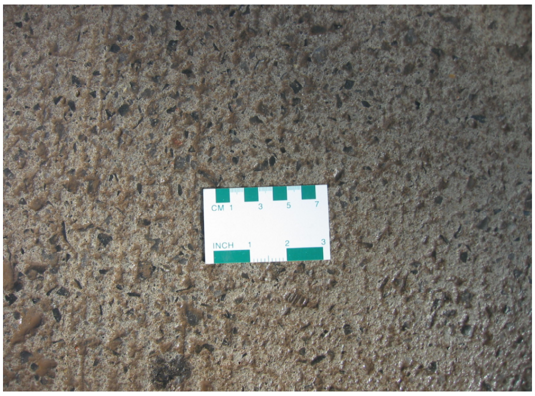

Figure 2: Exposed aggregate on part of 50% slag concrete in 2004 at 6 years due to de-icer scaling and/or abrasion.

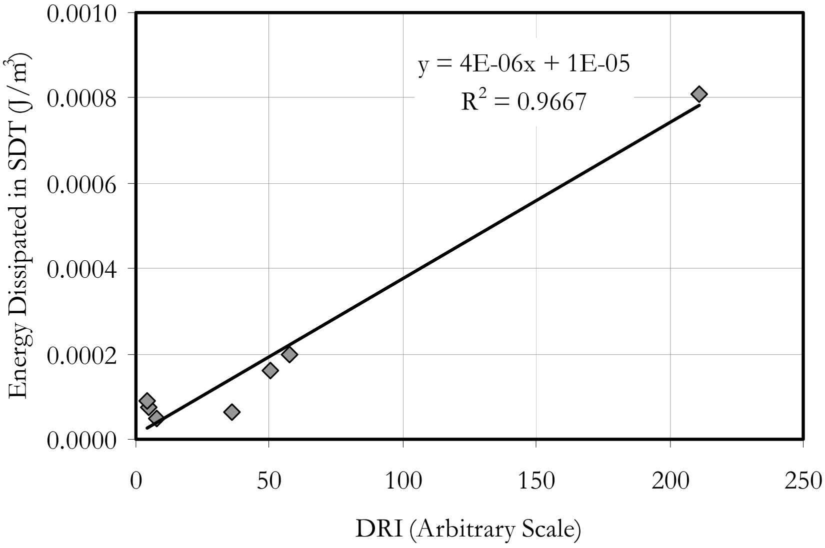

Figure 3: Relation between energy dissipated in stiffness damage test and damage rating index.