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Using Long-Term Outdoor Exposure Data to Benchmark Accelerated Durability Test Methods

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ABSTRACT

Many performance-based durability test methods adopted in various national and international standards were developed decades ago based on short-term evaluations. Most durability tests use various methods to accelerate reactions in order to obtain results in a reasonably short period of time. Then pass/fail criteria are set for these tests in standard specifications. However, the acceleration techniques used maybe overly severe, and preclude the use of concrete materials and mix designs that perform perfectly well in the field. The inclusion of long-term field tests or outdoor exposure tests can be used to verify the appropriateness of both the test methods and the test limits. This provides more confidence that the results from the test methods are meaningful and that the adopted specification limits are appropriate. This approach has been used to verify or modify ASTM and CSA test methods for sulfate resistance, mitigation of alkali-silica reaction, de-icer salt scaling resistance, and for resistance to chloride ingress for marine and deicer exposures. However, in addition to the time and costs for such programs, another limiting factor can be that the materials and mix designs used in the long-term tests may no longer be representative of those currently in use. As another issue, the precision of all test methods needs to be evaluated by inter-laboratory test programs to provide confidence in the reproducibility of test results obtained. This contribution describes results from several long-term test programs and inter-laboratory studies focused on verifying specific standard test methods for durability.

Keywords: durability; test methods; outdoor exposure; alkali-silica reactivity; sulfate resistance; freezing and thawing

1.0 INTRODUCTION

Standard test methods for assessing concrete durability have been developed in most national standards over time. Often these test methods, while rooted in an understanding of the particular degradation mechanism, were only developed based on laboratory evaluation. As well, the test criteria were often set somewhat arbitrarily based on differences between good and bad performance in the laboratory test. Until recently, the accuracy of these North American standard test methods in terms of predicting actual field performance has not been evaluated. There are notable exceptions with some examples including the now-completed Portland Cement Association (PCA) long-term exposure sites for sulfate resistance in Sacramento California (Verbeck 1967, Stark 2002), for freezing and thawing in Skokie Illinois (Kleiger 1956) and the US Army Corps of Engineers marine exposure site in Maine (Thomas 2016). However, while the PCA exposure sites provided information regarding the impact of water to binder ratio and types of cementing materials, the data were not used to calibrate actual standard test methods such as ASTM C666 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing* or C1012 *Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*. However, maximum limits for w/b and entrained air contents for resistance to freezing and thawing did result from Kleiger’s study (1956).

Recently, a number of outdoor exposure sites for assessing resistance to freezing and thawing, deicing salts, marine exposure, and alkali-aggregate attack have been initiated in various countries and data from these sites should prove useful in evaluation of the accuracy of the accelerated performance predicted by laboratory test methods. This contribution describes results from several long-term test programs and inter-laboratory studies that the author has been involved with that have focused on verifying ASTM and CSA standard test methods for durability.

2.0 TESTS FOR ASR MITIGATION

In the Canadian CSA A23.1/A23.2 standards the effectiveness of mitigation of ASR is evaluated using the CSA A23.2-28A (ASTM C1567) rapid mortar bar method (expansion measured after 14 days storage in 1M NaOH solution at 80 ºC needs to be < 0.10%) and the CSA A23.2-14A (ASTM C1293) concrete prism test (expansion of concrete prisms measured after 2 years storage at 100% RH and 38 ºC must be <0.04%). To ensure that these tests and expansion limits are sufficient to prevent ASR damage in structures, long-term evaluation of structures were evaluated as well as performance in field exposure sites. The first exposure site in Kingston, Ontario used concrete made with the reactive Spratt siliceous limestone coarse aggregate, along with six types of cementitious binders at 415 kg/m^3 in air-entrained concretes with w/b ranging from 0.34 to 0.40 (Rogers *et al.*, 2000, Hooton *et al.* 2013). The six binders were: low-alkali portland cement, high-alkali portland cement, then high-alkali cement with 25 or 50% slag, 18% Class F fly ash, and in a ternary blend with 3.8% silica fume and 25% slag. A non-reinforced beam and a steel reinforced beam (steel area of 1.41%) 0.6 x 0.6 x 2 m and a 0.2 x 1.2 x 4 m pavement slab were cast from each mixture. The concrete was compacted and finished by professional concrete finishers. The pavement slabs and beams were cured with wet burlap covered by plastic sheets for 4 days. The concretes beams and slabs were instrumented with expansion studs and were placed outdoors in Kingston Ontario and monitored for 20 years (Hooton *et al.* 2013). Mix designs and expansion test results are provided in Table 1.

Table 1. Mix Proportions and Expansion Values from the Kingston ASR Test Site (Rogers *et al.* 2000, Hooton *et al.* 2013)

	Description	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Portland cement	high-alkali, kg/m^3, 0.79% Na_2Oe	207.5	350.6	311.3	100.4	...	415
	low-alkali, kg/m^3, 0.46% Na_2Oe	...	...	...	...	415	...
Silica fume (SF)	silica-fume blended cement, kg/m^3, 0.88% Na_2Oe (8% silica fume)	...	...	...	210.8	...	...
Slag	granulated blast-furnace slag, kg/m^3, 0.66% Na_2Oe	207.5	...	103.8	103.8	...	...
Fly ash (FA)	Type F, kg/m^3, 0.27% Na_2Oe	...	77	...	...	...	...
Total binder	kg/m^3	415	427.6	415.1	415	415	415
Fine aggregate	natural sand, kg/m^3 + 3% moisture kg/m^3	622	606	628	622	636	636
Coarse aggregate	ASR Spratt quarry, kg/m^3 + 1% moisture kg/m^3	1152	1152	1152	1152	1152	1152
	Effective w/cm	0.38	0.37	0.39	0.34	0.40	0.39
Alkali Loading	kg/m^3 Na_2O equiv. of mix	3.01	2.98	3.14	3.33	1.91	3.28
ASTM C1567	Expansion at 14 days, %	0.059	0.111	0.187	0.041	0.435	0.315
ASTM C1293 (but at alkali loading shown above)	Expansion at 2 years, %	0.03	0.04	0.05	0.02	0.04	0.15
Expansion of unreinforced blocks at 20 years	Expansion, %	0.01	0.08, cracked	0.12, cracked	0.02	0.13, cracked	0.22, cracked

Based on the 14-day mortar bar test, only two of the six mixtures had expansions of less than 0.10%: the 50% slag mix and the ternary blend with 3.8% silica fume and 25% slag. These same two mixtures also had the lowest concrete prism expansions that did not exceed 0.04% until after 6 years (the test limit is 0.04% at 2 years). One other mixture (the 18% fly ash mix) had less than 0.04% expansion at 2 years, but the alkali loadings in these concretes were less than the 5.25 kg/m^3 Na_2O_{eq} specified in the CSA and ASTM test methods, so direct comparison to the 2-year expansion limit of 0.04% is not valid; the 18% fly ash mix did continue to expand above 0.04% by 3 years. The expansions were monitored annually at the same temperature and elements were visually examined for any signs of cracking. The field performance confirmed the predictions obtained from both the mortar bar and concrete prism expansion laboratory tests, the only two concretes that did not crack or expand greater than 0.04% after 20 years were the 50% slag mix and the ternary blend with 3.8% silica fume and 25% slag as shown in Fig. 2. More detailed results are provided elsewhere (Hooton *et al.* 2013).

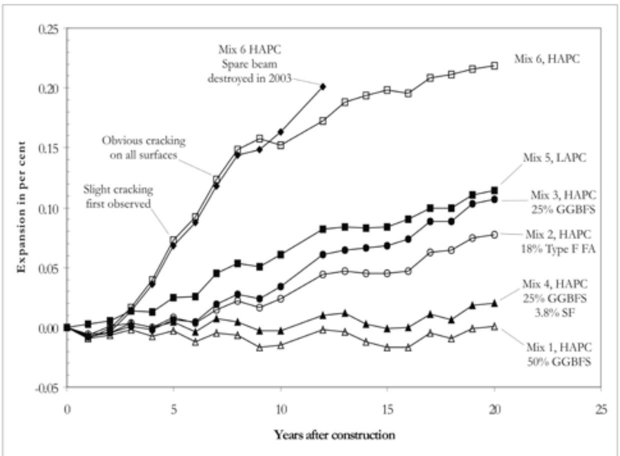

Fig. 1. 20-year Expansions of the Concrete Blocks at the Kingston Exposure Site (Hooton *et al.* 2013)

Since this site was created, several other exposure sites have been established in Canada (Ottawa, Picton, and Toronto Ontario, and Fredericton New Brunswick) and in the USA (Austin Texas, and Corvallis Oregon) that are being used to evaluate a wider range of reactive aggregates and methods of ASR mitigation. The site in Picton, Ontario (Hooton *et al.* 2008) involved seven pavement slabs exposed to heavy truck traffic and deicing salt exposure. Seven different binders were evaluated in air-entrained concretes cast with the alkali-reactive Spratt aggregate, w/b = 0.42 and a binder content of 420 kg/m^3. As shown in Table 2, binders included high-alkali portland cement in a control mixture as well as binary blends, 8% silica fume (SF), 35% slag, 50% slag, and ternary blends, 4%SF+ 25% slag, 6% SF+ 25% slag, and 5.2% SF+ 35% slag.

After 6 years, cores were taken and petrographic analysis and Damage Rating Index values were carried out. The only mixture showing visual damage was the Portland cement control mixtures, while Damage Ratings of that mix and the 8% SF mixture indicated ASR damage. This was found to match predictions based on ASTM C1293 concrete prism expansions, with both those mixtures exceeding the 2-year expansion limit of 0.04%, as shown in Table 3. Additional cores were taken in 2016 after 18 years and it was found that only the two mixtures mentioned above are showing petrographic evidence of damage, while the other five mixtures do not.

Table 2. Concrete Binders and Properties from Picton ASR Exposure Site (Hooton *et al.* 2008)

Mixture Label	Code	OPC (%)	SF (%)	Slag (%)	Na_2O_e (kg/m³)	Air Content (%)	Slump (mm)	28-Day Strength (MPa)
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	6/26	69	6	25	3.05	5	130	63.1
5SF/35Slag	5.2/35	59.8	5.2	35	2.65	5.2	170	68.3

Table 3. 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

As well, the condition of structures built with reactive aggregates and mitigation by SCMs have been monitored. For example, the Lower Notch dam in Ontario was built in 1970 using a known reactive greywacke crushed stone, and a high-alkali portland cement but was mitigated by use of 20% Class F fly ash (30% in mass concrete sections to also reduce heat of hydration). Visual inspection as well as petrographic analysis on cores after 40 years, showed no evidence of ASR (Thomas *et al.* 2012). A series of dams were built on the Magpie River near Wawa, Ontario in 1985 using an alkali-reactive siliceous gravel but using 50% slag for mitigation. The concrete was in excellent condition after 15 years (Hooton *et al.* 2000) and, after more than 30 years, no indications of ASR damage have been reported. A highway bridge was built nearby at the same time using the same aggregate but without the use of slag replacement for cement; it was already exhibiting map cracking after 15 years in service. In addition to the results from the various outdoor exposure sites, these successful field examples of ASR mitigation as well as others across Canada were used to set levels of SCMs in the Prescriptive ASR mitigation option in CSA A23.2-27A. Structures made with reactive aggregates combined with various levels of ASR mitigation continue to be monitored to update the standard recommendations.

3.0 FREEZING AND THAWING TESTS

The ASTM C666 Procedure-A cyclic freezing and thawing test is used to assess the resistance of concrete mixtures. Prisms are cured for 14 days then cycled while immersed in water (in Procedure-B, prisms are frozen in air, but immersed in water while thawing) between +4ºC and -18ºC at 5-8 cycles per day for 300 cycles. Failure is assessed using length and mass change but most commonly by loss of dynamic modulus of elasticity calculated from resonant frequency measurements. Failure limits, based the durability factor which is the percentage loss of the original dynamic modulus normalized to 300 cycles, are often 80% but in some cases 60%. These two versions of ASTM C666 evolved from four older test methods that were deleted after results from an interlaboratory test study showed them not to provide reproducible results (HRB 1959).

While employed at Ontario Hydro in the 1980's the author and colleagues summarized long-term data that related ASTM C666 laboratory results to those of outdoor exposure blocks and laboratory prisms semi-immersed outdoors, as well as to the performance of numerous air and non-air entrained concrete in hydraulic structures (Sturrup *et al.* 1987). In the ASTM C666 Procedure A test, concrete that has been wet cured for 14 days is exposed to between 4 and 6 rapid freezing and thawing cycles per day while immersed in water. It has been found that this accelerated test is more severe than both blocks in outdoor exposure. With the exception of low w/b, high strength silica fume concretes (Hooton 1991), no non-air entrained concrete can pass the ASTM C666 Procedure A test, but in an evaluation of numerous old non-air entrained concrete dams ranging in age from 35 to 50 years, it was found most parts of these structures were undamaged from freezing and thawing provided that the w/b was no higher than 0.50. Even concrete at the waterline on the upstream side of the dams was undamaged in most cases. The damage typically was limited to southern-facing, air-exposed downstream faces where saturation occurred as water was pulled through joints and cracks from the upstream side and, when the surfaces froze, water built up below the concrete surface then when it froze, it expanded and progressively delaminated the concrete at those locations to depths of up to approximately 1 m. These results, reported in 1987, indicated that none of the 15 to 25 year old air-entrained concrete structures exhibited any signs of freeze-thaw damage and it was concluded that air-entrainment was an effective way of preventing damage.

At the exposure site in Toronto both 300 x 300 x 450 mm blocks and ASTM C666 concrete prisms (90 x 100 x 400 mm) made of air-entrained and non-air entrained concretes at w/b of 0.5, 0.6, 0.8 and 1.0 were semi-immersed in water for approximately 22 years. The site in Toronto undergoes between 45-72 freeze-thaw cycles per year based on a freezing temperature in concrete of -3 ºC.

The air-entrained concrete blocks all performed well with only minor scaling at the waterline for the mixtures with w/b of 0.8 and 1.0. This was in general agreement with C666 Procedure A results where there was little damage to the prisms with w/b of 0.5 and 0.6, but reduced durability factors as w/b increased to 0.8 and 1.0.

While the high 1.0 w/b, non-air entrained concrete blocks were completely destroyed, the 0.8 w/b block showed surface scaling, and the blocks with w/b of 0.5 and 0.6 were in excellent condition. As shown in Table 4, this does not agree with results of ASTM C666 Procedure A where the low w/b prisms failed after relatively few cycles. The difference in performance is thought to be due to differences in maturity and degree of saturation at time of freezing-- the blocks were placed outdoors after 28 days and it was several months before the first exposure to freezing whereas in ASTM C666, prisms are wet cured for 14 days then freezing cycles are started. There was better agreement of the outdoor block performance and ASTM C666 Procedure B, where the non-air entrained prisms with w/b of 0.5 and 0.6 had durability factors of 100.

Table 4. Comparison of ASTM C666 Durability Factors to Condition of Outdoor Exposure Blocks after 22 Years for Air-Entrained and Non-Air Entrained Concretes (after Sturrup *et al.* 1987) Note: Relative performance factors of outdoor exposure blocks were calculated similar to the ASTM C666 durability factor (DF) based on both changes in ultrasonic pulse velocity and mass.

			Outdoor Exposure Blocks after 22 Years					
w/b	Air Content (%)	ASTM C666 Proc. A Durability Factor (%)	Change in Pulse Velocity (%)	Length Change (%)	Mass Change (%)	Relative Performance Factor (%) Pulse Vel.	Mass	Visual Rating of Blocks
0.50	1.3	5	106	0	0.31	100	100	0 (excellent)
0.60	1.7	4	106	0	0.52	100	100	0 (excellent)
0.80	1.6	2	97	0.038	-0.31	96	100	0 Above waterline, 1 below
1.00	1.7	1	47*	1.225	-68.42	14	32	4 (rubble)
0.50	5.9	85	104	0.006	-0.32	100	100	0 (excellent)
0.60	6.4	73	104	0.006	-0.11	100	100	0 (excellent)
0.80	5.5	50	101	0.006	0.22	100	100	0 Above/below waterline, 1 at WL
1.00	5.6	30	104	0.019	-1.19	100	98	0 Above/below waterline, 1 at WL

* Pulse Velocity readings no longer possible after 8 years

In spite of the fact that ASTM C666 Procedure A is overly severe to non-air entrained concretes, it continues to be the test most commonly used in North America because the test equipment is more widely available and less expensive.

4.0 DEICER SALT SCALING RESISTANCE TESTS

In the ASTM C672 *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals,* slabs are cast and finished, then wet cured for 14 days followed by 14 days of drying. The finished surfaces are then diked and ponded with a 4% $CaCl_2$ salt solution. The slabs are exposed to 50 cycles of freezing and thawing at one cycle per day of freezing at -18 ºC then thawing at 23 ºC. In a variant used by some agencies, the salt solution used is 3% NaCl. One problem with this test is that it was developed for evaluating portland cement concretes, and it does not provide concretes containing blended cements or SCMs to develop sufficient maturity prior to freezing, this it is overly severe for such concretes. Failure is judged by a visual rating of the finished surface at the end of 50 cycles, although some agencies also use a cumulative scaling mass loss criteria.

As part of a collaborative effort by the City of Montreal and researchers from CANMET, and three Universities, Sherbrooke, Laval and Toronto, a series of sidewalks were cast in Montreal in May 2002 where there is severe freezing and thawing in the presence of de-icer salts. The air-entrained (5 to 8%) concretes were cast at w/b = 0.45 as required in the CSA A23.1 standard and binders containing Portland cement (with 2% silica fume) and mixtures with 25 and 35% Class F fly ash as well as 25 and 35% slag and ternary blends of silica fume (SF) plus fly ash (FA) and silica fume plus slag. Sidewalks were moist cured for 2 days. Some additional sidewalks were placed in the fall of 2002. Companion test slabs were also cast and subjected to the ASTM C672 test as well as a modified test developed in Quebec (BNQ). The modifications consisted of only wood floating the finished surface to avoid premature trowelling, and ponding of the salt solutions for 7 days prior to freeze-thaw cycling, allowing salt penetration into the surface thus lowering the freezing point of the fluid in near-surface pores. Details of these studies are provided elsewhere (Bouzoubaâ *et al.* 2008, 2011). The air void spacing factors of all hardened concretes met the 230 um requirement in CSA A23.1. After 5 winters, the condition of the sidewalks cast in May 2002 was evaluated and it was found that the only significant scaling had occurred with the 35% fly ash concretes. Note: A visual rating system is used in ASTM C672 as shown in Table 5. The visual ratings from BNQ test results agreed with those of field performance but the ASTM C672 visual ratings were far more aggressive, as shown in Table 6.

Table 5. Visual Ratings for De-icer Scaling

Rating	Condition of Surface
0	no scaling
1	very slight scaling (3 mm [⅛ in.] depth, max, no coarse aggregate visible)
2	slight to moderate scaling
3	moderate scaling (some coarse aggregate visible)
4	moderate to severe scaling
5	severe scaling (coarse aggregate visible over entire surface)

In the ASTM C672 test using 3% NaCl solution, the 25 and 35% slag and the 25 and 35% fly ash slabs exhibited higher than acceptable mass losses, as did the 35% slag mix and both ternary blends.

However, then the Quebec version of the test was used, the lab performance better mimicked the field performance. It was also noted, as shown in Table 7, that when cores taken from sidewalk slabs were allowed to mature to 6 months before starting C672 freezing cycles that scaling mass losses were greatly reduced and only the 35% fly ash mix and the two ternary mixes failed the 0.8 kg/m^2 mass loss criteria used by the Ontario Ministry of Transport (MTO).

Table 6. Comparison of Visual Ratings from Sidewalks after 5 Years Exposure to Ratings from ASTM C672 and BNQ Test Methods (Bouzoubaâ *et al.* 2008).

Mixture	Sidewalk Sections	ASTM C672	BNQ
Control	0	1	1
35% FA	2--3	5	2
35% slag	0--1	4	1
25% FA	3	5	3
25% slag	1--2	3	
Ternary SF+ FA	>4	5	
Ternary SF+ Slag	0--1	4	

Table 7. ASTM C672 Deicer Scaling of cores Extracted from sidewalks after 28 and 180 days exposure (Bouzoubaâ *et al.* 2008).

	Cumulative scaling residue (kg/m^2) and (Visual Rating)	
Mixtures	28 days	180 days
Control	2.60 (4)	0.29 (0)
35% FA	3.91 (5)	0.74 (3)
35% slag	1.25 (4)	0.25 (3)
25% FA	2.93 (4)	1.24 (3)
25% slag	0.73 (3)	0.26 (2)
Ternary SF+ FA	3.05 (5)	3.70 (5)
Ternary SF+ Slag	2.18 (5)	1.22 (3)

This is consistent with findings of another field study by Boyd and Hooton (2007) where scaling of test slabs that were field cured for 4 months prior to scaling tests better mimicked field performance than tests starting at 28 days as per ASTM C672.

As a result of these field studies and further laboratory studies (Hooton and Vassilev 2016), CSA adopted a de-icer scaling test based on the Quebec test method. However, agencies using a version of ASTM C672 have not changed and continue to fail concretes with greater than 25% slag or 10% fly ash.

5.0 CHLORIDE PENETRATION TESTS

Concrete cores were obtained in 2001 and 2002 by the Silica Fume Association in the United States from different locations in five bridge decks containing silica fume in New York State and Ohio and four parking garage decks in Wisconsin, Utah, and Ohio. All concrete structures had been in service and exposed to de-icing salts for between 6 and 15 years old when cored. The concretes had w/b ranging from 0.33 to 0.42, silica fume replacements from 6 to 12% and several also contained fly ash. The cores were tested for (a) chloride penetration profiles using mm by mm profile grinding, (b) chloride bulk diffusion by ASTM C1556 *Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion* (similar to Nordtest NT Build 443) on slices taken below the depth of chloride penetration, and (c) rapid chloride penetration by ASTM C1202 *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration* also on slices taken below the depth of chloride penetration.

Hooton *et al.* (2010) tested these cores and found that all of the silica fume concrete bridge decks had high resistance to chloride penetration, with all full-depth decks having average coulomb values ranging from 290 and 690, while the portland cement concrete deck of the same age was 3900 coulombs. For parking decks, coulomb values ranged from 620 to 980. With the exception of a few outliers, ASTM C1556 bulk diffusion results for the silica fume concrete cores ranged from 1.6 to 7.0 x 10^{-12} m^2/s while those of the portland cement concrete ranged from 53 to 59 x 10^{-12} m^2/s. In general, there was a good relationship between the ASTM C1202 and C1556 test results.

In addition, the concrete materials and mix designs as well as the exposure conditions were used to predict time-to-corrosion service life, using the Life-365 model (Ehlen *et al.* 2009). Results indicated residual time-to-corrosion estimates of between 30 and 61 years for all of the silica fume concretes. The chloride penetration into a 5-year old portland cement concrete used in one approach slab to a bridge deck was found to have been sufficient to already cause corrosion of reinforcement at typical depths of cover. In comparison, extrapolating future ingress from existing chloride penetration profiles to predict residual service life were found to be conservative by an average of 10-years for all silica fume concretes in the bridge decks and the parking garage decks.

6.0 SULFATE RESISTANCE TESTS

Since the early 1980s, ASTM C1012 mortar bar expansion test has been used in Canada and the USA to evaluate the resistance of cementitious binders to sulfate attack. In this test, mortar bars are allowed to attain a strength of 20 MPa prior to immersion in solutions of 33,800 mg/L SO_4 as Na_2SO_4. Expansion is measured and limits of 0.10% at 12 months are placed on Sulfate resistant cementitious mixtures (equivalent to an ASTM C150 Type V cement with C_3A < 5%) and 0.10% at 6 month for moderate resistance (equivalent to a Type II cement with C_3A < 8%). The background on the development of this test method was discussed by Hooton and Brown (2009). A precursor of this test was used to evaluate sulfate resistance of cements and slag mixtures (Hooton and Emery 1990). To study slag concrete performance in sulfate exposure, in 1977, eight 3 m^3 batches of air-entrained concrete were mixed in a ready-mixed concrete truck at w/cm = 0.45 and 0.50 using CSA A3000 cement types GU, MS, HS (equivalent to ASTM types I, II, V respectively) and slag-blended cements at different replacement levels (Hooton and Emery 1990). These samples were stored in sodium or magnesium sulfate solutions and kept at room temperature. Once in 1990 and again in 2002, a series of samples from each solution were investigated as detailed previously (Brown *et al.* 2003, 2004). After 38 years, the condition of some of these concretes were investigated (Alapour and Hooton 2017). It was found that damage to Portland cement concretes was related to the C_3A content in the same fashion as predicted by ASTM C1012 bars. It was also found that mixtures containing 45, 65 and 72% slag and a 12.3% C_3A Portland cement showed no visible damage after 38 years immersion in 33,800 mg/L SO_4 as Na_2SO_4, while Type V cement (3.5% C_3A) and Type II cement (7.1% C_3A) concretes were severely damaged. Fig. 2 shows visual condition of concrete cylinders from three of these concrete mixtures. Thus the long-term immersed concrete test results are consistent with the ASTM C1202 mortar bar predictions (expansions at 12 months, 65% slag = 0.07%, HS cement = 0.09%, MS cement > 0.2%).

7.0 SUMMARY

To provide confidence in the results obtained from accelerated laboratory tests for assessing concrete durability in aggressive exposures, test values and adopted specification limits need to be validated with performance in relevant long-term field or at least outdoor exposure. While laboratory tests cannot mimic all the possible variations in field exposure and may not provide quantitative predictions, they should at least be useful in ranking relative field performance. Long-term exposure site and field data can influence changes to test methods and help adopt better test criteria for specifications. The examples discussed are for test programs where the author was involved and only describe a fraction of the many past and current field test programs being conducted for evaluating test methods for ASR, sulfate attack, resistance to freezing and thawing and de-icer penetration and de-icer salt scaling.

Fig. 2. Visual Condition of Concrete Cylinders after 38 Years Immersed in Sodium sulfate Solution: Left: in 3000 ppm SO_4; Right: in 50,000 ppm SO_4
Note: Type GU cement had 12.3% C_3A; Type MS cement had 7.1% C_3A; Type HS cement had 3.5% C_3A

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