#### <u>SP-317—7</u>

# CRITERIA FOR SELECTING MIXTURES RESISTANT TO PHYSICAL SALT ATTACK

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#### SYNOPSIS:

This paper presents the portion of a larger study and pertains to resistance of concrete to physical salt attack. The resistance of concrete to physical salt attack was evaluated by partially immersing concrete prisms in sulfate solution. The physical salt attack test results were correlated with results of rapid index test methods that provide an indication of the transport characteristics of concrete. Rapid index test methods included were the rapid chloride permeability, rapid migration, conductivity, absorption, and initial and secondary sorptivity. A set of tests and specification criteria that can reliably classify mixtures based on their resistance to physical salt attack are proposed. A new test procedure that can evaluate the resistance of concrete to physical salt attack within 50 days has also been developed.

**KEYWORDS:** physical salt attack, PSA, sulfate attack, specifications

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#### **INTRODUCTION**

Exposure to water-soluble sulfate ions from external sources such as in soil, sea water, waste water from industrial facilities, etc. is a major cause of concrete deterioration. Three mechanisms of external sulfate attack are recognized (Kosmatka and Wilson 2011):

- 1. Chemical sulfate attack resulting from reaction of aluminate phases with sulfate ions to form secondary calcium sulfo-aluminate hydrates and gypsum that can cause expansion and cracking (Mehta 1986).
- 2. Physical sulfate attack generally by crystallization of certain sulfate salts in the concrete that can cause surface scaling (Stark 2002, Haynes et al. 1996, Haynes and Bassouni 2011). Other forms of salts such as sodium carbonate and sodium chloride are also reported to cause distress (Haynes et al. 2010) and therefore this type of attack is typically referred to as physical salt attack (PSA). The same terminology is used in this paper.
- 3. Chemical attack on the calcium silicate hydrate matrix with the presence of carbonates, typically at cooler temperatures leading to thaumasite formation (Lamond and Pielert 2006).

Even though the research study looked at both chemical sulfate attack and PSA, this paper presents the portion of the study pertaining to PSA. Water soluble sulfates penetrate concrete by a combination of absorption and diffusion. Resistance of concrete to PSA is primarily governed by the measures that minimize the movement of water in the concrete such as low w/cm, adequate curing, vapor barriers, and use of adequate drainage of water away from concrete (ACI 201.2R).

In this study, the resistance of concrete to PSA was evaluated by partially immersing concrete prisms in sulfate solution. It was examined whether concrete resistance to PSA could be correlated with a rapid index permeability indicator test. These index tests and criteria can then be used to select mixtures resistant to PSA within a testing period of approximately 56 days. The development of a rapid (50 day) PSA test was also evaluated.

#### MATERIALS AND MIXTURE PROPORTIONS

The following materials were used for the concrete mixtures:

- ASTM C150 Type I portland cement (PC-I) with  $C_3A = 12\%$ ;
- ASTM C150 Type II portland cement (PC-II) with  $C_3A = 8\%$ ;
- ASTM C150 Type V portland cement (PC-V) with  $C_3A = 3\%$ , and 5%
- ASTM C618 Class F fly ash (FA);
- ASTM C989 slag cement (SL);
- ASTM C33 No. 57 crushed coarse aggregate;
- ASTM C33 natural sand with an FM=2.88; and
- ASTM C494 Type A and F water reducing chemical admixtures.

The physical and chemical characteristics of the cementitious materials are shown in Table 2. The fly ash is an ASTM C618 Class F fly ash with a low CaO content and the slag cement has a moderate alumina content. Generally these fly ashes and slag cements are expected to demonstrate good chemical sulfate resistance (Dhole et al. 2011; Ogawa et al. 2012; Hooton and Emery 1990) but their resistance to PSA is not well understood.

Sixteen concrete mixtures were made at varying w/cm, portland cement types, SCM types and dosages. The mixtures enabled one to study the effect of  $C_3A$  content of cement, SCM, and w/cm on PSA. All concrete mixtures were non-air-entrained. The Mixture designations were assigned by the w/cm followed by the SCM type, SCM quantity and cement type. For example 0.5SL35-II refers to a mixture with a w/cm of 0.50, 35% slag cement, and Type II cement. Mixtures without SCM used the designation "PC". PC-V1 refers to Type V cement brand 1, and PC-V2 refers to Type V cement brand 2, PC-II refers to Type II cement. The water reducing admixture dosages were adjusted to attain a target slump of 4 to 7 in. (100 to 175 mm). Mixture proportions and test results are provided in Tables 2 and Table 3. Table 2 includes mixtures prepared with Type I and Type II cements while Table 3 includes mixtures with Type II and Type V cements. The mixing water contribution from the chemical admixture was taken into account.

#### PROCEDURES

Concrete mixtures were mixed in a revolving drum laboratory mixer in accordance with ASTM C192. Fresh concrete was tested for slump (C143), temperature (C1064), air content (C231), and density (C138).

For the permeability-related rapid index tests, two curing procedures were adopted:

- 1. Standard curing when specimens were stored in a moist room at 73±3°F (23±2°C) immediately after casting the specimens and for the duration prior to testing.
- 2. Accelerated curing when specimens were subjected to seven days of standard curing followed by 21 days of curing in lime-saturated water at 100°F (38°C). The accelerated most curing procedure is the same as in ASTM C1202 and has been found useful in providing an earlier indication of potential property development with slower hydrating supplementary cementitious materials (Ozyildirim 1998).

Tests on hardened concrete included compressive strength (C39) measured on two 4x8 in. (100x200 mm) cylindrical specimens standard cured and tested at an age of 28 days. Rapid index tests to measure the transport characteristics of concretes included the rapid chloride permeability test (RCPT) (ASTM C1202), absorption, and initial and secondary sorptivity (ASTM C1585). These tests were conducted at the following ages – after 28 day accelerated curing; and after 56 days of standard curing. The durability tests involved casting two 4x8 in. (100x200 mm) cylindrical specimens for each test age and curing condition. The specimens were cut and the top 2 in. from the finished surface was tested. The details of the absorption test has been discussed elsewhere (Obla 2015).

Tests for PSA involved immersion of 3x3x11 <sup>1</sup>/<sub>4</sub> in. (75x75x285 mm) prism specimens to a depth of 5 in. (125 mm) in 10% sodium sulfate solution maintained in a laboratory environment. Sulfate exposure was started after 28 days of moist curing followed by 28 days of air drying. Two prisms were tested for each mixture and the average results are reported. All concrete mixtures were subjected to sulfate exposure for a period of 27 months.

With partial immersion, the primary deterioration mechanism was expected to be due to PSA (Ferraris 2006; Haynes et al. 2008; Haynes et al. 1996; Hartell et al. 2011). This exposure simulates sorption and wicking of sulfate solution in structures. As sulfate solution absorbed by the concrete migrates upwards, evaporation occurs from the exposed specimen surface resulting in salt crystallization. Phases changes with the sulfate salts and precipitation and crystal growth of salts that occupy a larger volume than the salt solution cause scaling and cracking.

The exposed specimen near the solution surface is most susceptible to damage by salt crystallization. Damage in the form of salt crystallization and scaling occurs at the solution surface and progresses upwards with time. For specimens subjected to partial immersion scaling distance, i.e. length of scaling front from solution surface, change in mass and visual deterioration ratings were obtained at different ages. The scaling distance was measured as the vertical distance along the exposed specimen surface between the solution level and the upper most point to which the scaling front had progressed. Crystallized salt was lightly brushed off so that the surface condition was easily visible. The specimen surface was marked in 0.5 in. (12.5 mm) height increments so that the scaling distance could be easily measured. For each specimen the scaling distance along all four specimen surfaces were measured and the average value is reported.

Figure 1 shows the test setup. To prevent evaporation, the solution was covered with a thin film of mineral oil. The specimens were placed inside a plastic tube which prevented contact between the specimen and the mineral oil (Ferraris 2006). The primary mechanism related to PSA, and specific to sodium sulfate, is a crystalline phase change between thenardite (Na<sub>2</sub>SO<sub>4</sub>) and mirabilite (Na<sub>2</sub>SO<sub>4</sub>.10H<sub>2</sub>O) (Haynes et al. 2008) that can occur in normal atmospheric conditions. The latter form has a greater volume that results in deterioration at a drying front, typically at the surface. Figure 2 shows the phase diagram of mirabilite-thenardite conversion under different environmental conditions (Flatt 2002). Significant surface scaling was reported when concrete was subject to numerous cycles of thernardite-mirabilite conversion (Haynes et al. 2008). Weekly temperature and relative humidity (RH) cycling was initiated to promote alternate cycles of conversion between thenardite and mirabilite. The specimens were kept in lab environment of 70°-75°F (21°-24°C) and 44-72% RH for one week followed by one week in an environment of 98°-100°F (37°-38°C) and 21-34% RH. Temperature and RH were measured at a height of 1 in. above the solution surface. The cycling was initiated at 15 months for Table 2 mixtures and at 12 months for Table 3 mixtures. For the initial period the specimens were maintained in the lab environment.

#### **PSA TEST RESULTS**

Mass change data was not useful in evaluating failure due to PSA (Obla 2015). Mass loss occurred both due to surface scaling from PSA and loss of concrete from the immersed portion of the specimen due to chemical sulfate attack. It was not possible to separate the mass loss resulting from each mechanism.

The average scaling distance on partially immersed specimens as a function of duration of exposure is plotted for the different mixtures in Figure 3 and Figure 6. The rate of scaling for all mixtures increased when the weekly temperature/RH cycling was initiated – 15 m for mixtures in the first part (Figure 3) and 12 m for mixtures in the second part (Figure 6). For the two portland cement mixtures at a w/cm of 0.50, similar scaling distances were observed at various exposure ages. The different cement types and associated different C<sub>3</sub>A contents (8% and 12%) did not result in a different rate of deterioration. This tends to validate that the deterioration is due to PSA. For the mixtures containing fly ash and slag cement, the scaling distance at a given age was less for the mixtures with a lower w/cm.

The condition of the specimens after approximately 25 months of exposure in sulfate solutions is shown in Figure 5 and Figure 8. The specimens clearly show surface scaling similar to deicer salt scaling which is indicative of PSA. Average (of all specimen surfaces) visual scaling ratings for each mixture after approximately 25 months of exposure in sulfate solution are reported in Table 2 and Table 3. The scaling ratings are based on those in ASTM C672. Figure 5 shows substantial loss of concrete from the immersed portion of specimens for the two mixtures with a w/cm of 0.60 and the 0.5PC-I mixture. This suggests chemical sulfate attack was predominant for the immersed portion of the specimens for those mixtures. The 0.5PC-II mixture did not suffer significant mass loss from the immersed portion suggesting that the mixture was more resistant to chemical sulfate attack than the 0.5PC-I mixture. The scaling and mass loss of the exposed areas observed in this project was similar to that reported in the literature (Haynes et al. 2008; Hartell et al. 2011).

The specimens were examined petrographically with a stereomicroscope and by thin section analysis with a petrographic microscope at various locations along the specimens (Figure 7). Figure 7a shows significant cracking and microcracking along the edge of the specimen in the exposed area but Figure 7b shows that the cracks are empty (no secondary gypsum or ettringite) and caused by PSA. In general, lesser amounts of secondary gypsum deposits were detected on the exposed area than the immersed area. If gypsum had caused scaling, it would have been observed on the scaled surface as well. But because gypsum was only observed in the interior uncarbonated section within cracks, microcracks, and voids of the immersed area it is likely that the scaling on the exposed surfaces was initiated by the PSA distress mechanism. Subsequently, expansion and cracking occurred by chemical sulfate attack. The aggregate particles within the scaled areas of the specimens were generally cracked and degraded which is symptomatic of PSA.

# Comparison between PC and SCM mixtures

The comparison of the scaling distances between the PC and SCM mixtures is shown in Figure 4 and Figure 8. From Figure 4 it can be seen that the SCM mixtures with a w/cm of 0.40 performed better than the PC mixtures with w/cm of 0.50. The two SCM mixtures at w/cm of 0.60 had similar scaling distances as the PC mixtures with w/cm of 0.50. From Figure 8 it can be seen that the 0.4SL35-II and 0.4FA30-VI mixtures had similar scaling distances as the two 0.45 PC mixtures (less than 3.0 in. (75 mm) after 16 month exposure) but the 0.4SL50-V1 and 0.4FA20-II mixtures

had higher scaling distances. The results seem to suggest mixtures with SCMs may not be worse than portland cement only mixtures but are probably not as effective in minimizing deterioration due to PSA as these materials are in improving resistance to chemical sulfate attack. This can be expected because porosity and sorptivity of concrete play a larger role in PSA than does the composition of the cementitious materials.

## **RAPID INDEX TEST RESULTS RELATED TO PSA TEST RESULTS**

Scaling distances at 19 months for mixtures listed in Table 2 and 16 months for mixtures listed in Table 3. At these exposure ages all specimens had been subjected to four months of temperature and RH cycling. The resistance to PSA for all these mixtures is categorized on the basis of scaling distance in Table 4. The scaling ratings reported in Table 2 and Table 3 resulted in the same categorization of mixtures for resistance to PSA as in Table 4 (Obla 2015).

The correlation between scaling distance and rapid index test results, w/cm, or strength for all the mixtures are provided in Figure 10. Scaling distances at 19 months for mixtures listed in Table 2 and at 16 months for mixtures in Table 3 were considered. These were the same periods used for mixture categorization in Table 4. Compressive strength and w/cm provide the best predictors for mixtures with high resistance to PSA. Other options such as absorption and initial sorptivity appear to have a reasonable correlation; however, it was not possible to choose definitive limiting criteria to characterize mixtures resistant to PSA. The correlation between visual ratings and rapid index test results and mixture indicators provided elsewhere (Obla et al. 2015) confirm that compressive strength and w/cm provide the best predictors for mixtures with high resistance to PSA. Figure 10 shows that a concrete mixture compressive strength of 7000 psi (48 MPa) at 28 days or a maximum w/cm of 0.45 captures all the mixtures that had low scaling distance (<3.0 in. (75 mm)). The 0.4SL50-V1 mixture seems to meet the strength and w/cm requirement but it has a high scaling distance suggesting that high SCM content mixtures need to be tested. For airentrained concrete the corresponding compressive strength criterion can be set at 80% of this value or 5600 psi (39 MPa). The average strengths can be converted to specified strengths based on an NRMCA survey of average levels obtained for specified strength and w/cm. Converting these average strength levels to specified strength requirements translates to 5500 psi (38 MPa) for non-air-entrained concrete and 4500 psi (31 MPa) for air-entrained concrete. Therefore, strength or a w/cm requirement appears to be sufficient for categorizing mixtures with high resistance to PSA. A w/cm requirement of 0.45 has also been suggested in the literature to prevent concrete deterioration from PSA (Haynes et al. 1996, ACI 201.2R). The proposed criteria are summarized in Table 5.

# PROPOSED TEST PROCEDURE FOR RESISTANCE TO PSA

In this portion of the study it was examined whether the PSA test could be further accelerated by starting the temperature and RH cycling at a much earlier age and by using daily instead of weekly cycling.

The 14 mixtures listed in Table 6 were evaluated by this method. The specimens used were 4x8 in. (100 x 200 mm) concrete cylinders. Since this evaluation was performed later in the study, these specimens had already been moist cured for approximately 32 months. The specimens were partially submerged in a 10% sodium sulfate solution to a height of 3 in. (75 mm) and subjected to daily cycling. The specimens were kept in lab environment of 70°-75°F (21°-24°C) and 77-85% RH for 16 h followed by 8 h in an environment of 98°-100°F (31°-38°C) and 21-34% RH. Higher RH was attained in the lab environment by covering the container with a perforated plastic lid. Temperature and RH were measured at a height of 1 in. above the solution surface. This cycling was to promote alternate cycles of conversion between thenardite and mirabilite daily. The specimens were subjected to 50 cycles. At the end of every 10 cycles, the scaling distance and the scaled mass were measured. The scaled mass was measured by washing the cylinders under water above a large pan so that both water and debris could be collected. The water was carefully decanted and the remaining wet scaled material was transferred to a small pan and dried in an oven at 230°-239°F (110°-115°C) for 16 h. The oven dried mass was measured and was recorded as the scaled mass after every 10 cycles. The specimens were also given a visual rating on the degree of deterioration. The results are provided in Table 6 and Figure 11.

The scaled mass with number of cycles, shown in Figure 11, illustrates the relative progressive deterioration of specimens from the different mixtures. The four SCM mixtures with a w/cm of 0.60 and the 0.50FA30-VI mixture had higher amounts of cumulative scaled mass after 50 cycles (between 7.6 and 12.3 g). In contrast, the other nine concrete mixtures had significantly lower amounts of cumulative scaled mass after 50 cycles (less than 2.1 g). The four SCM mixtures with a w/cm of 0.40 had very low amounts of cumulative scaled mass (less than 0.6 g). The 0.40 SCM mixtures had similar or lower cumulative scaled mass than the 0.45PC mixtures (0.1 and 1.6 g) while the 0.50 SCM mixtures had higher cumulative scaled mass (three of them ranged between 1.7 to 2.1 g) than the 0.45PC

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mixtures. This indicates that SCM mixtures did not improve the performance of concrete subjected to PSA when compared to PC mixtures. The SCM mixtures with Type V cement had an average cumulative scaled mass after 50 cycles of 5.3 g as compared to the measured cumulative mass of 3.5 g for SCM mixtures with Type II cement. This confirms that concrete's resistance to PSA is primarily a function of permeability and absorption capacity and not dependent on the type and composition of cement used. The visual rating and scaling distance results after 40 cycles also confirm that (Obla et al. 2015).

The condition of the specimens after 50 cycles in sulfate solution is shown in Figure 12. The specimens are sequentially displayed based on the amount of cumulative scaled mass after 50 cycles. Mixtures with the most amount of scaling (7.6 to 12.3 g) are shown in Figure 12a, followed by mixtures with moderate amount of scaling (1.6 to 2.1 g) in Figure 12b; followed by mixtures with the least amount of scaling (0 to 0.6 g) in Figure 12c. Due to space limitations pictures of all mixtures are not shown. The cumulative scaled mass after 50 cycles is plotted as a function of w/cm and 28 day compressive strength in Figure 13a and Figure 13b respectively. A w/cm of 0.45 or a compressive strength of 7000 psi (48 MPa) are suggested criteria to distinguish mixtures that have a low amount of scaling (< 2 g) due to PSA. Converting this strength to specified strength results in the same requirements identified earlier.

At the end of 50 cycles, the cylinder surfaces were wiped clean. The cylinders were kept in the curing room for one day and tested for strength in accordance with ASTM C39. At this point, the age of the cylinders was approximately 33 months after casting. The strength results are reported in Table 6 and also reported as a ratio of the measured 28 day strength. The strength results were considerably higher than the 28 day strengths for all of the mixtures. Closer evaluation of the ratios is not warranted as the fly ash mixtures gain more strength after 28 days when compared to the PC and SL mixtures. Strength of moist cured cylinders of these mixtures at an age of 43 months is also reported in Table 6. These strength data are plotted in Figure 14. The results indicate that the deterioration due to PSA over the 50 cycle period did not adversely impact the compressive strength of these concrete mixtures.

This proposed test procedure that cycles test specimens through a temperature and humidity range on a daily basis can be a potential method to evaluate concrete mixtures for resistance to PSA within a 50 day period. A shorter moist curing period could be established before specimens are subject to the test. The suggested cycling regime encompasses the temperature and humidity ranges that cause the phase transformation between the forms of sodium sulfate. This method would be appropriate when the concrete will be placed in soil or water that has a higher concentration of sodium sulfate. It would not be applicable for other sulfate salts, such as magnesium sulfate, potassium sulfate, or calcium sulfate (gypsum) because the same mechanism of deterioration is not expected. No distinction is made between different levels of solution concentration in the exposure condition to establish exposure class levels for PSA. It is possible that with lower concentration of sodium sulfate in soil or water, the rate of deterioration due to PSA will be slower.

#### CONCLUSIONS

The following conclusions apply for the mixture variables evaluated in this study:

- 1. A minimum compressive strength or a maximum w/cm requirement as stated in Table 6 appears to be effective in categorizing mixtures with high resistance to PSA. Other rapid index tests such as sorptivity, absorption, and RCPT were not as effective.
- 2. Supplementary cementitious materials such as fly ash and slag cement did not improve the resistance of concrete to PSA. They did not lead to poorer performance either.
- 3. A new test procedure that can evaluate the resistance of concrete to PSA within 50 days has been proposed. More evaluation needs to be carried out before this procedure can be standardized for PSA.

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Item	Type I	Type II	Type V	Type V	Slag Cement	Fly Ash
Cement Type	Ι	II	V-1	V-2	SL	FA
Silicon oxide (SiO <sub>2</sub> ), %	19.3	20.6	22.2	20.7	-	60.5
Aluminum oxide (Al <sub>2</sub> O <sub>3</sub> ), %	5.9	5.0	3.7	4.4	11.8	29.1
Iron oxide (Fe <sub>2</sub> O <sub>3</sub> ), %	1.9	3.2	4.1	4.0	-	2.9
Calcium oxide (CaO), %	62.3	62.8	64.7	64.8	-	0.7
Magnesium oxide (MgO), %	2.9	3.9	1.2	1.6	-	-
Sulfur trioxide (SO <sub>3</sub> ), %	3.9	2.9	2.1	2.5	2.40	0
Loss of Ignition, %	1.5	1.1	0.9	1.1	-	1.3
Fineness 45µm sieve, % retained	-	-	-	-	-	27.2
Blaine (Specific Surface) m <sup>2/</sup> kg	369	376	375	400	426	-
Relative Density	3.15	3.15	3.15	3.15	2.92	2.14
Autoclave Expansion %	-	0.13	-0.02	0.00	-	-0.06
Total Alkali (as Na <sub>2</sub> O eq), %	0.94	0.53	0.41	0.30	0.49	0.54
Tricalcium Silicate (C <sub>3</sub> S), %	53	53	58	64	-	-
Dicalcium silicate (C <sub>2</sub> S), %	16	-	20	11	-	-
Tricalcium Aluminate (C <sub>3</sub> A), %	12	8	3	5	-	-
Tetracalcium Aluminoferrite (C <sub>4</sub> AF), %	6	-	12	12	-	-

Table 1—Chemical and Physical Characteristics of Cementitious Materials

Mixture Designation	0.4SL25-I	0.6SL25-I	0.5PC-I	0.4FA15-I	0.6FA15-I	0.5PC-II					
Calculated Batch Quantities											
Cement Type	Ι	Ι	Ι	Ι	Ι	II					
Cement, lb/yd <sup>3</sup>	457	378	559	519	413	557					
Slag, lb/yd <sup>3</sup>	152	126									
Fly ash, lb/yd <sup>3</sup>				92	73						
SCM, %	25	25	0	15	15	0					
Total cementitious content, lb/yd <sup>3</sup>	609	578	559	611	486	557					
w/cm	0.40	0.56	0.50	0.40	0.60	0.50					
ASTM C494 Type A, oz/cwt	3	3	3	3	3	3					
ASTM C494 Type F, oz/cwt	9.15	0	3	10.29	2	2.41					
Fresh Concrete Properties											
ASTM C143, Slump, in.	5 1/2	6 1/2	7	4	7	5 1/4					
ASTM C138, Air, %	2.0	2.3	2.2	1.9	1.7	2.5					
ASTM C138, Density, lb/ft3	156.9	153.7	154.5	156.1	153.3	154.1					
ASTM C1064, Temperature, °F	72 (22)	72 (22)	73 (23)	72 (22)	72 (22)	72 (22)					
Hardened Concrete Properties											
ASTM C39, Compressive Strength, p	osi				-						
28 days	9,540	5,710	5,690	8,400	4,630	6,440					
Water Absorption Test (drying at 50	°C), % chang	e in mass			1						
28d accelerated cure	0.62	1.34	1.33	0.61	1.13	1.31					
56d standard cure	0.63	1.17	1.04	0.61	1.01	1.23					
ASTM C1202, Rapid Chloride Perm	eability, Coulo	mbs	<b>-</b>		1						
28d accelerated cure	728	1842	3132	509	1849	3459					
56d standard cure	704	1947	2947	913	2627	3610					
ASTM C 1585, Rate of Water Absor	ption (Sorptivi	ity), x10 <sup>-4</sup> mm/s <sup>1/2</sup>	2		-						
28d accel. cure (Initial/Secondary)	2/1.1	4.2/2.2	6.3/4.8	1.8/1.3	5.2/3.1	7.2/3.8					
56d standard cure Initial/Secondary)	3.1/2	8.1/3	5.8/3.3	4/2.4	7.4/4.2	6.2/4.3					
PSA Test Results After Different Periods of Exposure (months)											
Scaling distance, inch											
12 m	0.00	1.38	1.29	0.54	1.71	1.33					
19 m	0.63	4.67	3.83	1.54	3.83	4.58					
23 m	1.92	6.00	6.00	2.88	5.67	5.77					
27 m	2.46	NA	NA	3.50	6.00	6.00					
Visual Rating			n		1						
27 m	2.1	5.0	5.0	2.2	3.8	5.0					

 Table 2—Yield Adjusted Mixture Proportions and Test Results – First Series

**Conversion**: 1 lb/yd<sup>3</sup> = 0.5933 kg/m<sup>3</sup>, 1 oz/cwt = 65.3 ml/100 kg, 1 in. = 25 mm, 1 lb/ft<sup>3</sup>=16.02 kg/m<sup>3</sup>, 145 psi = 1 MPa

Mixture Designation	0.4FA 20-II	0.6FA 20-II	0.4SL 35-II	0.6SL35- II	0.4FA 30-V1	0.6FA 30-V1	0.4SL 50-V1	0.6SL 50-V1	0.45PC -V1	0.45PC- V2
Calculated Batch Quantities										
Cement Type	Π	II	II	II	V-1	V-1	V-1	V-1	V-1	V-2
Type II cement, lb/yd <sup>3</sup>	487	387	391	316						
Type V cement, lb/yd <sup>3</sup>					429	343	300	245	577	581
Slag cement, lb/yd <sup>3</sup>			210	170			300	245		
Fly ash, lb/yd <sup>3</sup>	122	97			184	147				
SCM, %	20	20	35	35	30	30	50	50	0	0
Total cementitious content, lb/yd3	609	483	601	486	613	490	600	490	577	581
w/cm	0.40	0.60	0.40	0.62	0.40	0.60	0.40	0.62	0.45	0.45
ASTM C494 Type A, oz/cwt	3	3	3	3	3	3	3	3	3	3
ASTM C494 Type F, oz/cwt	4.67	0	5.84	0	4.58	0	1.17	0	2.5	2.5
Fresh Concrete Properties	I		I		I			I	I	
ASTM C143, Slump, in.	4.5	5	7	4.5	4.75	7	7	6	4.5	6.5
ASTM C231, Air, %	1.6	1.7	3.2	1.7	2	1	1.7	1.3	1.9	1.6
ASTM C138, Density, lb/ft <sup>3</sup>	155.3	152.5	154.5	153.7	155.3	153.7	154.1	154.5	155.3	156.5
ASTM C1064, Temperature, °F	74	75	72	72	70	70	71	70	72	74
Hardened Concrete Properties										
ASTM C39, Compressive Strength, psi										
28 days	7,490	3,990	10,020	5,730	7,610	3,590	7,500	6,200	8,800	7,720
Water Absorption Test (drying at	50 °C), %	change in m	ass			[	[			
28d accelerated cured	0.96	1.81	0.69	1.14	0.91	1.98	1.08	1.30	1.12	1.30
56d standard cured	0.92	1.65	0.78	1.29	0.93	1.86	1.07	1.52	1.14	0.96
ASTM C1202, Rapid Chloride Per	meability,	Coulombs								
28d accelerated cured	1147	3081	576	1143	592	2618	470	586	2845	3437
56d standard cured	1848	3856	705	1790	1543	4772	593	1077	3456	3905
ASTM C 1585, Rate of Water Abs	orption (Se	orptivity), x	10 <sup>-4</sup> mm/s <sup>1/2</sup>	2						
28d accel. cure (Initial/Secondary) 56d standard cured	1.8/1.6	3.8/4	*	5/2.4	3.2/1.3	15.2/4.4	*	6.2/1.6	5.4/2	8.6/3.3
(Initial/Secondary)	6/2.8	22/11.1	5.4/1.7	12.9/2.2	6.4/2.6	9.4/4	*	6.9/1.8	6.5/2.9	10.3/4.9
PSA Test Results After Different H	Periods of l	Exposure (m	onths)							
Scaling Distance, in.										
9 m	1.19	1.81	0.38	1.81	0.81	1.69	1.56	1.88	0.38	0.56
16m	3.44	4.75	2.44	4.00	2.31	4.94	4.75	5.31	2.13	2.13
20 m	4.50	5.50	3.44	5.75	3.31	5.63	5.38	6.00	3.19	2.56
24 m	4.88	5.63	3.81	6.00	3.75	5.88	5.50	6.00	3.56	3.50
27 m	5.00	5.63	4.50	6.00	4.25	6.00	5.88	6.00	4.25	4.00
Visual Rating										
24 m	3.6	4.3	2.5	4.6	2.6	4.0	3.9	5.0	1.8	2.3

#### Table 3—Yield Adjusted Mixture Proportions and Test Results – Second Series

No correlations were found, so data is unavailable

Resistance to PSA	Mixtures
Low	0.5PC-I, 0.5PC-II, 0.6FA15-I, 0.4FA20-II, 0.6FA20-II, 0.6FA30-V1, 0.4SL50-V1, 0.6SL25-I, 0.6SL35-II, 0.6SL50-V1
High	0.45PC-V1, 0.45PC-V2, 0.4FA15-I, 0.4FA30-V1, 0.4SL25-I, 0.4SL35-II

Table 4—Categorization Based on Resistance to Physical Salt Attack

Basis for Categorizing Mixtures: Low - > 3.0 in. (75 mm) High - scaling distance  $\leq$  3.0 in. (75 mm)

# Table 5—Performance Criteria for Physical Salt Attack

Resistance to PSA	Prescriptive option	Performance Option, psi (MPa)
High	$w/cm \le 0.45$	Compressive Strength $\geq$ 4500* (31)*

\*for air-entrained concrete. For non-air-entrained concrete increase specified strength by 20%.

## Table 6—Results from Proposed PSA Test

1 4010 0	itesu	its if on	111000	seu i oi	1 1 656									
Mixture	0.4FA	0.5FA	0.6FA	0.4SL	0.5SL	0.6SL	0.4FA	0.5FA3	0.6FA	0.4SL	0.5SL5	0.6SL	0.45PC	0.45PC
Designation	20-II	20-II	20-II	35-II	35-II	35-II	30-V1	0-V1	30-V1	50-V1	0-V1	50-V1	-V1	-V2
Scaling Measurements														
Scaled Length	, in.		r	r	r				r	r		r		
40 cycles	1	1	2.5	0.5	1	1.5	0.5	1.5	2	1	1.5	2.5	0.5	1.5
50 cycles	1	2	2.5	0.5	1.5	2	1	2	2.5	1.5	2	3	1	2
Cumulative So	Cumulative Scaled Mass, g													
50 cycles	0.2	1.7	9.1	0.0	2.1	8.0	0.1	7.6	12.3	0.6	1.7	9.8	0.1	1.6
Visual Rating														
40 cycles	1	2	4	1	2	4	1	3	4	1	2	4	1	1
50 cycles	1	3	5	1	4	4	1	4	4	2	3	4	1	3
Compressive S	Strength,	psi - use '	"comma"	for num	bers									
After the Test	10810	7840	5970	12690	8580	7360	11640	8960	6150	9470	9960	8090	10880	10540
Factor of 28	1.44	1 49	1.50	1.27	1.27	1.29	1.52	1.94	1 71	1.26	1.22	1.20	1.24	1.27
day Strength	1.44	1.48	1.50	1.27	1.27	1.28	1.55	1.84	1./1	1.20	1.33	1.30	1.24	1.37
44 months standard	10105	7200		110/0	0005	70.50	11570	7000	6625	0.075	10510	0205	10(00	0565
cured	10125	/290	5/00	11860	8205	/250	11570	/800	6635	9675	10510	8305	10680	9565

**Conversion**: 1 in. = 25 mm, 145 psi = 1 MPa

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Figure 1— Partially Immersed PSA Test Specimens



Figure 2—Sodium Sulfate Conversions under Different Environmental Conditions (Flatt 2002)



Figure 3—PSA Test Results - Scaling Distance from Immersion Line Vs Exposure Age



Figure 4—PSA Test Results – 19 month Scaling Distance Comparison between PC and SCM Mixtures



(a)



(c) Figure 5— PSA Test Specimens after 27 months (a) 25% slag cement mixtures, (b) 15% fly ash mixtures, and (c) Portland cement mixtures



Figure 6— PSA Test Results - Scaling Distance from Immersion Line Vs Exposure Age (a) SCM Mixtures with Type II Cement (b) Mixtures with Type V Cements



(a) (b) Figure 7—Cross-sectional Image showing Cracks and Microcracks (a) Thin section (b) Crossed Polars



Figure 8—PSA Test Results - 16 month Scaling Distance Comparison Between PC and SCM mixtures



(a)

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(d)



(e)

Figure 9— PSA Test Specimens after 23 months (a) 20% fly ash mixtures, (b) 35% slag cement mixtures, (c) 30% fly ash mixtures, (d) 50% slag cement mixtures, and (e) portland cement mixtures





Figure 10— PSA Test Results (a) – (d) Correlation Between Scaling Distance and 56d Standard Cured Rapid Index Test Results, (e) – (f) Correlation Between Scaling Distance and 28d Compressive Strength, W/CM Respectively



Figure 11—Results of the Proposed PSA Test, Scaled Mass Vs Number of Cycles



Figure 12—PSA Test Specimens after 50 Cycles (Proposed PSA Test Procedure) (a) Cumulative Scaled Mass (7.6 to 12.3 g); (b) Cumulative Scaled Mass (1.6 to 2.1 g); (c) Cumulative Scaled Mass (0 – 0.6g)



Figure 13— Correlation between Cumulative Scaled Mass (Proposed PSA Test Procedure) after 50 Cycles and (a) W/CM, (b) 28d Compressive Strength



Figure 14—Compressive Strength Results of Specimens after the New PSA Test