An Evaluation of Performance-Based Alternatives to the Durability Provisions of the ACI 318 Building Code

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Please note: This report, also funded in part by the Portland Cement Association, was part of a larger project – TPF-5(179) – and included funding from the Pooled-Fund Study Program.

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Final Report

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1. Introduction

Concrete, especially for improved durability, is typically specified with prescriptive provisions. More recently there has been increasing interest in evolving towards performance-based specifications, both within state highway agencies and industry. One of the challenges in successfully implementing performance-based specifications is the existence and use of reliable test methods and specification criteria that can measure the potential durability of concrete mixtures and provide the expected service life. An important objective of this state pooled fund research project is to propose performance criteria for concrete that will be resistant to penetration of chlorides, cycles of freezing and thawing, and sulfate attack.

2. Exposure to Chlorides

Corrosion of steel is the primary cause of deterioration of reinforced concrete in transportation infrastructure. The principal factor causing corrosion is the ingress of chlorides resulting from the application of deicing salts or exposure to a marine environment. Carbonation is another factor, typically of lesser significance in the US. Carbonation occurs in dry concrete and the rate of carbonation has been correlated to air permeability and oxygen permeability of the concrete (Parrott 1996; Beushausen and Alexander 2008). Good quality concrete that resists the ingress of chlorides will generally not be susceptible to carbonation-related corrosion. When chloride ions at the steel exceed a threshold concentration, initiation of steel reinforcement corrosion occurs. Initiation of corrosion can be delayed by ensuring adequate cover and using good quality concrete (Broomfield 1997; Bentur et al. 1998). Use of corrosion inhibitors and alternative types of steel are other methods to minimize deterioration of concrete structures due to corrosion (Berke and Rosenburg 1989, Nmai et al. 1992).

The apparent chloride diffusion coefficient (D_a) of concrete, measured in accordance with ASTM C1556 (ASTM 2011), has been widely used in service life prediction of reinforced concrete exposed to chlorides (ACI Committee 365 2000; Thomas and Jones 1996). ASTM C1556 is an involved test method that takes a long time for results and is not conducive to pre-qualification and acceptance of concrete mixtures on projects. This portion of the research project evaluates several rapid index tests that simulate the transport characteristics of concrete and to recommend criteria that correlate well with the measured $D_{a.}$ These index tests and criteria can then be used to select mixtures of the desired chloride penetrability level within a testing period of about 56 days.

In concrete members that are exposed to moisture and close to a saturated condition, chloride ingress is primarily diffusion controlled. This is applicable for structures in a submerged marine exposure or possibly bridge decks in regions of higher precipitation and high humidity. In structures not exposed to water and in a drier condition, chloride ingress results by a combination of absorption and diffusion. To simulate these different service conditions, in this study, specimens, following initial curing, were subjected to either immersion in chloride solution or to a cyclic wetting and drying exposure in a chloride solution.

2.1 Literature Review

Fundamental mechanisms that involve transport of fluid and chemical species in cementitious systems and types of measurements are well discussed (Garboczi 1990; Martys 1995). A literature review of various tests to evaluate chloride penetration in concrete was commissioned by the Federal Highway Administration in an attempt to develop performance-based criteria for concrete pavements and bridge structures (Stanish et al. 1997). This reference discusses the mechanisms of chloride penetration and the characteristics of concrete mixtures that impact chloride penetrability. Longer term tests are discussed as well as a need for shorter term tests that could be used for mixture qualification, quality control and quality assurance of concrete mixtures used for transportation projects. The methods involved longer term diffusion tests, electrical methods and sorption methods to evaluate concrete mixtures with different w/cm and cementitious composition. A comprehensive evaluation of methods was also reported in Europe (RILEM TC 116 1989; RILEM TC 189 2008). An evaluation of the South African Durability Index concept to other tests used internationally was also reported (Beushausen and Alexander 2008). The South African Durability Index is established based on gas permeability, chloride ingress, and water penetrability measurements.

The popular test in the US for concrete mixture evaluation has been the Rapid Chloride Permeability Test (ASTM C1202; AASHTO T277) developed in the 1980s (Whiting 1981; Whiting and Mitchell 1992). The test measures the charge passed through a saturated concrete specimen with an electrical potential and the lesser charge passed was an indication of lower permeability or diffusion characteristics. In essence it is measuring the conductivity of concrete. As originally developed, the intent was to establish a correlation with the ponding test (AASHTO T259; ASTM C1543). The conductivity of the concrete is correlated to its diffusivity through the Nernst-Einstein equation (Shane et al. 1997) as follows:

$$\frac{\sigma}{\sigma_0} = \frac{D}{D_0} = FF$$

Where
σ = Overall bulk conductivity of concrete
σ_0 = Pore solution conductivity of concrete
D = Diffusivity of chloride ion in concrete
D_0 = Intrinsic diffusivity of chloride ion in pore solution
FF = Formation factor which is a function of porosity and pore connectivity in concrete

D_o is readily available in literature and does not show more than a 15% change from pure water to concentrated (0.5 molar) solution (Shane et al. 1997). σ_0 does vary between different concrete mixtures and can be measured by expressing the pore fluid from the hardened concrete or estimated based on chemical analysis of the cementitious materials (Snyder et al. 2003).

There have been considerable evaluations on whether ASTM C1202 provides an accurate indicator of the transport characteristics of concrete and whether it can be used to obtain an estimate of the diffusion coefficient of concrete to chloride penetration for service life modeling (Feldman et al. 1994; Mobasher and Mitchell 1988). In some work, concretes with low RCPT results (coulombs) had a high effective diffusion coefficient (Mackechnie and Alexander 2000). Ponding test results (AASHTO T259) do not always correlate well to the measured coulombs measured by ASTM C1202 (Scanlon and Sherman 1996, Pfeifer et al. 1994). The pore solution conductivity of the concrete is influenced by the use of pozzolanic materials and slag cement or certain admixtures like calcium nitrite. In particular, silica fume was reported to strongly influence pore solution conductivity (Shi et al. 1998; Liu and Beaudoin 2000; Lopez and Gonzalez 1993). Hence, the authors argued that it is possible to obtain a low indication of transport characteristics for a concrete mixture that has higher diffusion characteristics. For this reason, it has been suggested that correlations with ponding or other penetration type tests be developed for mixtures with specific cementitious material combinations. Other research studies indicate reasonable confidence with using ASTM C1202 to evaluate mixtures containing supplementary cementitious materials, provided the concrete mixtures are cured for a longer period for the SCMs to contribute to the beneficial performance of concrete (Oziyilidirim and Halstead 1988; Plauto and Bilodeau 1989). Various improvements to ASTM C1202 have been suggested (Feldman et al. 1994) to improve the reliability of the method, including saturating the specimens in a sodium chloride solution to minimize the impact of pore solution on the measured result (Streicher and Alexander 1995).

Variations of electrical measurements on concrete have been suggested by other researchers (Tang 1996; Stanish et al. 2004; Riding et al. 2008). The electrical conductivity of concrete can be measured on concrete using the same equipment used for ASTM C1202 and this method has been standardized (ASTM C1760). Surface or axial resistivity of concrete using the Wenner Probe is another electrical measurement that can be performed rapidly and with appropriate corrections addressed in this research program, reliable index measurements of the transport characteristics of concrete can be obtained (Presuel-Moreno et al. 2009; Rupnow and Icenogle 2011; Spragg et al. 2011).

2.2 Materials and Mixture Proportions

The following materials were used for the concrete mixtures:

- ASTM C150 Type II portland cement (PC) with C_3A = 8%, Lot 8209C;
- ASTM C618 Class F fly ash (FA), Lot 8209E;
- ASTM C989 slag cement (SL), Lot 8209D;
- ASTM C1240 silica fume (SF), Lot 8209F;
- ASTM C33 No. 57 crushed coarse aggregate, Lot 8209B;
- ASTM C33 natural sand with an FM=2.88, Lot 8209A;
- ASTM C494 Type A, Lot 8209I, polycarboxylate based; and
- ASTM C494 Type F, Lot 8209G, polycarboxylate based.

Mixture parameters were selected to ensure the following requirements:

1. Water-to-cementitious material ratio (w/cm) and supplementary cementitious material (SCM) types and quantities were chosen to cover the ranges typically used in high performance concrete.
2. The study was designed to use mixtures with a broad range of predicted D_a values. The two year predicted D_a for different mixture compositions was based on the Life 365 model and varied between 6.8×10^{-12} and 0.62×10^{-12} m^2/s.
3. Additionally, mixtures with high w/cm and high SCM dosages as well as mixtures with very low w/cm and no SCM were prepared. For example the two year predicted D_a for the 50% slag cement mixture with a w/cm of 0.62 was 5.4×10^{-12} m^2/s and for the PC mixture with a w/cm of

0.29 was $2.3x10^{-12}$ m^2/s. These mixtures were used with the intent to see whether the rapid index tests would reliably classify these mixtures according to the measured D_a.

Due to the number of tests planned and scheduling involved the 13 concrete mixtures were cast in two phases for this portion of the study. The mixtures were non-air-entrained. While it is recognized that concrete subject to cycles of freezing and thawing will need to be air-entrained, it was decided to eliminate this variable. It was felt that this validation will hold true for air-entrained concrete mixtures.

Mixture designations were assigned by the w/cm followed by the SCM type and dosage. For example, 0.49SL25 refers to mixture with a w/cm of 0.49 and 25% slag cement. Mixtures without SCM use the designation “PC”. The six concrete mixtures evaluated in Phase I and test results are provided in Table 2.1. The seven mixtures evaluated in Phase II and test results are provided in Table 2.2. The water reducing admixture dosages were adjusted to attain a target slump of 5 to 7 in.

2.3 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).

Two types of curing of the specimens were followed:

- Standard curing when specimens were stored in a moist room at 73±3°F immediately after casting the specimens for the duration prior to testing.
- Accelerated curing when specimens were subjected to seven days of standard curing followed by 21 days of curing in water at 100°F.

Tests on hardened concrete included compressive strength (C39) on two 4x8 in. cylindrical specimens standard cured and tested at an age of 28 days and length change (C157) on three 3x3x11 ¼ in. prisms, with seven days standard curing followed by up to 180 days of air drying in a 70°F, 50% RH environment.

Rapid index tests to measure the transport characteristics of concretes included the rapid chloride permeability test (RCPT) (ASTM C1202), rapid migration test (RMT) (AASHTO TP 64), conductivity, 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, 26 weeks, and 78 weeks (in some cases in Phase I) of standard curing. The durability tests involved casting two 4x8 in. cylindrical specimens for each test age and curing condition. The specimens were cut and only the top 2 in. from the finished surface was subjected to the test.

The conductivity and absorption tests are described below. ASTM has recently developed a test method for bulk electrical conductivity (ASTM C1760-12) and bulk water sorption (ASTM C1757-13). The conductivity and absorption tests described below differ from the ASTM test methods as this research was performed prior to the publication of these test methods.

The conductivity test was similar to the RCPT with the exception that it uses a 0.3N sodium hydroxide solution on both sides of the cell with an applied voltage of 60 V. The test was performed for five minutes after which the current reading (I) is recorded.

Conductivity (σ) is calculated in S/m (Siemens/meter) which is the metric unit for conductivity (siemens has a unit of 1/ohm). Conductivity is the inverse of resistivity. The conductivity is calculated as follows:

$$\sigma = \frac{I \times L}{V \times A}$$

where
V=applied voltage, V
I=measured current, amps
A=specimen cross-sectional area, mm^2
L = specimen length, mm.

The absorption test is based on the British Standard, BS 1881. It involves oven drying the specimen for 72±2 h followed by cooling for 24±0.5 h in a dry air-tight vessel. The specimen is immersed in water for 30±0.5 min and the quantity of water absorbed by the specimen is determined. Absorption is calculated as a percent increase in mass from the dried condition. For Phase I, the oven temperature was maintained at 220°F; whereas for Phase II, it was set at 140°F. The lower temperature was used for Phase II because it was felt that the high oven temperatures may lead to internal micro-cracking of concrete that could elevate the measured absorption of the concrete specimen being tested.

Testing to measure D_a, in accordance with ASTM C1556, involved casting two 4x8 in. cylindrical specimens. After being subjected to varying periods of standard curing, the specimens were cut at 3 in. from the finished surface. The sides of the specimens were coated with an epoxy and the specimens were immersed in an aqueous solution of sodium chloride. Chloride diffusion occurs from the finished surface of the specimen.

Specimens for measuring the apparent diffusion coefficient, D_a, were subjected to the following conditioning:

Phase I

i) 6 m standard curing + 35 days in solution
ii) 59 days standard curing + 16 m in solution – referred to as "Phase I Immersed"
iii) 59 days standard curing + cyclic wet/dry exposure to chloride solution for 4 m (4 days in chloride solution/3 days at 100°F air at 20% RH) – referred to as "Phase I Cyclic"

Phase II

i) 56 days standard curing + 35 days in solution
ii) 6 m standard curing + 35 days in solution
iii) 6 m standard curing + 15 m in solution – referred to as "Phase II Immersed"
iv) 56 days standard curing + cyclic wet/dry exposure to chloride solution for 5 m (3 days in chloride solution/4d at 73°F air at 50% RH)

v) 56 days standard curing + cyclic wet/dry exposure to chloride solution for 18 m (3 days in chloride solution/4d at 73°F air at 50% RH) – referred to as “Phase II Cyclic”

2.4 Discussions on ASTM C1556 Results (Phase I)

For the Phase I mixtures, the chloride profiles of specimens subjected to immersion or cyclic wet/dry exposure to chloride solution are plotted in Figure 2.1. The calculated D_a values for these mixtures are reported in Table 2.1.

1. Observations are made for results depicted in Figure 2.1b and 2.1c for specimens that were exposed for a longer duration of exposure to chloride solution. Based on the chloride profiles shown in Figure 2.1b for the Phase I immersed condition the best performing mixes (showing low chloride ingress) in order were 0.34SL40SF5=0.39SL50<0.39FA30<0.49SL25<0.49FA15<0.49PC.
   Based on the chloride profiles shown in Figure 2.1c for the Phase I cyclic condition the best performing mixtures (showing low chloride ingress) in order were 0.34SL40SF5=0.39SL50<0.49SL25=0.39FA30<0.49FA15<0.49PC. The 0.49SL25 mixture has a similar chloride profile as the 0.39FA30 mixture in the cyclic condition but shows greater chloride ingress in the immersed condition. This fly ash mixture had a lower level of chloride ingress when subjected to long term immersed condition when compared specimens immersed in the cyclic exposure. This is likely related to the higher early age absorption characteristics, as indicated by the sorptivity values, of the fly ash mixture relative to the slag mixture.
2. The D_a values for the Phase I mixtures are reported in Table 2.1 based on the chloride profiles in Figure 2.1b (Phase I immersed). The best performing mixtures (from the lowest D_a) in order were 0.34SL40SF5<0.39SL50<0.39FA30<0.49SL25<0.49FA15<0.49PC.
   The D_a values for the Phase I mixtures reported in Table 2.1 based on the chloride profiles in Figure 2.1c (Phase I cyclic). The best performing mixtures (from the lowest diffusion coefficient) in order were 0.34SL40SF5<0.39SL50<0.49SL25=0.39FA30<0.49FA15<0.49PC. The rankings of the mixtures based on visual observation of the chloride profiles and the chloride diffusion coefficient calculation are similar except for the 0.34SL40SF5 and 0.39SL50 mixtures which can be due to differences in the surface chloride content estimation. The D_a value is used for service life estimation and is the mixture parameter discussed in subsequent analysis. A visual observation of the chloride profiles is useful to ensure that the classification of the performance of these mixtures is generally similar to that surmised from the D_a values.
3. The range of D_a values for the Phase I mixtures in the different exposure conditions are as follows:
   i) 6m standard cured + 35d in solution - 0.35 to 3.29 $\times 10^{-12}$ m^2/s
   ii) Phase I immersed - 0.35 to 12.94 $\times 10^{-12}$ m^2/s
   iii) Phase I cyclic – 0.82 to 11.07 $\times 10^{-12}$ m^2/s

   There is at least one order of magnitude difference in the range of the D_a values for the Phase I mixture in each condition evaluated. This illustrates the broad range of D_a values for concrete mixtures possible with the materials and mixture proportions commonly used.

2.5 Discussions on Chloride ASTM C1556 Results (Phase II)

For the Phase II mixtures, the chloride profiles of specimens subjected to immersion or cyclic wet/dry exposure to chloride solution are plotted in Figure 2.2. The calculated D_a values for these mixtures are reported in Table 2.2.

1. Observations are made for the results depicted in Figure 2.2c and 2.2e for the specimens subjected to longer duration of exposure to chloride solution. Based on the chloride profiles shown in Figure 2.2 for the Phase II immersed condition the best performing mixtures (showing low chloride ingress) in order were 0.39SF7<0.29PC=0.62SL50<039FA15<0.39SL25=0.62FA30<0.39PC.
   Based on the chloride profiles shown in Figure 2.2 for the Phase II cyclic condition the best performing mixtures (showing low chloride ingress) in order were 0.29PC=0.39SF7=0.39SL25<0.39FA15<0.39PC=0.62SL50<0.62FA30.
   The 0.39SL25 seems to perform better than the 0.39FA15 mixture in the cyclic condition whereas the situation is the reversed for the immersed condition. Similar to Phase I, the fly ash mixture performed better in long term immersed condition relative to the cyclic condition.
2. The D_a values reported in Table 2.2 are based on the chloride profiles in Figure 2.2 (Phase II immersed). The best performing mixtures (from the lowest diffusion coefficient) in order were 0.39SF7<0.29PC=0.62SL50=039FA15<0.39SL25=0.62FA30<0.39PC.
   The D_a values reported in Table 2.2 are based on the chloride profiles in Figure 2.2 (Phase II cyclic). The best performing mixtures (from the lowest diffusion coefficient) in order were 0.29PC=0.39SF7=0.39SL25<0.39FA15<0.39PC=0.62SL50<0.62FA30.
   The performance rankings of the mixtures based on visual observation of the chloride profiles and the chloride diffusion coefficient calculation are essentially similar. For the immersed condition minor differences are attributed to the variation in the measured surface chloride content. The two mixtures with a 0.62 w/cm performed better in the immersed condition relative to the cyclic wetting and drying condition. The D_a values of specimens subject to the immersed condition are generally similar to those subject to the cyclic condition. Exception to this is observed for two mixtures with 0.62 w/cm. Significantly lower D_a values were determined for the specimens subjected to the immersed condition. The cyclic condition involves chloride ingress into a partially saturated concrete surface. It appears that mixtures with a lower w/cm performed better in the cyclic condition due to the tighter pore structure at the concrete surface and difference in drying rates.
3. For a given duration of chloride exposure the longer the initial curing period the lower should be the chloride diffusion coefficient since concrete undergoes pore refinement with continued hydration. For the same reason for a given curing duration the longer the chloride exposure the lower should be the chloride diffusion coefficient. As the duration of chloride exposure increases due to ongoing pore refinement it would become harder and harder for the chloride ions to penetrate inwards and as a result the calculated D_a values over the entire exposure period will also decrease. The above two conditions are satisfied for all seven concrete mixtures.
4. The range of the D_a values for Phase II mixtures in the different conditions are as follows:
   i) 56d standard + 35d in solution - 1.18 to 8.30 $x10^{-12}$ m^2/s
   ii) 6m standard + 35d in solution - 0.67 to 8.23 $x10^{-12}$ m^2/s
   iii) Phase II immersed - 0.22 to 1.75 $x10^{-12}$ m^2/s

iv) 56d standard + 5m cyclic – 0.90 to 12.08 x10^{-12} m^2/s
v) Phase II cyclic - 0.35 to 7.10 x10^{-12} m^2/s

For the Phase II mixtures at least one order of magnitude is observed for the range of the D_a values in each condition evaluated.

2.6 Correlating the Apparent Diffusion Coefficient and Rapid Index Test Results

The purpose of this study is to establish which of the rapid index tests performed best predicts the transport characteristics of concrete as indicated by the D_a value. For this purpose, a linear correlation between results of rapid index tests and the D_a values of specimens subjected to the longest period of chloride exposure was determined. The coefficient of determination (R^2) of the correlations is used as the statistical parameter for the analysis. The R^2 values between each of the rapid index test results and the D_a values are summarized in Table 2.3. An R^2 value of 1 indicates a perfect linear correlation.

For the rapid index tests, specimens were standard cured for 56 days and accelerated cured for 28 days. In Table 2.3, the R^2 values for the rapid index test results for 56-day standard-cured specimens are reported first followed by the R^2 values for 28-day accelerated cured specimens. The R^2 values beween rapid index test results and D_a measured on specimens in the immersed and cyclic conditions and the overall average R^2 values for both immersed and cyclic conditions have been included in Table 2.3.

Between the 56-day standard cured and 28-day accelerated cured test results the better correlation (higher R^2 values) are highlighted in bold font in the Table 2.3. It is observed that the rapid index test results of 28-day accelerated cured specimens have a better correlation to the D_a values measured on specimens in the immersed condition. Rapid index test results of 56-day standard cured specimens have a better correlation to D_a values measured on specimens in the cyclic condition, in four out of five cases.

Overall conductivity and RCPT test results had the best correlation (R^2 values >0.80). In most cases, a lower R^2 values was obtained because results of one mixture substantially deviated from the line of correlation. Initial sorptivity and absorption had low correlation with D_a values.

The data in this study indicates that the RCPT is the best predictor for D_a value of concrete mixtures measured in both the immersed and cyclic conditions. This finding is not surprising given that both RCPT values and diffusivities are correlated as discussed earlier. However, in some situations the RCPT did give misleading results. In Table 2.4 the rapid index results and the apparent chloride D_a for Phase II mixtures are reported. A linear relationship between the 56 day standard-cured RCPT results and the D_a value for specimens subjected to the cyclic exposure can be observed with the exception of the 0.62SL50 mixture. The 56 day standard-cured RCPT result (832 coulombs) for the 0.62SL50 mixture was lower than that for the 0.39SL25, 0.29PC, and 0.39FA15 mixture (1200 to 1600 coulombs). But the D_a value for the 0.62SL50 mixture was 1.5 to 3.5 times higher than those mixtures. A specification requirement of 1000 coulombs would have accepted the 0.62SL50 mixture and rejected the other mixtures even though they have a lower apparent chloride D_a measured by C1556! The RMT and conductivity test results also makes one conclude that the 0.62SL50 mixture is similar or better than the 0.39SL25, 0.29PC, and 0.39FA15 mixture. The absorption and sorptivity test results provide some clue as to potential discrepancy. The 56-day absorption and initial sorptivity test results were much higher for the 0.62SL50 as compared to the other mixtures, indicating that there is a higher rate of transport due to the higher w/cm of this mixture.

It is interesting to note that for D_a measured on specimens in the immersed condition, the 0.62SL50 mixture is consistent with the expectation. The 28-day accelerated cured RCPT result (661 coulombs) for the 0.62SL50 mixture was lower than that for the 0.39SL25, 0.29PC, and 0.39FA15 mixture (about 1100 coulombs). But the D_a value for the 0.62SL50 mixture was also 0.70 to 1.0 times that of the other mixtures.

The 0.62FA30 mixture portrayed a different story. Fly ash tends to react slowly and therefore the 56-day standard-cured rapid index test results of the 0.62FA30 mixture indicate a high chloride ion penetration, consistent with expectations.

The 56-day standard cured RCPT result (299 coulombs) for the 0.39SF7 mixture was much lower than that for the 0.39SL25, and 0.29PC mixture (1200 coulombs). Yet the D_a values for all three mixtures for specimens subjected to the cyclic condition were similar. The RMT and conductivity test results also allows one to conclude that the 0.39SF7 mixture has much lower transport characteristics than the 0.39SL25, and 0.29PC mixtures. This suggests that silica fume is more effective in achieving a lower RCPT result that is not reflected in reduction in the D_a value.

However, for specimens subjected to the immersed condition, there seems to be a better indicator from the RCPT result. The 28-day accelerated cured RCPT result (276 coulombs) for the 0.39SF7 mixture was lower than that for the 0.39SL25, and 0.29PC mixture (about 1100 coulombs). But the D_a value for the 0.39SF7 mixture was 0.30 to 0.40 times that of the other mixtures suggesting that the RCPT indication is consistent for D_a measured on specimens in the immersed condition.

The data reveal that the problem with solely depending on the RCPT, RMT and conductivity tests is the potential for a false indication of low transport characteristics for some types of mixtures. Specifically, high w/cm mixtures containing slag cement or silica fume can have lower RCPT values that are not consistent with the transport characteristics of the concrete as indicated by the apparent diffusion coefficient.

2.7 Mixture Classification Based on Chloride Penetrability

Since the apparent chloride D_a varied over a wide range as a result of the varying curing and exposure conditions it was decided to normalize the D_a by dividing each mixture's D_a by the calculated average D_a for all the mixtures tested in that condition. In other words, all Phase I immersed D_a values will be divided by their average value and so on. The resulting value for each mixture was called as the normalized apparent chloride diffusion coefficient (ND_a). The normalization of D_a helped classify mixtures at three levels of chloride penetrability as follows:

- "Very Low" when $ND_a \leq 0.4$,
- "Low" when $0.4 < ND_a < 1.0$, and
- "Moderate" when $ND_a \geq 1.0$.

Mixtures were also classified at three levels based on all of the rapid index test results. Table 2.5 summarizes these criteria. If the class of chloride penetrability determined by a rapid index test matched the class of the ND_a then the rapid index test is effective at categorizing mixtures for resistance to chloride penetrability. Figure 2.3 through Figure 2.6 illustrate mixture classification based on the rapid index test results and the ND_a.

2.8 Chloride Diffusion Coefficient and Rapid Index Test Results Comparisons

Figure 2.3 shows that the 28-day accelerated test results for conductivity, RCPT, RMT, and secondary sorptivity tests correlate well with the ND_a for the Phase I immersed condition. Initial sorptivity and absorption test results do not correlate well.

Figure 2.4 shows that the 56-day standard cured test results for conductivity, RCPT, and Secondary sorptivity tests correlate well with the ND_a for the Phase I cyclic condition. Initial sorptivity and absorption test results do not correlate well while RMT was acceptable.

Figure 2.5 shows that the 28-day accelerated test results for conductivity, RCPT, and secondary sorptivity tests correlate well with the ND_a for the Phase II immersed condition. RMT and Initial sorptivity test results do not correlate well. The conductivity, RCPT, RMT test results classify the 0.62SL50 mixture as “Very Low” chloride penetrability where as the ND_a classifies that mixture as “Low”.

Figure 2.6 shows that the 56-day standard cured test results for RMT, initial sorptivity and secondary sorptivity tests correlate well with the ND_a for the Phase II cyclic condition. Absorption test results do not correlate well. RCPT and conductivity test results don’t correlate for the 0.62SL50 mixture; the 0.39SL25 and 0.29PC mixtures were conservatively classified as “Low” whereas they were actually “Very Low”. Once again, as noted earlier, that if only the RCPT criteria is used, an incorrect conclusion is possible.

Figure 2.3b, Figure 2.4, Figure 2.5, Figure 2.6 show that the RCPT is effective at categorizing mixtures for “Very Low” and “Low” chloride penetrability. However, in the case of mixtures with high w/cm and containing either high slag cement or high silica fume content the RCPT indicates “Very Low” chloride penetrability even though based on the ND_a values those mixtures are expected to have “Low” chloride penetrability. It is thereby suggested that, despite the generally good correlation of the RCPT, another performance criterion that validates this potential performance may be required.

2.9 Using a Combination of Rapid Index Tests

In considering more than one rapid index test, the intent is to ensure that the combination of the indications provide reasonable assurance of achieving concrete with the desired level of chloride penetrability. Table 2.6 suggests using 28 day compressive strength as a rapid index test to supplement the RCPT criteria. If the two rapid index test results suggested that a mixture belonged to two different chloride penetrability levels that mixture was conservatively classified as belonging to the higher chloride penetrability level. Using these two index tests, all of the mixtures were re-classified in Table 2.6.

In Table 2.6, the mixture categorization based on the RCPT and strength criteria matches their performance levels as categorized by the ND_a value. The consistency of this categorization is illustrated in Figure 2.3 through Figure 2.6.

The value in using two rapid index criteria - strength and RCPT - is observed for the 0.62SL50 mixture. Using both results it is now placed in the "Low" category whereas if only the RCPT criteria is considered it would have been incorrectly placed in the "Very Low" category. However, mixtures 0.29PC and 0.39SL25 are placed in the "Low" category even though they had a "Very Low" D_a value. Nevertheless, the combined RCPT and strength criteria are conservative and appropriately categorize the high w/cm slag cement mixture.

For the "Very Low" chloride penetrability mixtures, state highway agencies typically specify 4000 psi air-entrained concrete which translates to approximately 5700 psi average strength for the non-air-entrained concrete that was tested in this project. When non-air-entrained concrete is used, the specified strength requirement should be 5000 psi.

An alternative to compressive strength as the companion rapid index test is to use secondary sorptivity (ASTM C1585). If RCPT and secondary sorptivity test results for the mixtures in this study are taken together the classification matches Table 2.6. From a mechanism standpoint, if the RCPT is forced to a lower value by the composition of the mixture, the higher porosity of the concrete due to its high w/cm will be revealed in the higher result for the secondary sorptivity as well as a lower compressive strength.

The sorptivity test as well as the calculation of secondary sorptivity is relatively complicated. For it to be useable as an acceptance criterion in the mixture qualification phase the method can be simplified as suggested here. The secondary sorptivity test results obtained in this study were plotted against the mass gain (due to moisture) during the period of the test in which the secondary sorptivity test result is calculated. This corresponds to the mass gain between one and seven days after the specimen is placed in contact with the water. Figure 2.7 illustrates a good correlation between the secondary sorptivity values and the mass gain. As many as 130 data points corresponding to 43 different mixtures from a wider test program were included. It is proposed that the secondary sorptivity test criteria listed in Table 2.5 be replaced by criteria for mass gain of test specimens due to absorption of water. The appropriate equivalent criteria between secondary sorptivity for 2.2×10^{-4} mm/s$^{0.5}$ and 4.4×10^{-4} mm/s$^{0.5}$ are 1.2 g and 2.4 g for mass gain respectively. This simplifies the ASTM C1585 sorptivity test procedure considerably. Specimen conditioning and testing is identical except that only 2 mass measurements are needed - mass at one day and at seven days. From this the mass gain between 1 and 7 days (secondary absorption) can be calculated and compared with the suggested criteria. Note that the suggested mass gains are valid only for specimen dimensions and conditioning required in ASTM C1585.

The RCPT and conductivity test results for all the mixtures are plotted as Figure 2.8. The results indicate a good correlation as expected.

2.10 Evaluation of Performance Test Criteria for Robustness

In this research project, a total of 43 concrete mixtures were tested. Of these, 13 concrete mixtures were tested in the chloride exposure portion (Table 2.1 and Table 2.2), seven mixtures were tested in the freeze-thaw exposure portion and 22 mixtures were tested in the sulfate exposure portion. The mixture details for freeze-thaw and sulfate exposures are provided in later sections. The 13 mixtures tested in Table 2.1 and Table 2.2 were first categorized for chloride penetrability based on the measured D_a (see Table 2.7). Mixtures from the freeze-thaw and sulfate exposures were classified in the chloride penetrability categories based on the measured rapid index test results. The adequacy of this classification was evaluated by comparing against the chloride penetrability levels of similar mixtures reported in Table 2.1. If the comparisons were off it would be an indicator that the selected combinations of performance criteria (of rapid index tests) were not robust enough when a broader range of mixtures and materials were considered. For example, based on the rapid index test results a mixture tested in the freeze-thaw or sulfate exposure portion could be classified as having "Very Low" chloride penetrability but its expected chloride penetrability level based on measured ND_a for similar mixtures (Table 2.1) could be "Low" or "Moderate". These are false positive cases and are identified. Similarly, in some cases the situation may be reversed, i.e. based on rapid index test results a mixture could be classified as having "Low" chloride penetrability but its expected chloride penetrability level based on measured ND_a could be "Very Low". These are false negative cases. False negative cases are conservative but an excess of false negative cases would indicate that the rapid index test criteria are too stringent. On the other hand, false positives add to the risk and need to be reduced as much as possible by making the rapid index test criteria more stringent.

For each of the 43 mixtures there are two possible cases – specimens immersed in chloride and specimens subjected to cyclic wetting and drying in chloride solution. This results in 86 possible cases for which their chloride penetration category has to be determined. Out of the 43 mixtures, 35 were non-air-entrained and eight (Table 2.3 in the freeze-thaw exposure portion) were air-entrained. When the compressive strengths of the air-entrained concrete and non-air-entrained concrete mixtures are compared at a w/cm of 0.50 it was found that the strength of the air-entrained concrete mixtures was at about 80% of that of the non-air-entrained concrete mixtures. Since compressive strengths of air-entrained and non-air-entrained concrete mixtures cannot be directly compared it was necessary to do two separate analyses - 1. By converting the strength of air-entrained concrete to equivalent strength of non-air-entrained concrete (by multiplying by 1.25). 2. By converting the strength of non-air-entrained concrete to equivalent strength of air-entrained concrete (by multiplying by 0.80).

2.10.1 Selecting Mixtures with "Very Low" Chloride Penetrability

For the air-entrained concrete analysis the combinations of criteria in Table 2.8 were used to classify mixtures that would provide mixtures with "Very Low" chloride penetration level.

Table 2.8 shows that both combinations of criteria concluded that in about 20% of all cases (i.e. 17-18 out of 86 total cases) chloride penetration level is expected to be "Very Low". Also included are those cases meeting the respective combinations of criteria but not expected to give "Very Low" chloride penetrability level based on D_a values of similar mixtures (Table 2.7). These cases are considered to be false positives, whereby despite meeting the combinations of criteria, these mixtures might not have a D_a value indicative of a mixture with "Very Low" chloride penetrability. In this regard, it appears that both combinations of criteria are similar with about 4% false positives (i.e. 3-4 out of 86 cases have combination criteria predicting "Very Low" chloride penetrability but are not expected to have chloride D_a values indicative of a "Very Low" chloride penetrability level). If an initial sorptivity criterion of $5x10^{-4}$ mm/s$^{1/2}$ is added then the percent of false positives drops to about 2% (i.e. two cases out of 86 cases - 0.40SL25-I, 0.40FA15-I), i.e. the 0.50SL25SF5 mixture is no longer classified as a mixture with a "Very Low" chloride penetrability. Unfortunately, having this additional restriction excludes one additional case (0.4SL35-II) that actually is expected to have "Very Low" chloride penetrability. In other words, the additional initial sorptivity criterion does not improve the classification of mixtures. So it is suggested that either one of the two combinations of criteria be considered for specifications.

For the non-air-entrained concrete analysis the combinations of criteria in Table 2.9 were used to classify mixtures that would provide mixtures with "Very Low" chloride penetration level. The third combination of criteria was selected since at the same w/cm non-air-entrained concrete is expected to have about 25% higher compressive strength.

Table 2.9 shows that first combination of criteria had a much higher number of false positive cases. The last two combinations of criteria concluded that in about 20% of all cases (i.e. 15 to 18 out of 86 total cases) chloride penetration level is expected to be "Very Low". Both combinations of criteria had a low percentage of false positives. So it is suggested that either one of the last two combinations of criteria be considered for specifications.

2.10.2 Selecting Mixtures with "Low" Chloride Penetrability

For the air-entrained concrete analysis the combinations of criteria in Table 2.10 were used to classify mixtures that would provide mixtures with "Low" (but not "Very Low") chloride penetration level.

Table 2.10 shows that the chosen combination of criteria concluded that in about 32.6% of all cases (i.e. 28 out of 86 total cases) chloride penetration level is expected to be "Low". None of the mixtures were incorrectly categorized for this level of penetrability. Since the first combination of criteria is adequate in screening out the mixtures and second combination of criteria which contains the additional secondary sorptivity criterion does not lead to any benefits in reducing the compressive strength requirement as in the case of "Very Low" chloride permeability concrete it is suggested that only the first combination of criteria be considered.

For the non-air-entrained concrete analysis the combination of criteria in Table 2.11 were used to classify mixtures that would provide mixtures with "Low" (but not "Very Low") chloride penetration level. The second combination of criteria involving the additional secondary sorptivity did not lead to reducing the compressive strength requirement as in the case of "Very Low" chloride penetrability concrete and so it is not included in the discussions below.

Table 2.11 shows that the chosen combination of criteria concluded that in about 40% of all cases (i.e. 34 out of 86 total cases) chloride penetration level is expected to be "Low". The percent of false positive cases is 7% (i.e. six out of 86). If the strength is increased to 6000 psi then all the false positive cases are eliminated. In addition, having this increased strength does not make the combination of criteria so stringent that it excludes any other mixture that actually is expected to have D_a indicative of "Low" chloride penetrability. So it is suggested that this combination of criteria be considered with the strength at 6000 psi.

To conclude, it is suggested that the performance tests and specified performance criteria for chloride exposure be as shown in Table 2.12.

The recommended specified strength and RCPT criteria are slightly different as these refer to specified values as opposed to the target average values that Tables 2.8 to 2.11 were referring to. The sorptivity criteria are the same as before since the sorptivity test is suggested as a target average for mixture prequalification only.

The specified strength values have been calculated to the nearest 500 psi from the average strengths used in the earlier tables based on an NRMCA survey of average strengths and reported standard deviations. The specified RCPT values are calculated from the average values and are conservative recommendations.

2.11 Conclusions

1. Among the rapid index tests evaluated the RCPT was the best predictor in selecting mixtures based on their chloride penetrability for specimens in saturated and cyclic wet/dry conditions. However, RCPT by itself did not reliably categorize some mixtures, generally with high w/cm and high dosages of some types of SCMs.
2. It is proposed that the RCPT requirements be supplemented with compressive strength criteria to categorize mixtures for chloride penetrability. For the “Very Low” chloride penetrability requirement if a secondary sorptivity criterion is also incorporated the specified strength requirement can be lowered for the air-entrained concrete mixtures.
3. Use of the above criteria can reliably replace prescriptive criteria like w/cm, SCM types and dosages.
4. A good correlation is observed between RCPT and conductivity test results and conductivity criterion can be used as an alternative to the RCPT.
5. Since the sorptivity test (ASTM C1585) is more involved, a simplified version that measures mass gain due to absorption is suggested.

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Table 2.1 Yield Adjusted Mixture Proportions and Test Results

Mixture Designation	**0.49PC**	**0.49SL25**	**0.39SL50**	**0.49FA15**	**0.39FA30**	**0.34SL40SF5**
Calculated Batch Quantities						
Type I/II cement, lb/yd^3	554	416	306	472	431	382
Slag, lb/yd^3		139	306			277
Fly ash, lb/yd^3				83	185	
Silica Fume, lb/yd^3						35
SCM, %	0	25	50	15	30	45
Coarse Agg. (No.57), lb/yd^3	2075	2074	2070	2081	2081	2086
Fine Aggregate, lb/yd^3	1303	1293	1314	1273	1267	1264
Mixing Water, lb/yd^3	272	272	239	273	240	236
w/cm	0.49	0.49	0.39	0.49	0.39	0.34
ASTM C494 Type A, oz/cwt	4.0	4.0	4.0	4.0	4.0	4.0
ASTM C494 Type F, oz/cwt	2.5	2.9	4.3	2.4	5.0	7.8
Fresh Concrete Properties						
ASTM C143, Slump, in.	7 ½	4 ½	8	7	6 ¾	9
ASTM C231, Air, %	1.4	1.7	1.3	1.5	1.6	1
ASTM C138, Air, %	1.3	1.4	1.5	1.0	1.1	0.8
ASTM C138, Density, lb/ft^3	156.5	156.1	157.7	155.7	156.5	159.3
ASTM C1064, Temperature, °F	76	76	75	76	75	75
Hardened Concrete Properties						
ASTM C39, Compressive Strength, psi						
28 days	6,830	7,550	10,520	6,640	7,970	12,440
Water Absorption Test (drying at 220 °F), % change in mass						
10d standard cure	2.89	2.24	1.69	3.25	2.33	1.43
28d accelerated cure	2.52	1.77	1.34	2.44	1.63	1.26
196d standard cure	2.30	1.80	1.29	2.29	1.44	1.49
ASTM C1202, Rapid Chloride Permeability, Coulombs						
28d accelerated cure	4657	1992	561	2414	723	166
56d standard cure	4674	1912	581	3013	1417	270
196d standard cure	3356	1581	496	1551	340	147
550d standard cure	3891^{--}	1465^{--}	394^{--}	1070^{--}	174^{--}	166^{--}
Conductivity, Sm^{-1}						
28d accelerated cure	0.0189	0.0083	0.0030	0.0091	0.0030	0.0009
56 standard cure	0.0154	0.0072	0.0034	0.0129	0.0058	0.0013
196d standard cure	0.0099	0.0055	0.0021	0.0057	0.0018	0.0008
550d standard cure	0.0076^{--}	0.0054^{--}	0.0018^{--}	0.0054^{--}	0.0008^{--}	0.0009^{--}
AASHTO TP64, Rate of Penetration (RMT), mm/(V-hr)						
28d accelerated cure	0.065	0.030	0.004	0.046	0.015	0.003
56d standard cure	0.044	0.025	0.006	0.043	0.024	0.002
196d standard cure	0.047	0.016	0.006	0.025	0.006	0.002

Mixture Designation	0.49PC	0.49SL25	0.39SL50	0.49FA15	0.39FA30	0.34SL40SF5
550d standard cure	0.048^{--}	0.017^{--}	0.003^{--}	0.017^{--}	0.005^{--}	0.001^{--}
ASTM C157, Length Change, %						
28 days	0.035	0.039	0.031	0.029	0.028	0.028
56 days	0.046	0.048	0.037	0.039	0.036	0.032
90 days	0.055	0.054	0.044	0.048	0.043	0.039
180 days	0.062	0.060	0.049	0.054	0.049	0.044
ASTM C1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$						
28d accel. cure (Initial/Secondary)	10.4 / 7.5	3.0 / 3.4	1.7 / 1.7	7.5 / 4.6	4.7 / 2.1	2.5 / 0.9
56d standard cure (Initial/Secondary)	9.9 / 6.9	8.5 / 2.6	2.5 / 1.4	16.6 / 10.7	7.0 / 3.3	4.1 / 1.9
196d standard cure (Initial/Secondary)	5.9 / 5.5	3.4 / 1.3	3.7 / 1.1	4.2 / 2.4	3.6 / 1.8	1.3 / 0.8
ASTM C1556, Apparent Chloride Diffusion Coefficient (D_a), x 10^{-12} m^2/s						
6m std + 35d in solution	3.29	1.32	0.68	2.31	1.97	0.35
Phase I immersed	12.94	3.09	0.58	4.11	1.07	0.35
Phase I cyclic	11.07	3.11	1.24	6.34	3.42	0.82
ASTM C1556, Surface Chloride, % by weight of concrete						
6m std + 35d in solution	0.78	1.29	1.87	1.77	2.20	1.80
Phase I immersed	1.05	1.20	1.80	1.35	1.60	1.90
Phase I cyclic	1.03	1.52	1.63	1.23	1.46	2.10

$^{--}$ Result of only one specimen

Table 2.2 Yield Adjusted Mixture Proportions and Preliminary Test Results

Mixture Designation	0.39PC	0.39FA15	0.39SL25	0.39SF7	0.62FA30	0.62SL50	0.29PC	0.39PC**-R
Calculated Batch Quantities								
Type I/II cement, lb/yd^3	612	520	462	565	349	249	803	612
Slag, lb/yd^3	-	-	154	-	-	249	-	-
Fly ash, lb/yd^3	-	92	-	-	149	-	-	-
Silica Fume, lb/yd^3	-	-	-	43	-	-	-	-
SCM, %	0%	15%	25%	7%	30%	50%	0%	0%
Coarse Agg. (No.57), lb/yd^3	2066	2068	2081	2052	2094	2093	2069	2066
Fine Aggregate, lb/yd^3	1331	1296	1331	1307	1216	1258	1183	1331
Mixing Water, lb/yd^3	238	239	240	237	287	290	236	238
w/cm	0.39	0.39	0.39	0.39	0.58	0.58	0.29	0.39
ASTM C494 Type A, oz/cwt	4	4	4	4	3	3	5	4
ASTM C494 Type F, oz/cwt	8.8	8.3	6.9	8.2	-	-	11.7	8.4
Fresh Concrete Properties								
ASTM C143, Slump, in.	5	6 1/2	7 3/4	6	6 1/2	7	8 3/4	7
ASTM C231, Air, %	1.8	1.6	1.2	1.8	1.6	1.4	1.1	1.7
ASTM C138, Air, %	1.8	1.7	1.0	2.4	1.7	1.6	1.6	1.8
ASTM C138, Density, lb/ft^3	158.1	156.9	158.9	156.5	152.5	154.1	159.7	158.1

Mixture Designation	**0.39PC**	**0.39FA15**	**0.39SL25**	**0.39SF7**	**0.62FA30**	**0.62SL50**	**0.29PC**	**0.39PC**-R**
ASTM C1064, Temperature, °F	75	75	75	75	75	75	76	76
Hardened Concrete Properties								
ASTM C39, Compressive Strength, psi								
28 days	10,460	9,590	10,300	10,740	3,880	5,380	13,480	9,890
Water Absorption Test (drying at 140 °F), % change in mass								
56d standard cure	1.03	1.02	1.00	0.82	1.88	1.75	0.91	-
213d standard cure	0.85	0.79	0.91	0.76	1.55	1.40	0.70	-
ASTM C1202, Rapid Chloride Permeability, Coulombs								
28d accelerated cure	2180^{-}	1031	1186	276	2495	661	1078	1980
56d standard cure	1722	1557	1272	299	4012	832	1209	-
213d standard cure	1607	563	873	252	1177	572	936	-
Conductivity, Sm^{-1}								
28d accelerated cure	0.0101^{-}	0.0054	0.0061	0.0014	0.0089	0.0037	0.0061	0.0102
56 standard cure	0.0089	0.0070	0.0058	0.0014	0.0119	0.0034	0.0056	-
213d standard cure	0.0062	0.0026	0.0037	0.0014	0.0042	0.0020	0.0040	-
AASHTO TP64, Rate of Penetration (RMT), mm/(V-hr)								
28d accelerated cure	0.034^{-}	0.017	0.013	0.004	0.047	0.007	0.012	0.029
56d standard cure	0.027	0.017	0.011	0.004	0.046	0.012	0.011	-
213d standard cure	0.021	0.009	0.009	0.002	0.033	0.006	0.007	-
ASTM C157, Length Change, %								
28 days	0.032	0.037	0.032	0.028	0.041	0.044	0.024	-
56 days	0.039	0.047	0.038	0.034	0.054	0.052	0.029	-
90 days	0.042	0.054	0.047	0.043	0.064	0.053	0.030	-
180 days	0.049	0.056	0.052	0.045	0.066	0.061	0.038	-
ASTM C1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$								
28d accel. cure (Initial/Secondary)	-	3.1 / 2.1	4.7 / 2.0	3.3 / 2.1	9.6 / 3.8	7.6 / 2.8	3.1 / 2.6	9.5 / 5.2
56d standard cure (Initial/Secondary)	8.3 / 4.0	6.1 / 4.1	-	3.8 / 2.1	9.9 / 7.0	7.1 /2.8	2.1/ 2.9	-
213d standard cure (Initial/Secondary)	4.7/ 3.0	2.1 / 1.7	3.6 / 1.9	2.6 / 0.7	4.6 / 3.7	5.5 / 1.6	1.6/1.3	-
ASTM C1556, Apparent Chloride Diffusion Coefficient (D_a), x 10^{-12} m^2/s								
56d std + 35d in solution	4.86	2.89	2.21	1.18	8.30	2.90	1.32	-
6m std + 35d in solution	2.72	1.40	1.19	0.67	8.23	2.02	1.08	-
Phase II Immersed	1.75	0.67	0.77	0.22	0.95	0.55	0.56	-
56d std + 5m cyclic exposure (3d solution+ 4d air)	2.20	1.51	1.08	0.90	12.08	2.27	1.28	-
Phase II Cyclic	1.96	0.94	0.42	0.35	7.10	1.45	0.53	-
ASTM C1556, Surface Chloride, % by weight of concrete								
56d std + 35d in solution	0.96	1.17	1.50	1.23	1.11	1.40	1.10	-
6m std + 35d in solution	0.94	1.46	1.58	1.27	1.00	1.20	1.46	-

Mixture Designation	**0.39PC**	**0.39FA15**	**0.39SL25**	**0.39SF7**	**0.62FA30**	**0.62SL50**	**0.29PC**	**0.39PC**-R**
Phase II Immersed	0.80	0.80	1.20	1.20	1.00	1.20	1.10	-
56d std + 5m cyclic exposure (3d solution+ 4d air)	0.80	1.00	1.30	1.10	1.30	1.30	1.00	-
Phase II Cyclic	1.05	1.00	1.60	1.35	1.30	2.00	1.10	-

$^{-}$Tested at 21d instead of 28d
** Exact repeat of designated mixture

Table 2.3 Correlation Between the Rapid Index and Apparent Chloride D_a Test Results

Rapid Index Test	**Linear Coefficient of Determination, R^2, with Apparent Chloride D_a 56 day/28 day accelerated**						
	Phase I Immersed	**Phase II Immersed**	**Average for Immersed**	**Phase I Cyclic**	**Phase II Cyclic**	**Average for Cyclic**	**Overall Average**
Conductivity	0.76/**0.96**	0.48/**0.80**	0.62/**0.88**	**0.92**/0.91	**0.63**/0.31	**0.78**/0.61	0.83
RCPT (ASTM C1202)	0.89/**0.95**	0.20/**0.57**	0.55/**0.76**	**0.97**/0.92	**0.88**/0.65	**0.93**/0.79	0.85
RMT (AASHTO TP64)	0.58/**0.84**	0.36/**0.40**	0.47/**0.62**	0.80/**0.93**	**0.89**/0.82	**0.85/0.87**	0.74
Absorption	0.42/**0.68**	0.01/NA	NA	0.67/**0.87**	0.59/NA	0.63/NA	NA
Initial Sorptivity (ASTM C1585)	0.20/**0.80**	0.38/**0.50**	0.29/**0.65**	0.41/**0.95**	**0.60**/0.52	0.51/**0.74**	0.70
Secondary Sorptivity (ASTM C1585)	0.30/**0.93**	0.21/**0.79**	0.26/**0.86**	0.53/**0.96**	**0.88**/0.26	**0.71**/0.61	0.79

Table 2.4 Comparison Between the Rapid Index and Apparent Chloride D_a Test Results for the Phase II Mixtures

Mixture Designation	**D_a, Phase II Cyclic** $\times 10^{-12}$ m^2/s	**56 day RCPT** Coulombs	**56 day Initial Sorpt** $\times 10^{-4}$ $mm/s^{1/2}$	**56 day Abs.** %	**D_a, Phase II Immersed** $\times 10^{-12}$ m^2/s	**28 d acc RCPT** Coulombs	**28 d acc Initial Sorpt** $\times 10^{-4}$ $mm/s^{1/2}$
0.62FA30	7.10	4012	9.9	1.88	0.95	2495	9.6
0.39PC	1.96	1722	8.3	1.03	1.75	1980	8.3
0.39FA15	0.94	1557	6.1	1.02	0.67	1031	3.1
0.29PC	0.53	1209	2.1	0.91	0.56	1078	3.1
0.39SL25	0.42	1272	NA	1.00	0.77	1186	4.7
0.62SL50	1.45	832	7.1	1.75	0.55	661	7.6
0.39SF7	0.35	299	3.8	0.22	0.22	276	3.3

Table 2.5 Chloride Penetrability Level For Test Criteria

Chloride Penetrability Level	ND_a	RCPT, Coulombs	RMT, mm/(V-hr)	Conductivity, S/m	Sec. Sorptivity, $\times 10^{-4}$ mm/s$^{0.5}$
Very Low	≤ 0.4	≤ 1000	≤ 0.012	≤ 0.0045	≤ 2.20
Low	0.4 to 1.0	1000 to 2000	0.012 to 0.024	0.0045 to 0.0084	2.20 to 4.40
Moderate	≥ 1.0	≥ 2000	≥ 0.024	≥ 0.0084	≥ 4.40

Table 2.6 Mixtures Categorized By ND_a and (RCPT + Strength) for Chloride Penetrability

Chloride Penetrability Level	ND_a	RCPT, Coulombs	Compressive Strength, psi	Mixtures*	Mixtures**
Very Low	≤ 0.4	≤ 1000	≥ 5700	0.34SL40SF5, 0.39SF7, 0.39SL50, 0.39FA30	0.34SL40SF5, 0.39SF7, 0.39SL50
Low	0.4 to 1.0	1000 to 2000	≥ 3200	0.29PC, 0.39FA15, 0.39SL25, 0.62SL50	0.29PC, 0.39FA15, 0.39SL25, 0.39PC, 0.62SL50, 0.39FA30, 0.49SL25
Moderate	≥ 1.0	> 2000	≥ 3200	0.49FA15, 0.49PC, 0.39PC, 0.49SL25, 0.62FA30	0.62FA30, 0.49PC, 0.49FA15

* D_a measured on specimens in immersed condition (Phase I+II); RCPT accelerated cure for 28 days

** D_a measured on specimens with cyclic condition (Phase I+II); RCPT standard cure for 56 days

Table 2.7 Mixtures Categorized By ND_a for Chloride Penetrability

Chloride Penetrability Level	Immersed in Chloride Solution	Cyclic Chloride Environment
Very Low	0.34SL40SF5, 0.39SF7, 0.39SL50, 0.39FA30*	0.34SL40SF5, 0.29PC, 0.39SF7, 0.39SL50, 0.39SL25
Low	0.29PC, 0.39FA15, 0.39SL25, 0.62SL50, 0.49SL25*, 0.62FA30*	0.39FA15, 0.39PC*, 0.62SL50, 0.39FA30, 0.49SL25
Moderate	0.49FA15**, 0.49PC 0.39PC	0.62FA30, 0.49PC, 0.49FA15

*Mixtures are within 20% of the dividing line and could be classified in the higher level of chloride pentratability.

**Mixtures are within 20% of the dividing line and could be classified in the lower level of chloride pentratability.

Table 2.8 Mixtures Categorized as “Very Low” Chloride Penetration Based on Rapid Index Test Results (Air-entrained)

	≥ 5700 psi, ≤ 800 coulombs	≥ 5000 psi, ≤ 800 coulombs, ≤ $2.2\text{x}10^{-4}$
% of all cases that meet criteria for “Very Low” chloride penetration	20.9	19.8
% of all cases that meet criteria but not expected to give D_a indicative of “Very Low” chloride penetrability	4.7 0.50SL25SF5, 0.40SL25-I, 0.40FA15-I	3.5 0.50SL25SF5, 0.40SL25-I, 0.40FA15-I

Table 2.9 Mixtures Categorized as "Very Low" Chloride Penetration Based on Rapid Index Test Results (Non-air-entrained)

	≥ 5700 psi, ≤800 coulombs	≥ 5000 psi, ≤ 800 coulombs, ≤ 2.2x10^{-4}	≥ 6750 psi , ≤ 800 coulombs
% of all cases that meet criteria for "Very Low" chloride penetration	24.4	20.9	20.9
% of cases that meet criteria but not expected to give D_a indicative of "Very Low" chloride penetrability	8.1 0.50SL25SF5, 0.60SL25SF5, 0.40SL25-I, 0.40FA15-I, 0.5SL35-II, 0.60 SL50-V1	4.7 0.50SL25SF5, 0.40SL25-I, 0.40FA15-I, 0.60 SL50-V1	4.7 0.50SL25SF5, 0.40SL25-I, 0.40FA15-I

Table 2.10 Mixtures Categorized as "Low" Chloride Penetration Based on Rapid Index Test Results (Air-entrained)

	≥ 4800 psi and (any one of the following 2): 800 < L ≤ 2000 coulombs ≤ 800 coulombs + < 5700 psi	≥ 4800 psi and (any one of the following 3): 800 < L ≤ 2000 coulombs + ≤ 4.4 x10^{-4} < 2000 coulombs + < 5000 psi + ≤ 4.4 x10^{-4} < 2000 coulombs + 2.20 x10^{-4} < L ≤ 4.4 x10^{-4}
% of all cases that meet criteria for "Low" chloride penetration	32.6	32.6
% of all cases that meet criteria but not expected to give D_a indicative of "Low" chloride penetrability	0	0

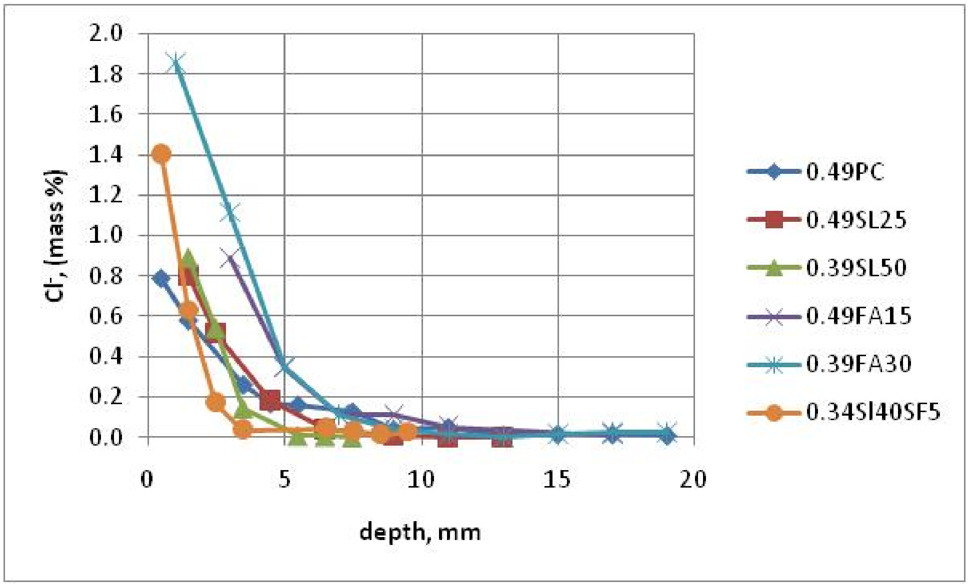
Table 2.11 Mixtures Categorized as Low Chloride Penetration Based on Rapid Index Test Results (Non-air-entrained)

	≥ 5700 psi (and any one of the following 2): 800 < L ≤ 2000 coulombs < 800 coulombs + < 6750 psi
% of all cases that meet criteria for low chloride penetration	39.5
% of all cases that meet criteria but not expected to give D_a indicative of "Low" chloride penetrability	7 0.60SL25-I, 0.50FA15-I, 0.60SL35-II

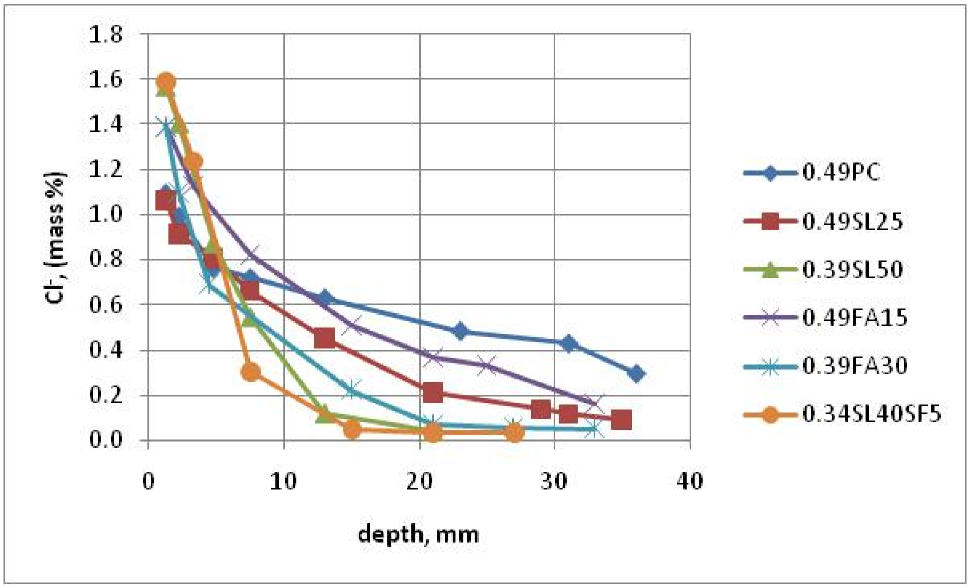
Table 2.12 Recommended Specification Criteria for Chloride Penetrability

Chloride Penetrability Level	Specified RCPT, Coulombs	Specified Compressive Strength, psi non-air-entrained concrete	Specified Compressive Strength, psi Air-entrained concrete
Very Low	≤ 1000	≥ 5500*	≥ 4500*
Low	1000 to 2500	≥ 4500	≥ 4000

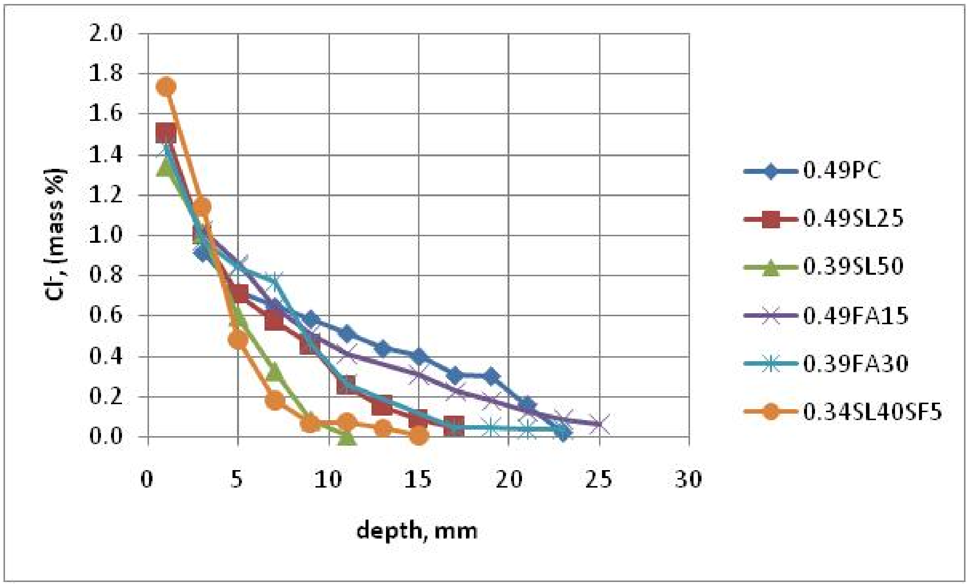
* Alternative: strength requirement of 4000 psi with secondary sorptivity ≤2.2x10^{-4} mm/s$^{1/2}$



(a) Chloride Profile (ASTM C1556) for 6m standard curing followed by 35d in solution

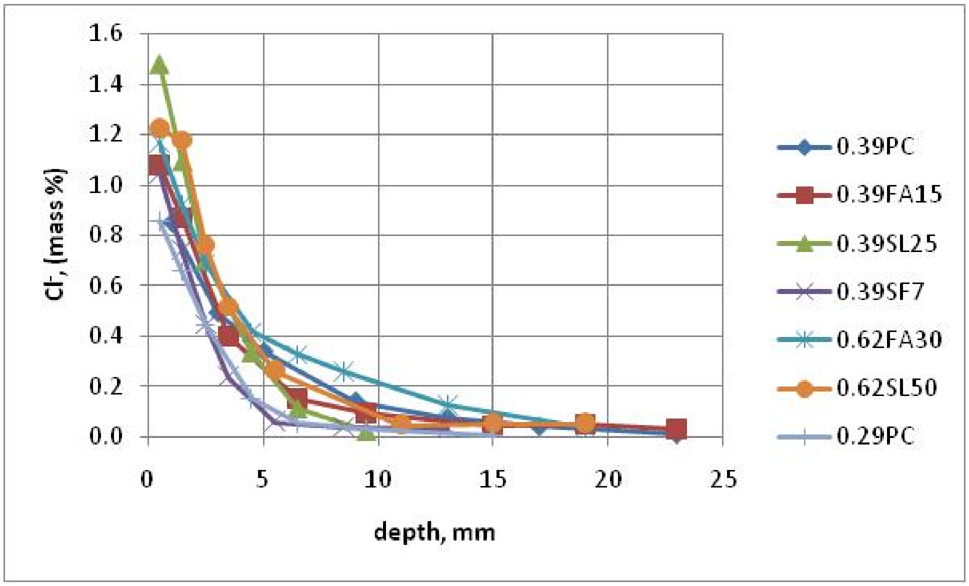


(b) Chloride Profile for 59 days standard curing + 16m in solution (Phase I Immersed)

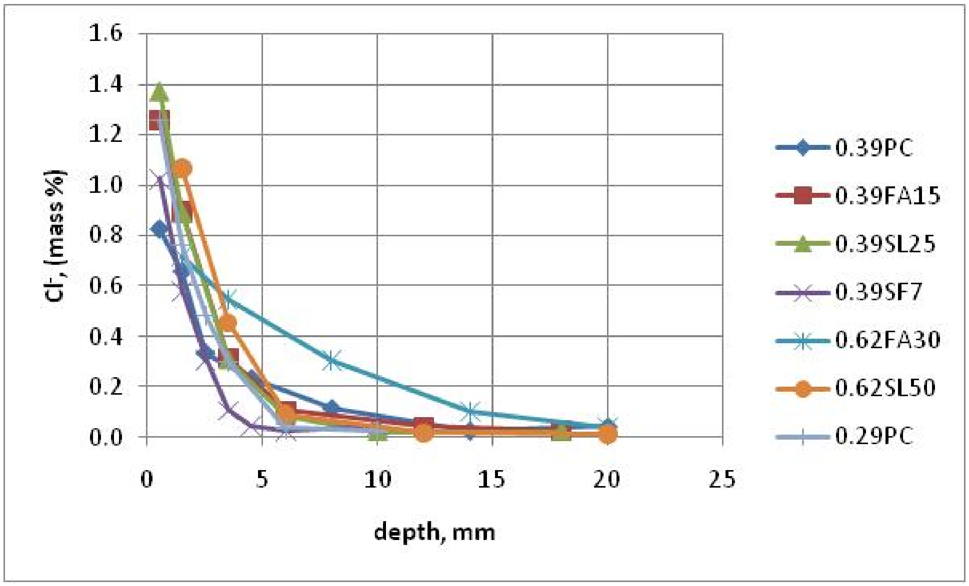


(c) Chloride Profile for 59 days standard curing + 4m cyclic exposure to solution (Phase I Cyclic)

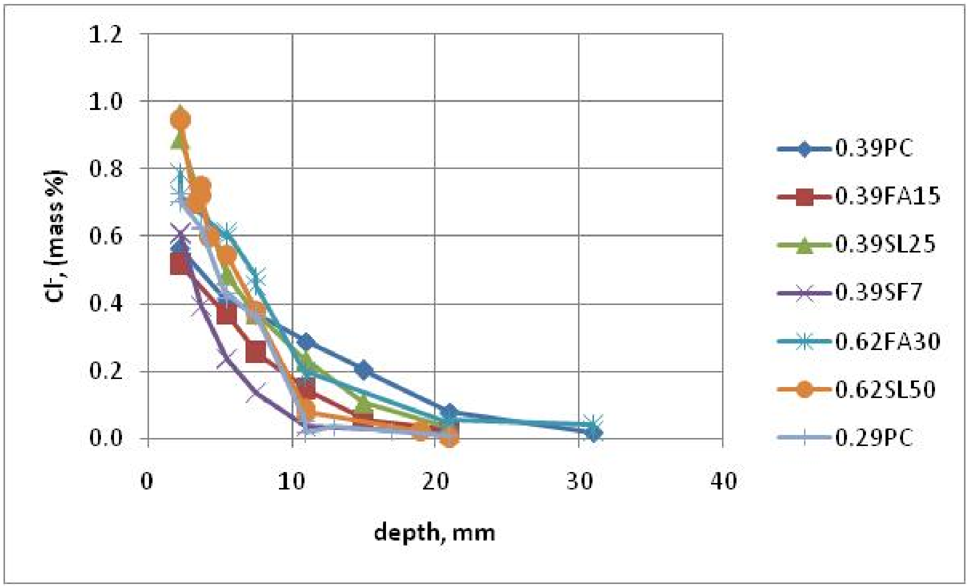
Figure 2.1 Chloride Profile (ASTM C1556) for Phase I



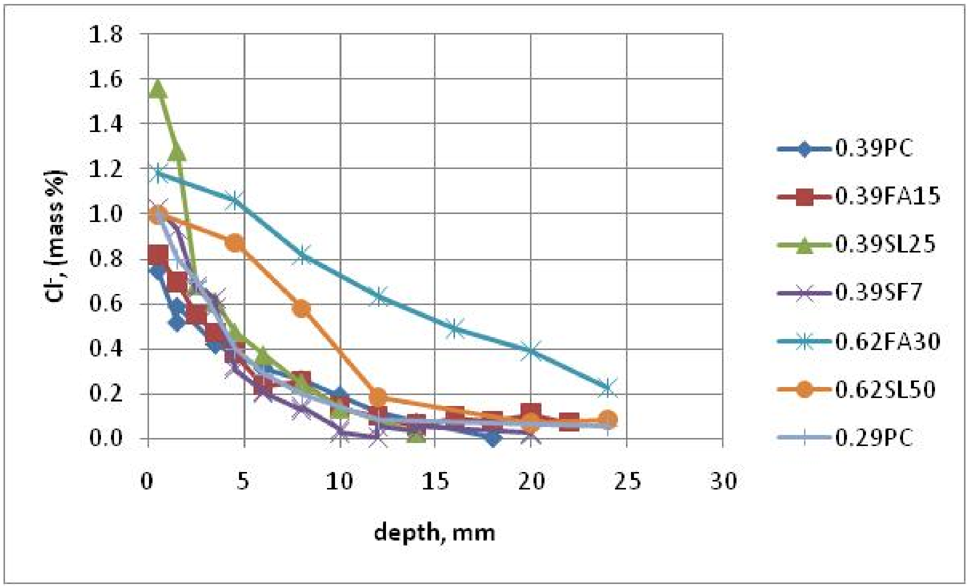
(a) Chloride Profile (ASTM C1556) for 56d standard curing followed by 35d in solution



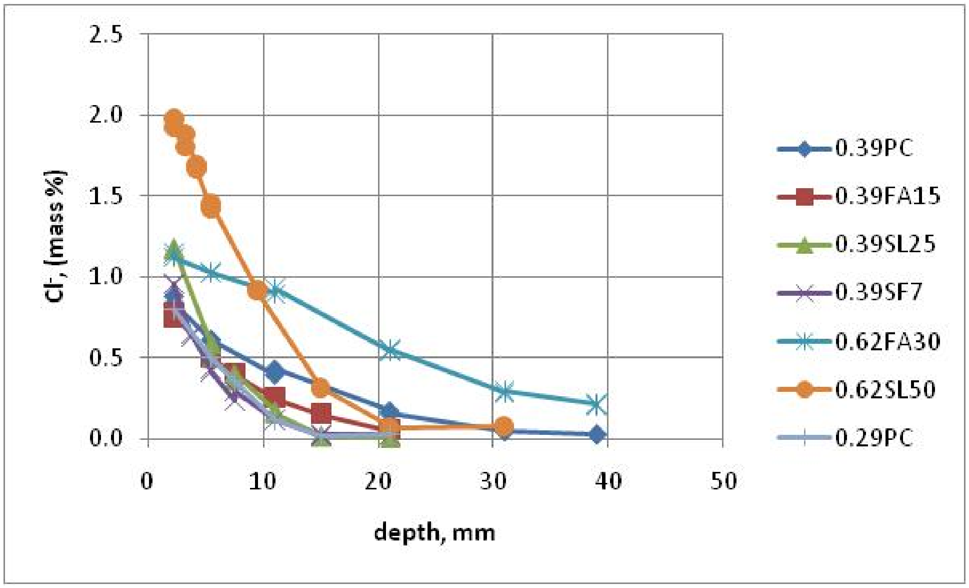
(b) Chloride Profile for 6m standard curing followed by 35d in solution



(c) Chloride Profile for 6m standard curing + 15m in solution (Phase II Immersed)

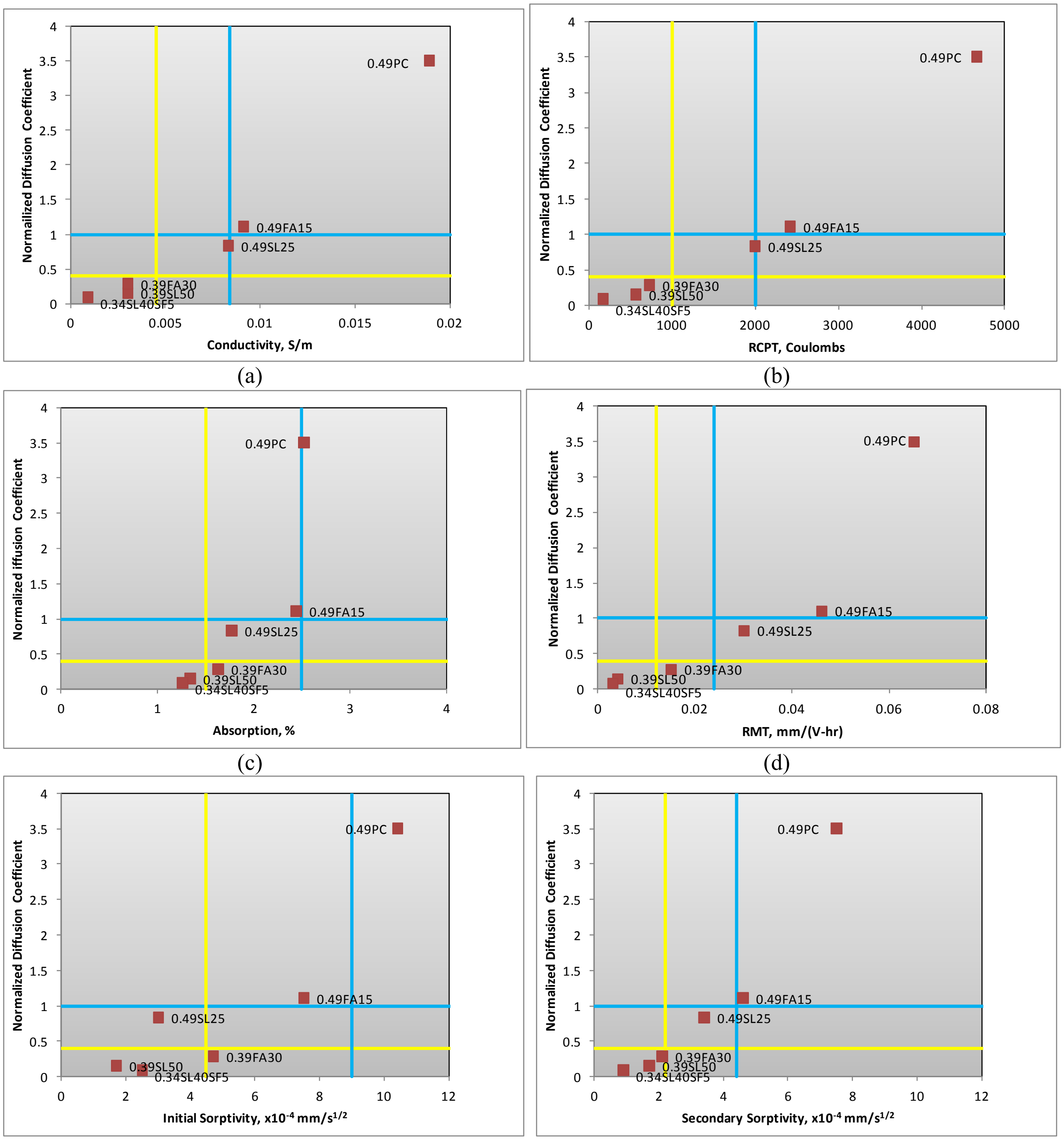


(d) Chloride Profile for 56d standard curing + 5m cyclic exposure to solution



(e) Chloride Profile for 56d standard curing + 18m cyclic exposure to solution (Phase II Cyclic)

Figure 2.2 Chloride Profile (ASTM C1556) for Phase II

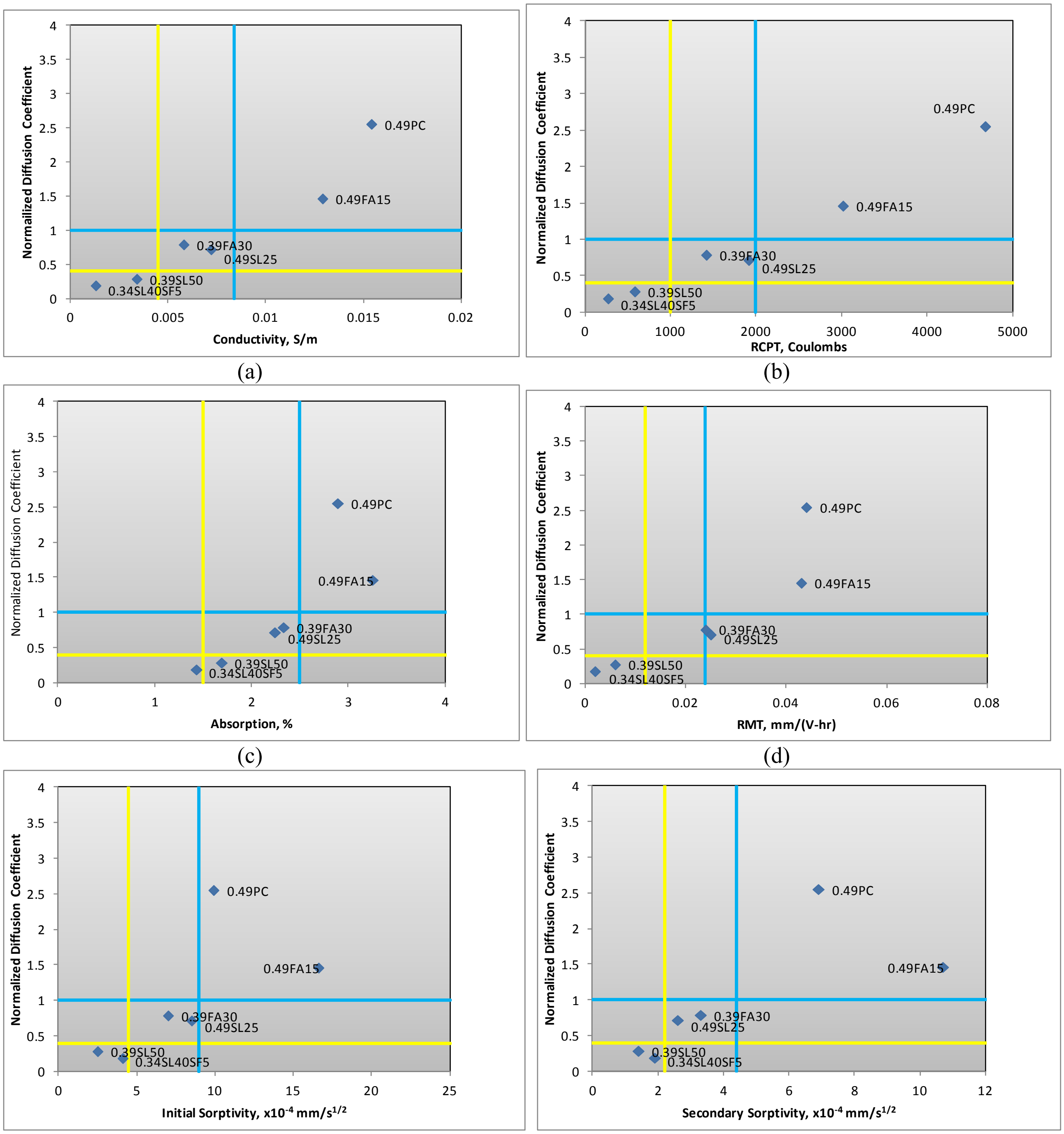


(a) (b)

(c) (d)

(e) (f)

Figure 2.3 (a) – (f) Mixture Categorization Based on 28 day Accelerated Cured Rapid Index Test Results and Normalized Chloride Diffusion Coefficients for the Phase I Immersed Condition (Lines Signify “Very Low” and “Low” Chloride Penetrability Regions)

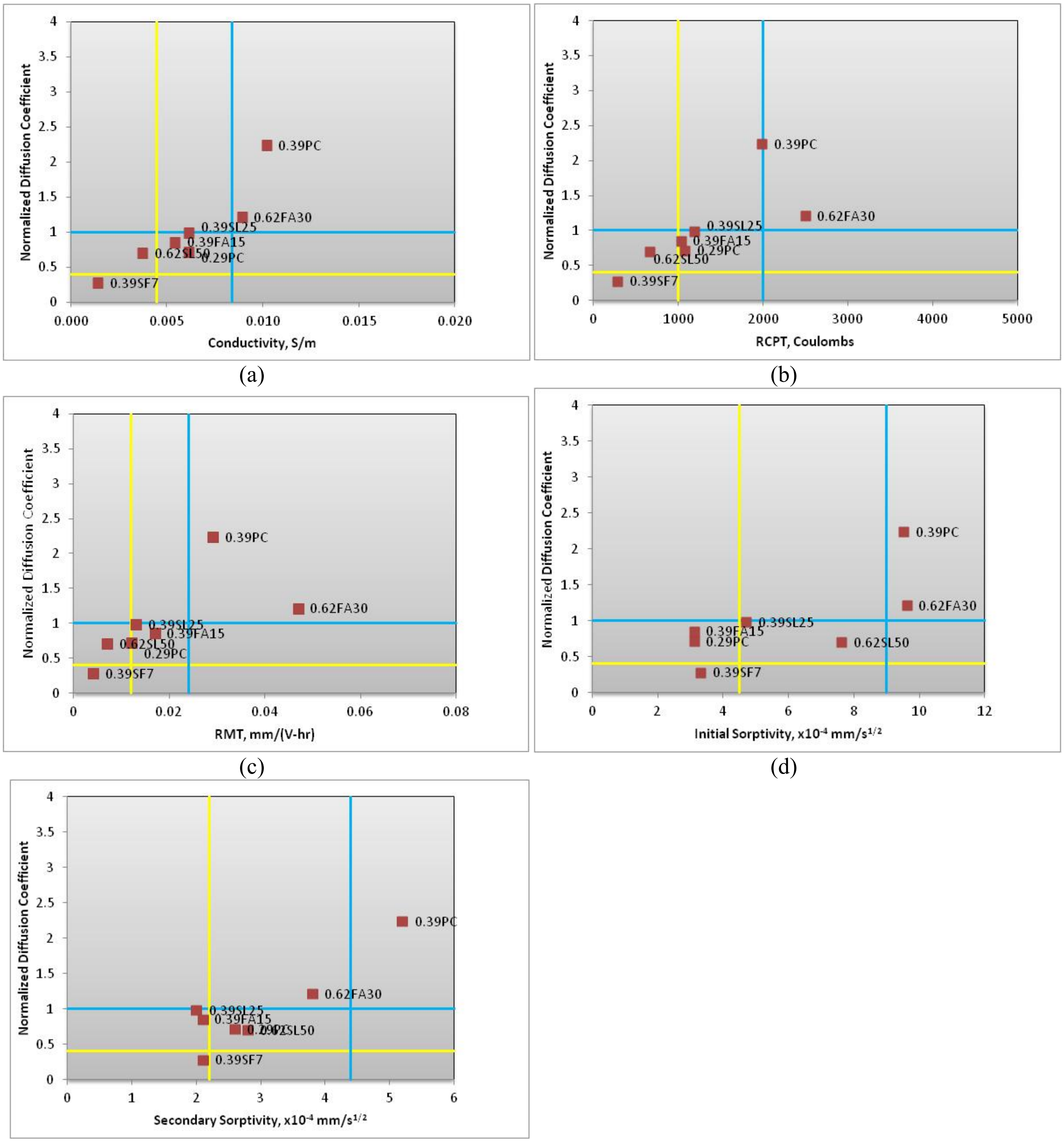


(a) (b)

(c) (d)

(e) (f)

Figure 2.4 (a) – (f) Mixture Categorization Based on 56 day Standard Cured Rapid Index Test Results and Normalized Chloride Diffusion Coefficients for the Phase I Cyclic Condition (Lines Signify "Very Low" and "Low" Chloride Penetrability Regions)

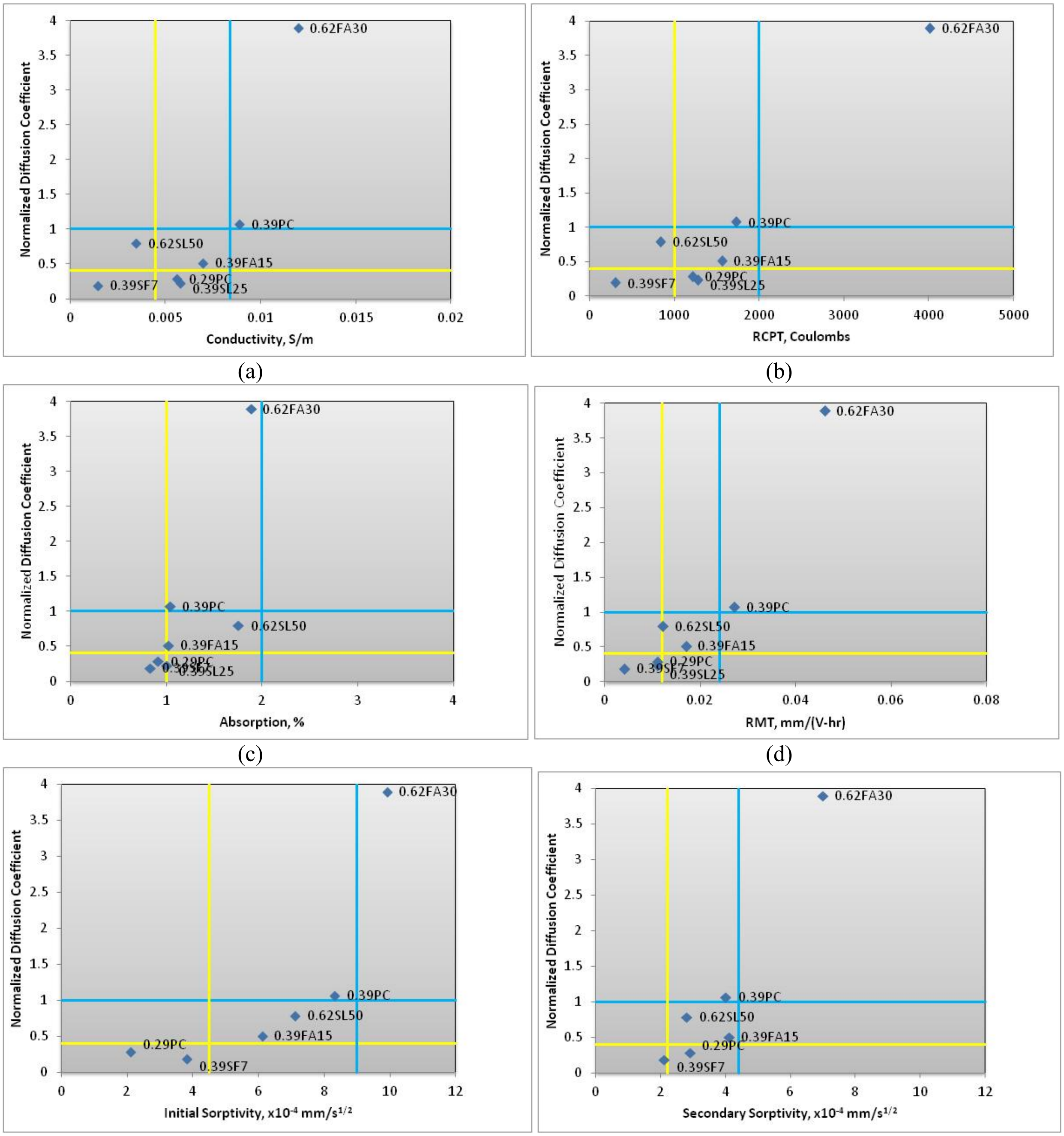


(a) (b)

(c) (d)

(e)

Figure 2.5 (a) – (e) Mixture Categorization Based on 28 day Accelerated Cured Rapid Index Test Results and Normalized Chloride Diffusion Coefficients for the Phase II Immersed Condition (Lines Signify "Very Low" and "Low" Chloride Penetrability Regions)



(a) (b)

(c) (d)

(e) (f)

Figure 2.6 (a) – (f) Mixture Categorization Based on 56 day Standard Cured Rapid Index Test Results and Normalized Chloride Diffusion Coefficients for the Phase II Cyclic Condition (Lines Signify "Very Low" and "Low" Chloride Penetrability Regions)

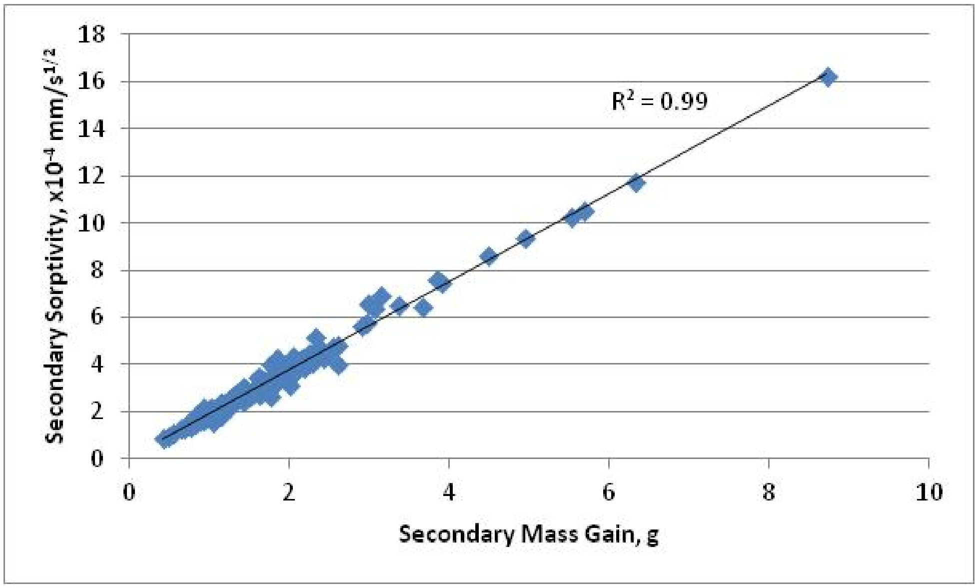


Figure 2.7 Correlation Between Secondary Sorptivity and Mass Gain

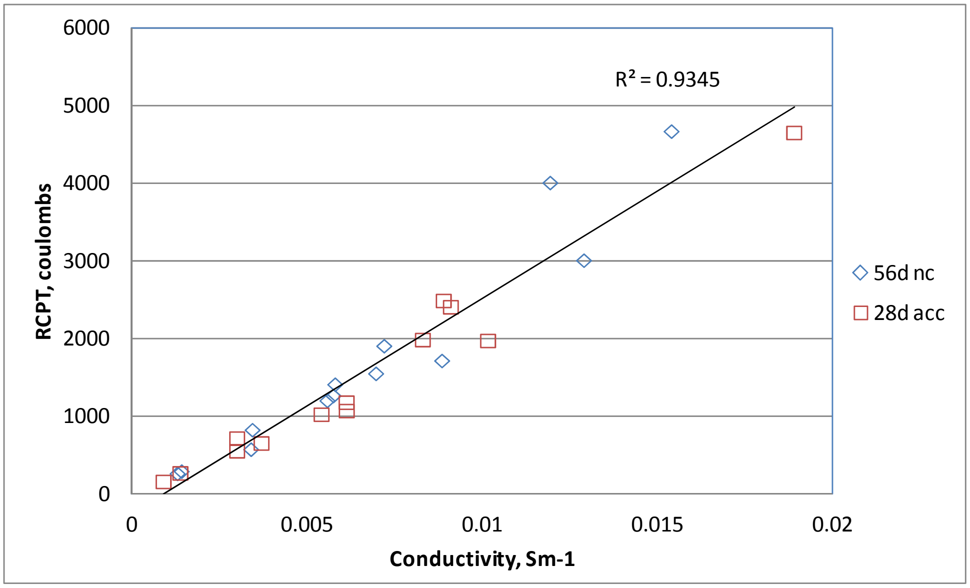


Figure 2.8 Correlation Between RCPT and Conductivity

3. Exposure to Freezing and Thawing

Exposure to cycles of freezing and thawing (F-T) can be a major cause of concrete deterioration when concrete is not designed for this service condition. Water expands by about 9% as it cools to become ice and this volume expansion can generate significant tensile stresses and lead to cracking in the concrete. Based on this, it is generally accepted that when a capillary is above 91.7% filled with water, hydraulic pressure results as freezing progresses (Kosmatka and Wilson 2011). Deterioration due to exposure to freezing and thawing cycles on exposed concrete surfaces is called scaling. Scaling manifests itself as loss of paste and in severe cases can result in raveling of the underlying coarse aggregates. Scaling is exacerbated in the presence of deicing salts as this tends to increase water absorption and retention (Spragg et al. 2011).

In this report, the degree of saturation is defined as the ratio of the actual volume of absorbed water to the total volume of water that can be absorbed by the concrete (also referred as absorption capacity). It has been suggested that when the saturation level of concrete exceeds a critical degree of saturation, DOS_{cr} freeze-thaw damage can occur (Fagerlund 1975; Bentz et al. 2001; Litvan and Serada 1980; Li et al. 2012). Fagerlund (2006) proposed that the air voids slowly fill with water during environmental exposure and when the saturation of concrete exceeds DOS_{cr}, a single freezing cycle results in tensile stresses that exceed concrete tensile strength causing damage.

Air entrainment provides freezing and thawing resistance of the concrete. The presence of multiple well-distributed and small air voids relieve pressure generated as water freezes to form ice. The expanding water enters the air voids to prevent pressure build up. In addition to air entrainment a minimum compressive strength of 500 psi is required before concrete is subjected to its first freezing event, and a minimum compressive strength of 4000 psi is required before concrete is subjected to cycles of freezing and thawing (ACI 306R-10). A maximum w/cm is also typically specified.

For buildings, the ACI 318-11 Building Code for Structural Concrete establishes exposure classes for concrete members based on anticipated exposure and has requirements as shown in Table 3.1. Guidance is provided in the ACI 318R-11 commentary whereby exterior walls, beams, girders, slabs not in direct contact with soil can be assigned an exposure class F1 as those members are not subject to snow and ice accumulation; Exterior elevated slabs, foundation or basement walls extending above grade that have snow and ice buildup against them can be assigned an Exposure Class F2 as those members will be subject to snow and ice accumulation; and horizontal members exposed to deicing chemicals can be assigned to Exposure Class F3.

The objective of this portion of the research project was to suggest performance criteria as an alternative to the maximum w/cm requirement in ACI 318-11 and other project specifications. The maximum w/cm limit is invoked as a prescriptive requirement to reduce water penetration and the potential to attain a DOS_{cr} in a portion of the member that results in F-T damage. However, the composition of the cementitious materials that impacts water penetration is not taken into consideration by the singular w/cm requirement in the specifications.

The study was conducted into 2 phases:
In Phase A, air-entrained concrete mixtures were made at varying w/cm, supplementary cementitious material (SCM) type and dosages. Concrete F-T performance was measured by ASTM C666

(Procedure A) and scaling resistance by ASTM C672. Rapid index tests that provide an indication of fluid transport characteristics of concrete were performed and it was attempted to correlate results of these tests to the F-T performance of the concrete mixtures and thereby develop performance criteria for F-T resistant concrete mixtures.

In Phase B, by varying the degree of saturation of specimens, it was attempted to quantify the DOS_{cr} that caused F-T failure in ASTM C666. It is postulated that mixtures that take longer to reach DOS_{cr} are likely to perform better when exposed to cycles of freezing and thawing. The time to attain DOS_{cr} depends on the current degree of saturation (DOS), mixture sorptivity (ASTM C1585), and absorption capacity (M_m). On this basis, performance criteria for F-T resistant concrete could be developed.

3.1 Phase A. Concrete F-T Test Performance and Correlation with Rapid Index Test Results

3.1.1 Materials and Mixture Proportions

The same materials used in the chloride ingress testing program were used. But instead of a Type A water reducing admixture, an ASTM C260 air-entraining agent was used to attain a target air content of 5 to 8%. The air-entraining agent was reported as a blend of saponified rosin and organic salts. The Type F high range water reducing admixture dosage was varied to attain a target slump of 5 to 7 in. The mixture proportions and test results are provided in Table 3.2. Of the eight mixtures evaluated in Phase A, six mixtures had a w/cm that is higher than that suggested for F-T exposure in Table 3.1. This was intentional because it was expected that air-entrained mixtures with a w/cm ≤ 0.45 would not experience F-T failure by ASTM C666.

3.1.2 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 by the pressure method (C231), and density (C138). The gravimetric air content was also calculated in accordance with ASTM C138.

Tests on hardened concrete included compressive strength (C39) measured on two 4x8 in. cylindrical specimens at an age of 28 days and length change (C157) on three 3x3x11 ¼ in. prisms, with seven days standard curing followed by up to 180 days of air drying in a 70°F, 50% relative humidity (RH) environment. This is a variation of ASTM C157 that requires 28 days of moist curing.

The two curing procedures discussed in the chloride ingress testing program were used for specimens tested with the rapid index tests. Rapid index tests to measure the transport characteristics of concretes included the rapid chloride permeability test (RCPT) (ASTM C1202), absorption, initial and secondary sorptivity (ASTM C1585) and were conducted at the following ages – after 28 day accelerated curing; and after 56 days and 26 weeks of standard curing. All the rapid index tests involved casting two 4x8 in. cylindrical specimens. Before the test, the specimens were cut and only the top 2 in. from the finished surface was tested.

For the ASTM C666 F-T test, two replicate beam specimens (3 x 4 x 15.5 in.) were prepared. Procedure A that involves freezing and thawing in water was utilized. Specimens were standard cured for 28 days followed by air drying in a 70°F, 50% RH environment for 28 days. The standard ASTM C666 test requires 14 days of moist curing unless otherwise specified. In this research program, a longer curing period was used to allow for the mixtures containing SCMs to achieve their potential durability properties. This is consistent with longer curing adopted in ASTM C1202 rapid indication of chloride ion penetrability tests. A drying period prior to the F-T exposure was incorporated to simulate the Exposure Class F1. Deterioration of concrete was measured by the relative dynamic modulus of elasticity (RDM) (ASTM C215) and mass change measurements after different number of F-T cycles.

For the ASTM C672 deicer salt scaling test, two replicate slab specimens (14 x 8 x 3 in.) were prepared. Specimens were standard cured for 28 days followed by air drying in a 70°F, 50% RH environment for 28 days. The surface of the specimens was ponded with a 4% calcium chloride solution and subjected to F-T cycles by placing the slabs in a freezer for 17 h and in laboratory air at 73°F for 7 h. The surface of the specimens was visually rated from 0 to 5 after every 5 cycles – 0 = no scaling and 5 = severe scaling. Ratings were made by four individuals and the averages are provided in Table 3.2 after 50 and 180 cycles.

Note that ASTM C666 is typically terminated after 300 cycles and C672 after 50 cycles.

3.1.3 Discussions of the F-T Test Results

At the end of 3120 F-T cycles the specimens were removed from the F-T machine, surface dried, weighed and placed in the moist room to cure 90 days. After moist curing, the specimens were weighed again and subjected to an additional 80 F-T cycles. The results at the end of 3200 F-T cycles are provided in Table 3.2. At the end of the 3200 cycles, the specimens were moist cured again for 90 days and were subjected to an additional 300 F-T cycles. The results at the end of 3500 cycles showed the same trend as the results at the end of 3200 cycles. Therefore, the discussions below are primarily focused on F-T performance up to 3200 F-T cycles.

Even after 3200 F-T cycles, with the exception of Mixture 0.50SL30, all mixtures indicated excellent freeze-thaw performance as indicated by RDM that exceeded 80%. These results are consistent with observations where air-entrained concrete with w/cm of 0.55 have been found to show excellent F-T performance (Lomboy and Wang 2009). Typically, concrete mixtures with RDM>80% after 300 cycles are considered to have excellent performance to F-T exposure (Goodspeed et al. 1996). The test data are consistent between specimens from a given mixture. It is unclear why Mixture 0.50SL30 showed reduced performance, as a very similar mixture (0.45SL30) did not show deterioration with 97% RDM after 3200 F-T cycles.

Figure 3.1 shows the appearance of the specimens after 3200 F-T cycles. Figure 3.2 shows mass loss increasing as a function of the number of F-T cycles for all mixtures. After 3200 F-T cycles, all mixtures had substantial scaling and the mass loss varied between 5.6% and 9.2%. After 300 F-T cycles, the mass loss of all mixtures was less than 0.5% except for the 0.60SL25SF5 mixture; however, unlike RDM, there are no limits for mass loss to classify mixtures based on their F-T durability.

The average visual rating of specimens due to deicer salt scaling tested by ASTM C672 varied widely between 0.5 and 5.0 after 50 cycles. Figure 3.3 shows a comparison of specimen deterioration of various mixtures and the corresponding visual ratings after 180 cycles.

The 28 day compressive strength of the concrete mixtures varied between 4100 and 6250 psi with most between 4100 and 4900 psi. The air contents varied between 6 and 7.6%. These results suggest that mixtures with acceptable RDM can be made even with w/cm as high as 0.60, as long the air content is above 6% and specified compressive strength is greater than 3500 psi. Results of the 56-day rapid index tests (RCPT, sorptivity and absorption) on the mixtures evaluated varied considerably. No conclusive relationship could be obtained between the 56-day rapid index tests and the F-T performance suggesting that mixtures with poor transport properties measured by the rapid index tests can be F-T durable provided they are not exposed to deicing salts. It is important to remember that the specimens were introduced in the F-T chamber following 28 days of air drying. It is surmised that the air drying process lowered the degree of saturation of the specimens considerably thereby improving the performance of the concrete specimens in ASTM C666.

3.1.4 Correlating the F-T Test Results and Rapid Index Test Results

Figure 3.4 shows that there was no correlation observed between the rapid index test results, w/cm, or strength and F-T performance related to C666 mass loss due to scaling after 3200 F-T cycles. This is due to the considerably good F-T performance of most of the mixtures.

Correlations between visual ratings after 50 cycles tested by C672 are plotted against rapid index test results, w/cm and strength in Figure 3.5. The rapid index test results, strength, air content or w/cm do not correlate well with the visual rating from ASTM C672 tests. A minimum measured 28 day strength of 5100 psi, separates the better performing mixtures with a scaling rating after 50 cycles varying between 0.5 and 3.0 from the mixtures that had greater scaling. These mixtures are 0.45PC, 0.45SL30, 0.50SL30, and 0.50SL25SF5. All mixtures contained at least 6% air. Increasing the strength requirement to more than 5100 psi does not help categorize mixtures with an even lower scaling rating as Mixture 0.50SL25SF5 had the highest strength (6250 psi) but had slight to moderate scaling (rating of 2.3). Average 28 day strength of 5100 psi approximately corresponds to specified 28 day strength of about 4500 psi. If the strength requirement is combined with a 0.45 maximum w/cm criterion; or only the 0.45 maximum w/cm criterion is used this separates mixtures that have a scaling rating after 50 cycles that vary between 0.5 and 2.0, a narrower range. The w/cm requirement could not be replaced with a suitable rapid index test requirement. Interestingly, sorptivity has been found to correlate with scaling resistance (Gagne et al. 2011).

It is generally recognized that ASTM C672 is a severe test and does not correlate well to scaling resistance in field concrete. Surface scaling in field concrete is significantly influenced by the finishing and curing procedures used (Lankard 2001).

3.1.5 Phase A Summary

Members assigned to exposure class F1 are exposed to cycles of freezing and thawing with limited exposure to moisture. These members are not subjected to snow and ice accumulation and are not exposed to deicing salts; hereby, it is anticipated that these members will not be critically saturated to result in deterioration due to F-T. These members might be exterior walls, beams, girders, slabs not in direct contact with soil. Based on the excellent ASTM C666 F-T performance (acceptable RDM) of Phase A mixtures in this study, even those with w/cm as high as 0.60, it is suggested that the w/cm ratio requirement for concrete assigned to an ACI 318 exposure class of F1 can be as high as 0.60. Based on results in this study, a minimum specified strength requirement of 3500 psi is considered to be adequate. Concrete mixtures have to be air-entrained.

Members assigned to exposure class F3 are exposed to cycles of freezing and thawing and are frequently exposed to moisture and deicing salts. These members might be horizontal members in parking structures and most transportation structures. In this study, ASTM C672 results indicate that a maximum w/cm of 0.45, specified compressive strength of 4500 psi and air content of 6% is required for resistance to deicer scaling. However, specifiers should consider the impact of finishing and curing practices on scaling.

3.2 Phase B. Effect of Degree of Saturation on Concrete F-T Performance

This phase of the research evaluates the effect of degree of saturation of concrete relative to DOS_{cr} and the performance of concrete when tested in accordance with ASTM C666. If DOS_{cr} is established for a concrete mixture, it follows that mixtures where it takes a longer time to reach DOS_{cr} are likely to perform better when exposed to F-T cycles. The time to attain DOS_{cr} depends on the current degree of saturation (DOS), mixture sorptivity (ASTM C1585), and absorption capacity (M_m).

3.2.1 Relation between DOS, Sorptivity, Mm and F-T Resistance of Concrete

It is suggested that concrete at low DOS (drier), low sorptivity and a high M_m will result in a longer time to attain DOS_{cr}. With these conditions, concrete will perform better when exposed to cycles of freezing and thawing.

This is explained as follows based on presumed specimen characteristics in Table 3.3:

Specimen 1 with a certain mass (m_i) and known mass in dry (m_d) and saturated (m_s) conditions (Table 3.3) is exposed to water. With time the specimen absorbs water and its mass and DOS increases. The degree of saturation at any given instant (DOS_i) can be calculated by the following equation:

$$DOS_i = \frac{M_i}{M_m} = \frac{(m_i - m_d)}{m_d} \times \frac{m_d}{(m_s - m_d)} = \frac{(m_i - m_d)}{(m_s - m_d)}$$

Where m_d = mass of dry specimen (0% saturation)
m_i = mass of specimen at given instant
m_s = mass of saturated specimen (100% saturation)
M_i = Moisture content at DOS_i, percent of dry specimen mass
M_m = Absorption capacity of specimen, i.e. at 100% saturation, $M_m = \frac{(m_s - m_d)}{m_d}$
DOS_i = Degree of saturation at a given instant

With continued water absorption, the DOS of the specimen reaches critical DOS (assumed 90%). For specimen 1 the increase in mass (Δm_{cr}) necessary for the specimen to change its saturation level from DOS_i to DOS_{cr} can be calculated as 1.5 g.

ASTM C1585 determines the rate of absorption (sorptivity) of water by concrete by measuring the increase in the mass of a specimen as a function of time when only one surface of the specimen is exposed to water. From ASTM C1585 it can be stated that

$$\Delta m = k \times \left(S \times \sqrt{t} + b\right)$$

Where
Δm = calculated mass increase for the specimen over time (t) due to sorptivity (S)
S=Sorptivity of concrete
t = time
k, b are constants

Concrete with a higher sorptivity absorbs water at a faster rate. Alternatively, it would require a shorter time for the specimen from its initial moisture condition to gain mass (Δm_{cr}) so that the DOS reaches DOS_{cr}.

Specimen 2 is identical to specimen 1 except that it has double the absorption capacity (M_m). As a result, the specimen's DOS_i can be calculated as half that of specimen 1 and the increase in mass necessary for the DOS_i to reach DOS_{cr} is now calculated as 6 g, i.e. four times the increase in mass of that of specimen 1. Assuming that specimens 1 and 2 have the same sorptivity it will require a much longer time for specimen 2 to attain DOS_{cr}. If specimen 2 were to have the same DOS_i as specimen 1 (see specimen 3 in Table 3.3) it would need twice the increase in mass necessary for the specimen DOS_i to reach DOS_{cr} as specimen 1.

However, a specimen with a higher M_m does not always increase the freeze thaw resistance of the concrete. If specimen 2 were to be at higher DOS_i than specimen 1 (such as specimen 4 in Table 3.3) it would need only two thirds the increase in mass necessary for the specimen DOS_i to reach DOS_{cr} as specimen 1! Results from this study discussed later show that mixtures with lower w/cm and SCMs reduce M_m but also lower the DOS.

From Table 3.3 Δm_{cr} can also be expressed as:

$$\Delta m_{cr} = m_d \times M_m \times (DOS_{cr} - DOS_i)$$

Generally, a structure is cured and at the end of the curing period its DOS is said to be DOS_{mc}. Since a structure could be exposed to moisture immediately after the end of the curing period DOS_i=DOS_{mc}. Clearly, DOS_{mc} should be less than DOS_{cr} or else the structure will fail if it is exposed to F-T cycling immediately after the end of the moist curing period. In general, structures are not immediately exposed to F-T cycles. They undergo wetting and drying and correspondingly their DOS will increase and decrease respectively depending on their sorptivity and drying rate. Cracked specimens will experience a rapid increase in DOS.

It has been reported that exposed concrete in the field can have relative humidity in excess of 80% at a depth greater than 2 in. from the surface of the concrete (Stark 1991; Jensen 2003). However, relative humidity is not a direct measure of DOS (Grasley et al. 2006). Service life models have been developed that calculate the service life as the time taken for the DOS of the concrete to attain DOS_{cr} when the concrete is exposed to moisture (Fagerlund 2006; Barde et al. 2009; Bentz et al. 2001). DOS measurements in the field can also help validate these service life models.

3.2.2 Materials and Mixture Proportions

The same materials used in Phase A were used except that a different source of coarse aggregate was used as the original source was no longer available. Four mixtures were selected for this phase of the study – three with portland cement and one containing slag cement. Variables include w/cm (0.65 and 0.45) and air content. Marginal air content was chosen so that the specimens would have a greater potential to fail during the F-T test. The mixture proportions and test results are provided in Table 3.4. The four mixtures were selected to evaluate the effect that changes in intrinsic porosity (w/cm, and presence of slag cement) and air content will have DOS_{cr}.

3.2.3 Procedures

Concrete mixtures were mixed in a revolving drum laboratory mixer in accordance with ASTM C192. An ASTM C494 Type F water reducing admixture was used at varying dosage to attain a slump in the range of 4 to 7 in. An ASTM C260 air-entraining agent was used to attain the target air content. Fresh concrete was tested for slump (C143), temperature (C1064), air content (C231), and density (C138). A total of nine 4x8 in. cylinders and twelve 3x3x11.25 in. beams for the F-T test were made. Specimens were moist cured till testing age.

Tests on hardened concrete included compressive strength (C39) at an age of 28 and 56 days; measured on two 4x8 in. cylindrical specimens at each age.

Rapid index tests to measure the transport characteristics of concretes included the rapid chloride permeability test (RCPT) (ASTM C1202), initial and secondary sorptivity (ASTM C1585) after 56 days. The sorptivity test was extended up to 6 m. All the durability tests involved casting two 4x8 in. cylindrical specimens. Before the test, the specimens were cut and only the top 2 in. from the finished surface was subjected to the test. One of the cylindrical specimens was reserved for hardened air void analysis (ASTM C457).

3.2.4 Conditioning of the F-T Test (ASTM C666) Specimens

The ASTM C666 test was conducted on specimens that had been conditioned and maintained at four different target degree of saturation (DOS) levels – 100%, 92%, 86% and 82% (two specimens at each DOS). In addition, standard cured control specimens that were not controlled to a target DOS were tested. The DOS of the standard-cured ASTM C666 specimens is expected to vary during the test as the specimens are not sealed. Since ASTM C666 Procedure A was used it can be surmised that the DOS of the control specimens progressively increases as the test progresses.

Following 28 days of moist curing, the six prisms were wiped dry to the saturated surface dry condition and the mass was measured. The specimens were dried at 140°F for 7 days following which their dry mass (m_d) was measured. The specimens were vacuum saturated (VS) (pressure of 0 mm Hg) in accordance with the procedure in ASTM C1202. The SSD mass of the vacuum saturated specimens was measured after the 18 h water immersion period (m_s). The VS process was repeated until the gain in mass due to water absorption by the specimens was less than 2 g (0.05% of specimen mass). The total mass gain from the dry condition to the VS condition is referred to as M_m, representing the absorption of water by the specimen subjected to a vacuum and is considered as the absorption capacity (100% DOS).

In preliminary tests on separate samples, M_m was also measured on specimens that were dried at 220°F to constant mass (48 h oven drying followed by oven drying every 24h until specimen mass did not change by more than 0.05%). While drying specimens at 220°F was more effective, the moisture uptake during the VS phase was lower. In other words, the saturation level of specimens dried for seven days at 140°F was higher than that of specimens dried at 220°F. Moreover, it was felt that drying specimens at 220°F could cause internal cracking which could adversely impact F-T performance. For these reasons, specimens in this study were conditioned by drying for seven days at 140°F followed by vacuum saturation to constant mass.

It should be noted that the vacuum applied to the specimens likely extracted air from the entrained air void system of the concrete also and the subsequent soaking allowed for some or all of the entrained air voids to be filled with water. This DOS, therefore, may be considered a higher level of saturation than water saturating the capillary porosity of concrete. The DOS of the air void system, however, cannot be isolated from that of the capillary porosity. It is also assumed that during the subsequent drying to a target DOS, the water filled air voids emptied to some extent to allow for the typical functionality of the entrained air void system.

Following the final VS phase, four out of the six specimens were removed while the other two specimens were left submerged in water. The four specimens were dried at 70°F and 50% RH. The mass of the specimens was measured every 30 min until the specimens reached an estimated DOS of 86% and 92%.

When the target DOS was attained the specimens were wrapped with shrink wrap. The wrapped specimen was double layered with a vacuum bag and sealed using vacuum sealers used for food storage. For 100% DOS condition, two specimens were sealed in the vacuum saturated condition. Two specimens, representing control specimens, were tested without additional conditioning from the moist cured condition. The degree of saturation of the moist cured specimens (DOS_{mc}) was determined as the average value from the six other specimens for that mixture. It is recognized that this would increase as the test progressed. For the 82% DOS condition, two specimens were removed from the moist room. If their DOS_{mc} exceeded 82% the specimens were dried at 70°F and 50% RH to reach DOS of 82% and sealed. If their DOS_{mc} was less than 82% the specimens were immediately sealed.

In summary the following were the specimens used:

- Vacuum saturated specimens (two each) at 100%, 92% and 86% DOS
- Moist cured specimens (two each) conditioned to 82% DOS or below and control specimens at DOS_{mc}

The specimens conditioned to a target DOS were sealed to ensure that the DOS did not change during the F-T testing. ASTM C666 testing was commenced three days after the specimens were sealed to allow for some moisture redistribution within the specimens. The specimen masses were measured at the end of the three day period and the DOS value was corrected as in some case there was a slight moisture loss. The control specimens, representing the typical specimen moisture condition used in C666 tests, were not sealed.

Specimens were placed in the F-T machine at the same time at an age of about 56 days. After about every 25 F-T cycles the specimen seals were removed and the RDM and mass were measured. Changes in mass of sealed specimens were used to estimate the DOS. The specimens were then resealed as before and placed in the F-T machine. Specimens were considered to reach failure when the RDM dropped below 60% before 300 F-T cycles.

3.2.5 Discussions of the Phase B Test Results

The compressive strengths were in line with expectations with the w/cm of the mixtures. The total air contents of the fresh concrete, measured by C231, were within the tolerance of the target air content. The measured hardened air void content is reasonably consistent with the measured air content of fresh concrete. With the exception of mixture 0.45PC-6.5, all mixtures have an inadequate air void system considering the spacing factor and specific surface of air voids. The air void system is considered to be adequate when the spacing factor is equal to or less than 0.008 in. and the specific surface is greater than 600 in^2/in^3.

The following observations can be made from Table 3.4 results:

1. For high w/cm (0.65) and low air content (4%) mixtures a 35% slag cement replacement decreased the M_m from 4.9% to 3.9%, decreased the DOS_{mc} from 93% to 89% and decreased the sorptivity. The RCPT value indicates an expected reduction with the use of slag cement.
2. For a PC mixture reducing the w/cm from 0.65 to 0.45 at the same low air content (4%) decreased the M_m from 4.9% to 3.9%, decreased the DOS_{mc} from 93% to 86% and decreased the sorptivity. The RCPT value indicates an expected reduction for the reduction in w/cm.
3. For a PC mixture at a low w/cm of 0.45 increasing the air content from 4.1% to 6.4% increased the M_m from 3.9% to 5.1%, decreased the DOS_{mc} from 86% to 77% and increased the sorptivity. The RCPT value is similar for these mixtures as expected from the same w/cm.

The results suggest that concrete mixtures with a lower w/cm or use of 35% slag cement at the same air content of 4% results in lower absorption capacity, M_m, lower DOS_{mc} and lower measured sorptivity. It can be surmised that these mixtures have a finer pore structure and this is validated by RCPT test results. Increased entrained air content at the same w/cm of 0.45 increased the M_m value due to increased water uptake into the air voids during VS which in turn lowered the DOS_{mc}.

3.2.5.1 ASTM C666 Results Discussions

Ideally, a sealed specimen should not experience a change in mass (or DOS) during F-T cycling. An increase in mass is likely if the specimen seal is compromised during the F-T cycling, thereby permitting water to be absorbed and causing the calculated DOS to exceed 100%. Drying of specimens, when seals are removed during measurements, can result in reduced DOS. Each specimen had a mass of about 4000g and a change in DOS of 1% corresponds to mass change of about 2 g. The

F-T test results (RDM) are plotted as a function of the number of F-T cycles in Figure 3.6a-Figure 3.9a. It was noted during the experiment that in some of the test specimens it was not possible to maintain a constant DOS as the F-T cycles increased. So for those test specimens the F-T test results (RDM) and the DOS are plotted as a function of the number of F-T cycles in Figure 3.6b-Figure 3.9b. For all 4 mixtures the control specimens had severe scaling on the surface whereas none was observed for the sealed specimens.

Mixture 0.65PC-4.0 Specimens with DOS of 100%, 92%, and 87% failed before 300 F-T cycles. The specimens with a lower DOS withstood a greater number cycles prior to failure. Observing the 87% DOS specimen (Figure 3.6b) shows that the seal appears to have been compromised between 160 and 212 cycles resulting in an increase in the DOS from 87% to 96%. Between 212 and 257 cycles the DOS dropped back to 91%. RDM began to decrease after 160 F-T cycles, with a significant rate of decrease noted after 212 cycles. The specimens at DOS of 78% showed no reductions in RDM. But in one of those specimens the seal had been compromised between 0 and 51 cycles and the DOS increased from 78% to 88% and stayed around 87% throughout the test. No reduction in RDM was noted throughout the test. From these data it is surmised that for the 0.65PC-4.0 mixture DOS_{cr} is between 88% and 91%. Control specimens failed at around 444 cycles. The DOS of the control specimens was 93% at the start of F-T test but was not sealed during the F-T test.

Mixture 0.65SL35-4.0 Specimens with DOS of 100%, 92%, and 85% failed before 300 F-T cycles. The specimens with a lower DOS withstood a greater number of cycles. Observing the 85% DOS specimens (Figure 3.7b) it is seen the DOS increased from 85% to 88% between 138 and 193 cycles; and stayed above 90% after that. An initial reduction in RDM was observed at 193 F-T cycles which progressed to decrease thereafter. The specimens at DOS of 78% showed no reductions in RDM. From these data it is surmised that for the 0.65SL35-4.0 mixture DOS_{cr} is about 88%. The DOS of the control specimens was 89% at the start of F-T test. The control specimens failed rapidly.

Mixture 0.45PC-4.0 Specimens with DOS of 99% failed before 60 F-T cycles. Specimens at DOS of 92%, 78% and 77% did not fail. The acceptable performance of the 92% DOS specimens was unusual. Observing the 92% DOS specimens (Figure 3.8b) shows that even though the DOS started at 92% it had decreased to 89% by 180 cycles. DOS decreased to 85% by 391 cycles and leveled off. Correspondingly RDM decreased until about 180 cycles and steadied off suggesting no further F-T deterioration. If RDM had continued to decrease at the same rate then it should have indicated a failure by 250 cycles. From these data it is surmised that for the 0.45PC-4.0 mixture DOS_{cr} is around 90%. The DOS of the control specimens was 88% at the start of F-T test and did not show reduction of RDM at 300 F-T cycles. The excellent F-T performance of a marginal air content mixture is not unusual (Tanesi and Meininger 2006).

Mixture 0.45PC-6.5 Specimens with DOS of 99%, 92% failed before 300 F-T cycles. Observing the 92% DOS specimens (Figure 3.9b) shows a reduction of the DOS to 90% by 98 cycles, remaining constant thereafter. A rapid decrease in RDM is observed through 98 cycles and a much more gradual decrease thereafter. By 147 cycles the RDM had reached the failure point. It is surmised that for the 0.45PC-6.5 mixture DOS_{cr} is around 90%. Specimens at DOS of 86%, 80% did not show any reduction in RDM. The DOS of the control specimens was 77% at the start of F-T test and did not show reduction of RDM at 300 F-T cycles.

The RDM for the DOS at 92% specimens after 98 cycles was about 63%. In comparison, for the 0.45PC-4.0 mixture the RDM for the DOS at 92% specimens after about 100 cycles can be estimated as about 75%. The DOS at that stage was comparable at 90% for both mixtures. This suggests that at a similar DOS greater than DOS_{cr}, the higher air content of the 0.45PC-6.5 mixture does not really help improve F-T resistance over that of the 0.45PC-4.0 mixture.

3.2.6 Phase B Summary

3.2.6.1 Critical DOS

When the ASTM C666 test results are analyzed it appears that there is a critical degree of saturation, DOS_{cr} for failure due to exposure to cycles of freezing and thawing to occur. Failure is defined as RDM<60% within 300 F-T cycles. For any mixture, as expected, the lower the specimen's DOS the better the F-T performance. The critical degree of saturation, DOS_{cr}, for F-T failure is around 88%. This represents the total available porosity in the concrete including entrained air voids. This observation appears to be independent of the air content, SCM type/content and w/cm evaluated in this study. Note that the DOScr defined here includes more than saturation of the capillary porosity. The value of DOS_{cr} is similar to that reported in the literature (Fagerlund 2006; Li et al. 2012).

When the DOS was greater than DOS_{cr} even air-entrained concrete with a low w/cm resulted in failure due to cycles of freezing and thawing in ASTM C666 as indicated by the RDM. Conversely when the DOS was lower than DOS_{cr} even concrete with a w/cm of 0.65, a low air content, and low compressive strength did not fail in these tests. The latter observation is consistent with the observation in Phase A that a maximum w/cm as high as 0.60 may be acceptable for ACI 318 exposure class F1.

3.2.6.2 Developing F-T Resistant Concrete Mixtures

The control specimens of both mixtures with a 0.65 w/cm had significant reductions in RDM and failed in the F-T test. These specimens had $DOS_{mc} \geq 89\%$. The control specimens of the 0.45PC-4.0 mixture had adequate F-T resistance as measured by ASTM C666 RDM even though they had a marginal air content and air void spacing factor. These specimens had a DOS_{mc} of 86%. The ASTM C666 test of 300 F-T cycles takes about 50 days and for only about 10 days the specimens thaw in water (they are frozen for the remainder of the time). Since it is very unlikely for a moist cured specimen to undergo an increase in DOS during the 10 day exposure to below 40ºF water it can be argued that as long as $DOS_{mc} < DOS_{cr}$ the specimen should not suffer a reduction in RDM during the 300 F-T cycles of the ASTM C666 test even if the DOS is not controlled by sealing during the F-T cycles.

From Table 3.4 it is clear that increased air content leads to a higher M_m and lowers the DOS at any point (as evidenced by the lower DOS_{mc}) which can extend the time to attain DOS_{cr}. The F-T resistance of the higher entrained air content mixture can be improved further if its sorptivity is also reduced. From Table 3.4 it can be observed that concrete mixtures with a lower w/cm or SCMs have lower sorptivity. These mixtures also reduce the M_m but are expected to have a lower DOS (as evidenced by the lower DOS_{mc}) and therefore the net result is expected to be an increase in the time to attain DOS_{cr}. Another option would be to seal the concrete which would reduce the sorptivity without affecting M_m. Sealers could be a good choice particularly for those areas that have a high tendency to become critically saturated. Based on the excellent ASTM C666 performance of the 0.45 w/cm mixtures a maximum w/cm criterion of 0.45 or a maximum secondary sorptivity of 1 $\times 10^{-3}$ mm/s$^{1/2}$ is suggested. However, more experimental validation is required to confirm the sorptivity requirement. The corresponding 28 day specified strength requirement would be 4500 psi.

For all the mixtures, the specimens at 100% DOS (that were sealed) showed significant reductions in RDM and failed in the F-T test. There was no surface scaling for these specimens. If scaling occurs primarily due to freezing and thawing of water inside the concrete at the surface then the sealed specimens should have scaled as there was adequate moisture. It appears that the physical formation of ice on the concrete surface is necessary for surface scaling. A possible explanation is that the freezing and thawing of ice on the concrete surface may be subjecting the concrete surface to restrained tensile forces which causes scaling. Since the presence of the shrink wrap and double layered vacuum bag prevented that from happening (the ice formed on the bag and not on the concrete surface) scaling did not occur. From a practical point of view, if similar results are demonstrated with a sealer or membrane it could help achieve scale-resistant concrete driveways and sidewalks even with a high w/cm of 0.65 and low compressive strength. However, it is possible that shrink wrap and double layered vacuum bag provides a physical barrier of greater magnitude than any sealer or membrane.

3.3 Suggested Performance Criteria for Concrete F-T Durability

Based on the Phase A and B conclusions the performance criteria for F-T durability are summarized in Table 3.5.

The effect of higher amounts of SCM on scaling was not studied in this project. So no recommendations are made as to these limits in ACI 318 for concrete with application of deicing chemicals (Exposure Class F3). Alternative criteria for the prescriptive w/cm requirement are $DOS_{mc} < DOS_{cr}$ and maximum secondary sorptivity of 1×10^{-3} mm/s$^{1/2}$. More experimental validation is required to recommend these criteria though. Sealers are recommended particularly for those applications that have a high tendency to become critically saturated.

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Table 3.1 ACI 318-11 Requirements for Concrete Exposed to Freezing and Thawing

Exposure Class	Max. w/cm	Minimum *f'*$_c$, psi	Air Content,%	Limits on SCM
F0 – Concrete not exposed to F-T cycles	N/A	2500	N/A	N/A
F1 - Concrete exposed to F-T cycles and occasional exposure to moisture	0.45	4500	4.5[*]	N/A
F2 - Concrete exposed to F-T cycles and in continuous contact with moisture	0.45	4500	6.0[*]	N/A
F3 – F2+expoure to deicing chemicals	0.45	4500	6.0[*]	Table 4.4.2

[*] These air contents are for ASTM C33 No. 57 (1 in. nominal maximum size) aggregate. For different size aggregates the air contents are provided in Table 4.4.1 in ACI 318-11. The measurement tolerance for air content as delivered is ±1.5%.

Table 3.2 Yield Adjusted Mixture Proportions and Test Results (Phase A)

Mixture Designation	0.57 PC	0.50 PC	0.50 FA20	0.50 SL30	0.50 SL25SF5	0.60 SL25SF5	0.45 PC	0.45 SL30
Calculated Batch Quantities								
Type I/II cement, lb/yd^3	506	539	442	385	385	353	592	414
Slag, lb/yd^3				165	137	126		177
Fly ash, lb/yd^3			111					
Silica Fume, lb/yd^3					27	25		
SCM, %	0	0	20	30	30	30	0	30
Coarse Agg. (No.57), lb/yd^3	2087	2021	2071	2060	2058	2077	2035	2029
Fine Aggregate, lb/yd^3	1094	1083	1066	1093	1084	1072	1062	1048
Mixing Water, lb/yd^3	290	270	276	275	275	302	267	266
w/cm	0.57	0.50	0.50	0.50	0.50	0.60	0.45	0.45
ASTM C260 AEA, oz/cwt	0.79	0.84	4.26	1.17	0.86	1.39	0.74	1.87
ASTM C494 Type F, oz/cwt	-	0.56	0.40	0.58	2.59	0.51	1.37	1.16
Fresh Concrete Properties								
ASTM C143, Slump, in.	7	6	6	5	5	6.5	5.25	6
ASTM C231, Air, %	6	7.2	6	6.2	6.5	6.2	7	7.6
ASTM C138, Gravimetric Air, %	5.7	7.8	5.5	6.0	6.1	5.2	7.2	7.4
ASTM C138, Density, lb/ft^3	148.1	145.7	147.7	148.1	147.7	147.3	147.3	146.5
ASTM C1064, Temperature, °F	75	75	73	70	72	70	70	70
Hardened Concrete Properties								
ASTM C39, Compressive Strength, psi								
28 days	4,918	4,895	4,101	5,376	6,249	4,844	5,427	5,182
Water Absorption Test (drying at 122 °F), % change in mass								
28d accelerated cure	2.28	1.81	1.41	1.47	1.24	1.56	1.61	1.20
56d normal cure	1.85	1.65	1.81	1.36	1.44	1.74	1.76	1.39
182d (26w) normal cure	1.67	1.47	1.19	1.45	1.29	1.51	1.49	1.20
ASTM C1202, Rapid Chloride Permeability, Coulombs								
28d accelerated cure	5015	3578	2014	1077	332	516	2630	851[--]
56d normal cure	4876	3633	4287	1554	469	848	2957	1143[--]

Mixture Designation	**0.57 PC**	**0.50 PC**	**0.50 FA20**	**0.50 SL30**	**0.50 SL25SF5**	**0.60 SL25SF5**	**0.45 PC**	**0.45 SL30**
182d (26w) normal cure	5297	3879	2193	1340	532	622	2722	1094
ASTM C157, Length Change, %								
28 days	0.045	0.039	0.041	0.049	0.053	0.063	0.036	0.039
56 days	0.061	0.046	0.050	0.052	0.056	0.069	0.049	0.049
90 days	0.069	0.054	0.057	0.058	0.065	0.075	0.055	0.055
180 days	0.076	0.059	0.057	0.063	0.065	0.077	0.058	0.058
ASTM C1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$								
28d accelerated cure (Initial/Secondary)	17.5/6.7	10.7/4.7	8.7/ 3.0	-	5.4/ 1.9	7.1/ 3.3	5.9/ 4.1	-
56d normal cure (Initial/Secondary)	13.7 /3.6	8.1/ 3.4	14.1/9.8	-	6.0/ 3.2	6.2/ 3.5	-	5.0/ 3.1
196d normal cure (Initial/Secondary)	4.3 /1.6	2.9 / 2.1	5.5 / 2.3	5.0 / 1.2	-	4.9 / 1.7	-	2.7 / 1.5
ASTM C666, Freezing and Thawing Resistance - Relative Dynamic Modulus, % and Mass Loss, %								
RDM @ 300 c	99	100	99	100	99	97	100	100
RDM @ 2,500 c	97	98	95	72	96	96	98	97
RDM @ 3,200 c[***]	86	91	82	46	93	91	90	97
Mass Loss @ 300 c	0.0	0.1	0.1	0.0	0.5	1.1	0.0	0.1
Mass Loss @ 2,500 c	5.0	2.8	5.9	5.9	4.3	6.8	3.7	5.4
Mass Loss @ 3,200 c[***]	8.2	5.6	9.2	7.8	6.4	8.8	6.2	5.8
ASTM C 672, Salt Scaling Resistance - 0 – no scaling; 5 - severe								
Visual Rating (0 – 5) @ 50 cyc	5	3.0	3.0	3.0	2.3	3.8	2.0	0.5
Visual Rating (0 – 5) @ 180 cyc	5[++]	3.5	4.5	3.0	3.6	4.3	2.8	1.5

[++] Terminated at 75 cycles

[***] Result of only one specimen. All F-T specimens were taken out of the F-T chamber at about 3120 F-T cycles and kept in the moist room (to enhance saturation and thereby accelerate potential for F-T damage) for 90 days prior to the final F-T exposures for 80 cycles on one specimen only.

Table 3.3 Example to Illustrate the Relation Between DOS, Sorptivity, M_m and Time to DOS_{cr}

Specimen #	**m_d, g**	**m_i, g**	**m_s, g**	**M_m, %**	**DOS_i, %**	**DOS_{cr}, %**	**m_{cr}, g**	**Δm_{cr}, g**
1	100	103	105	5	60	90	104.5	1.5
2	100	103	110	10	30	90	109	6
3	100	106	110	10	60	90	109	3
4	100	108	110	10	80	90	109	1

m_d = mass of dry specimen (0% saturation)
m_i = mass of specimen at given instant
m_s = mass of saturated specimen (100% saturation)
M_m = Absorption capacity of specimen, i.e. at 100% saturation, $M_m = \frac{(m_s - m_d)}{m_d}$
DOS_i = Degree of saturation at a given instant, $DOS_i = \frac{(m_i - m_d)}{(m_s - m_d)}$
DOS_{cr} = Critical degree of saturation
m_{cr} = mass of specimen at DOS_{cr} , $m_{cr} = m_d + (m_s - m_d) \times DOS_{cr}$
Δm_{cr} = mass increase for the specimen DOS to attain DOS_{cr} , $\Delta m_{cr} = m_{cr} - m_i$

Table 3.4 Yield Adjusted Mixture Proportions and Test Results (Phase B)

Mixture Designation	0.65PC-4.0	0.65SL35-4.0	0.45PC-4.0	0.45PC-6.5
Calculated Batch Quantities				
Type I/II cement, lb/yd^3	424	279	596	596
Slag cement, lb/yd^3		150		
SCM, %	0	35	0	0
Coarse Agg. (No.57), lb/yd^3	2019	2046	2038	2036
Fine Aggregate, lb/yd^3	1303	1311	1202	1092
Mixing Water, lb/yd^3	276	279	268	268
w/cm	0.65	0.65	0.45	0.45
ASTM C494 AEA, oz/cwt	0.25	0.25	0.25	0.70
ASTM C494 Type F, oz/cwt	-	1.27	1.91	1.30
Fresh Concrete Properties				
ASTM C143, Slump, in.	5.00	6.25	4.00	6.75
ASTM C231, Pressure Air, %	4.0	4.0	4.1	6.4
ASTM C138, Gravimetric Air, %	5.0	3.7	4.1	6.7
ASTM C138, Density, lb/ft^3	150.1	151.7	153.1	148.9
ASTM C1064, Temperature, °F	78	73	72	75
Hardened Concrete Properties				
ASTM C39, Compressive Strength, psi				
28 days	3,940	3,570	5,740	5,040
56 days	-	3,920	6,280	5,650
77 days	4,430			
ASTM C1202, Rapid Chloride Permeability, Coulombs				
56 days	-	985	3451	3716
77 days	5570			
ASTM C 1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$				
56d normal cure (Initial/Secondary)	29.4 / 17.9	19.4 / 7.8	14.1 / 7.0	20.8 / 9.9
ASTM C 457, Air Void System in Hardened Concrete				
Air Content, %	2.5	3.1	3.6	5.6
Spacing Factor, in.	0.0143	0.0129	0.0086	0.0074
Specific Surface, in.^{2}/in.^{3}	423	426	613	585
Moisture Condition of ASTM C666 Specimens				
M_m, % of dry mass	4.9	3.9	3.9	5.1
DOS$_{mc}$, %	93	89	86	77

Table 3.5 Recommended Mixture Selection Criteria for F-T Resistance

ACI 318 Exposure Class	Strength	Air Content	w/cm
F1	3500	4.5%*	0.60
F2	4500	6.0%*	0.45
F3	4500	6.0%*	0.45

*These air contents are for ASTM C33 No. 57 (1 in.) aggregate. For different size aggregates the air contents provided in Table 4.4.1 in ACI 318-11 can be used. The air content tolerances are ±1.5%.

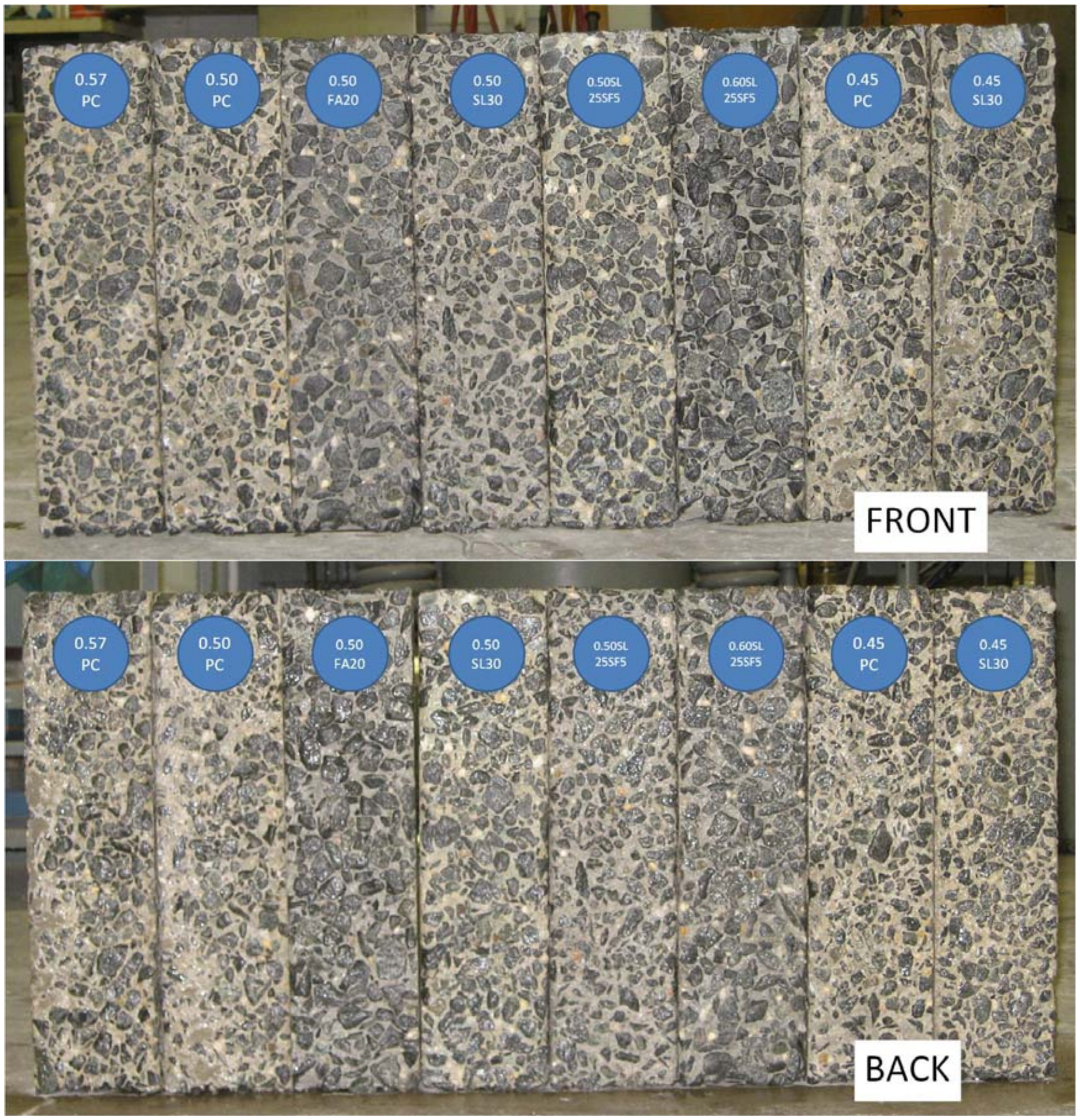
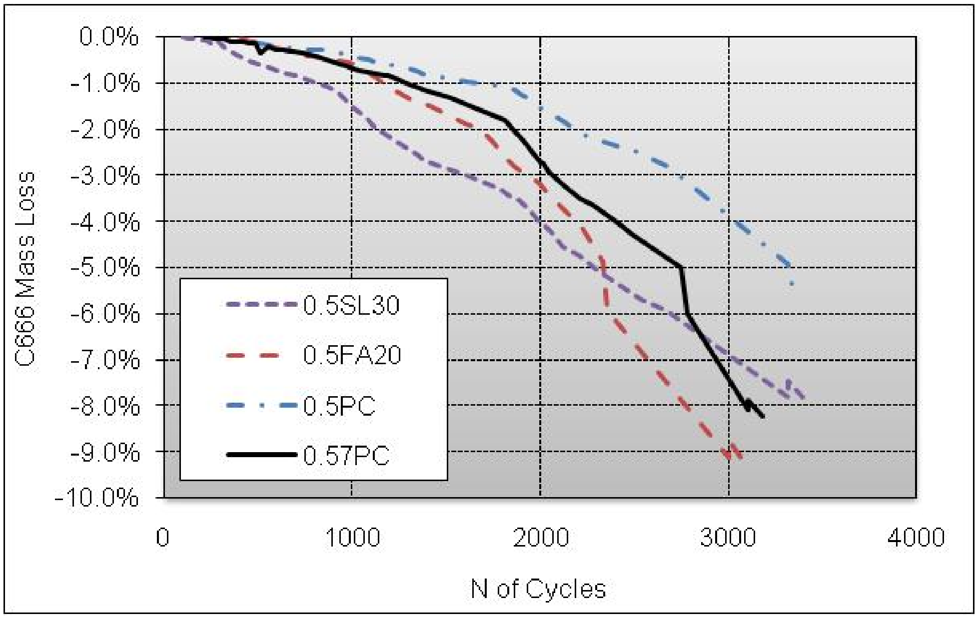
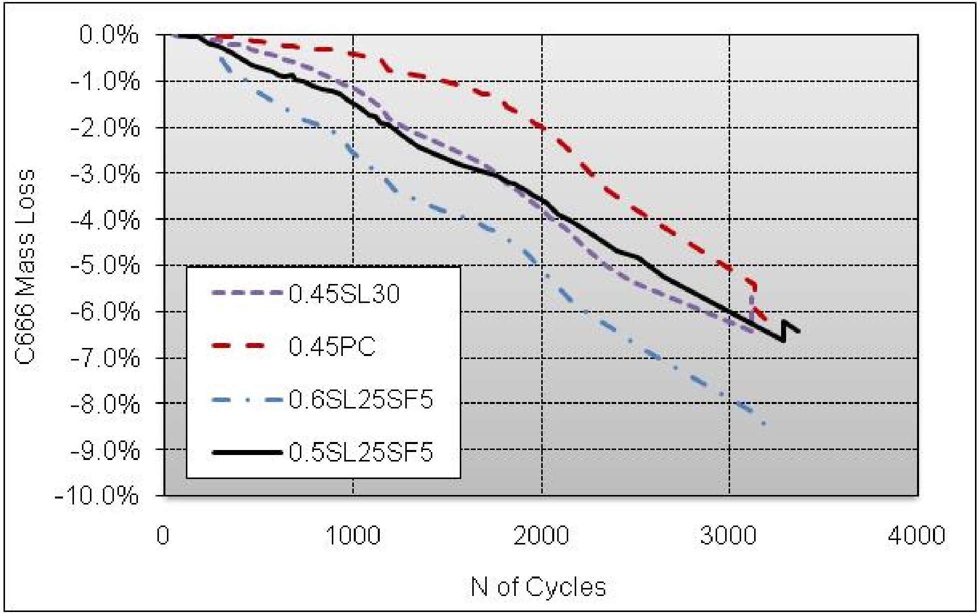


Figure 3.1 Scaling of C666 specimens After 3200 F-T cycles



(a)



(b)

Figure 3.2 ASTM C666 Mass Loss vs N of cycles

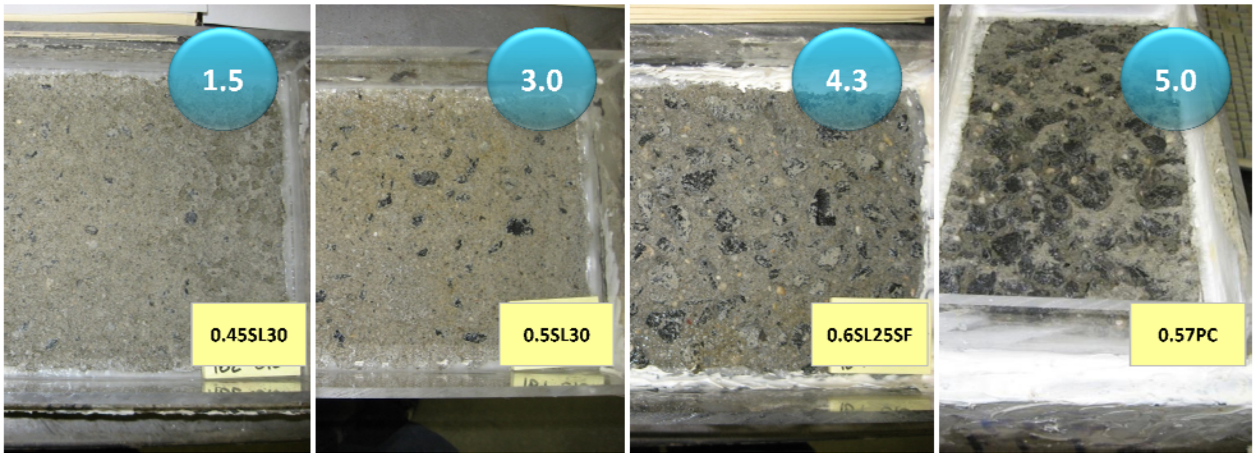
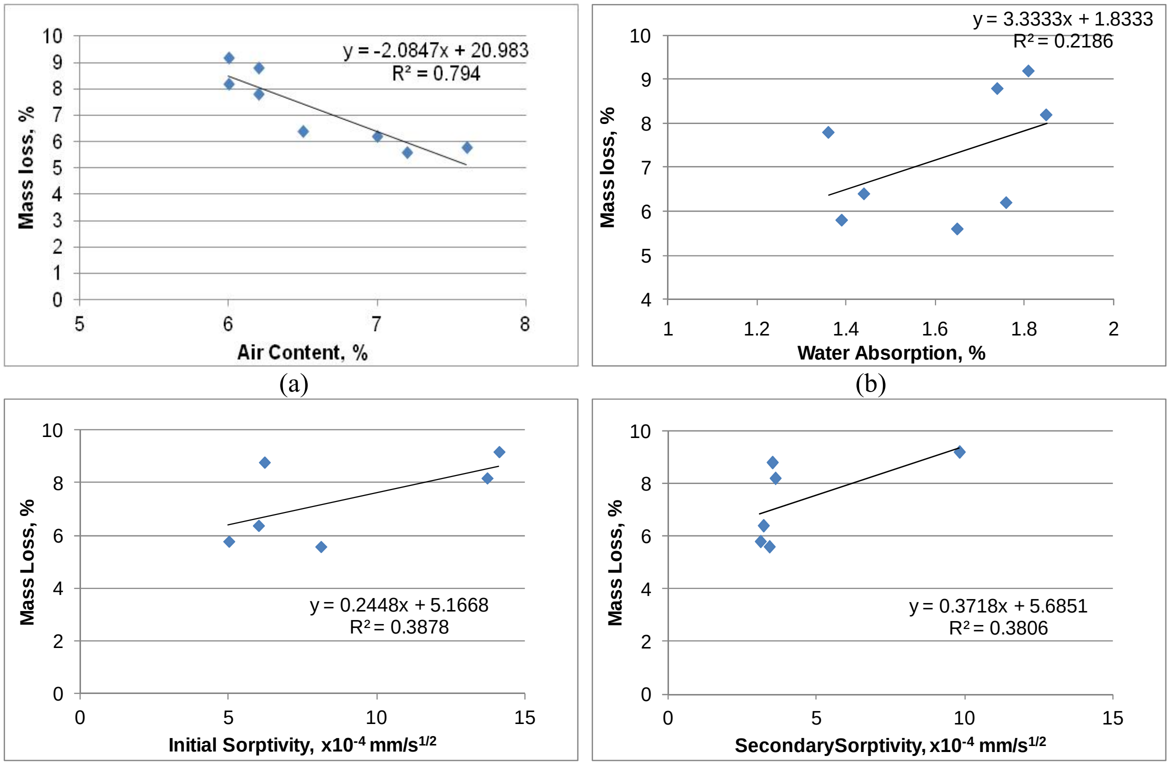
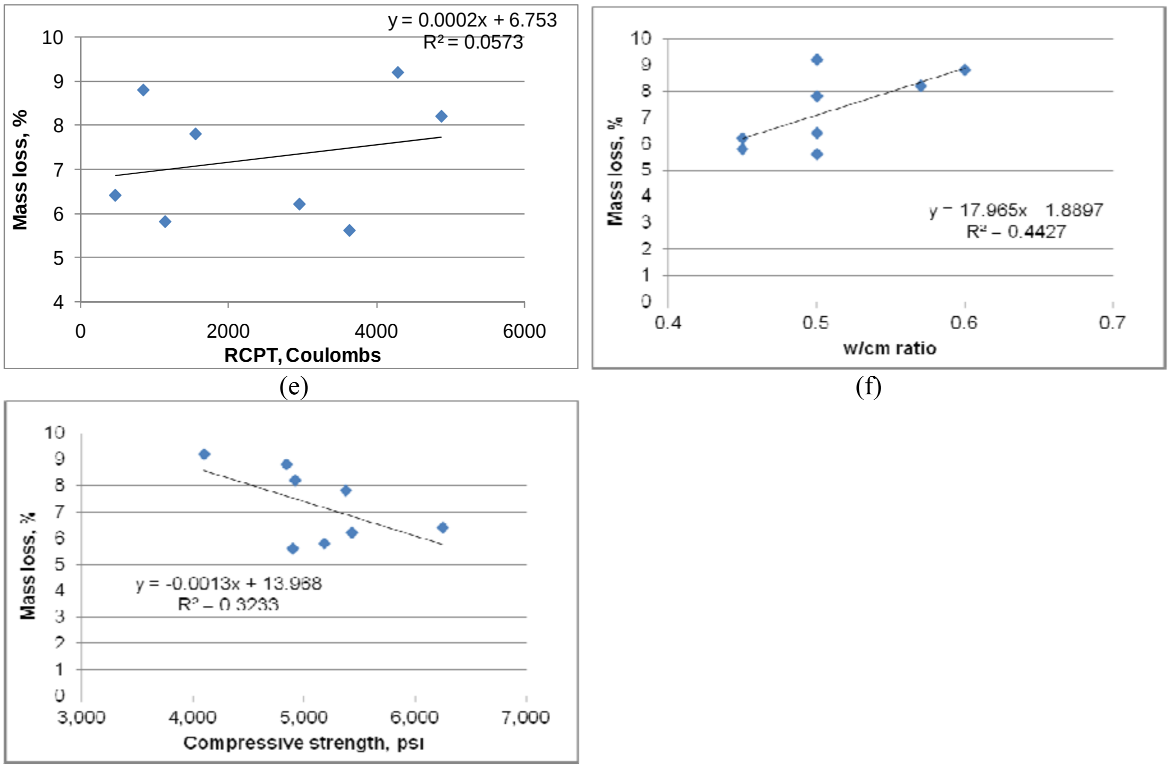


Figure 3.3 Specimens Subjected to ASTM C672 Salt Scaling After 180 F-T Cycles



(a) (b)

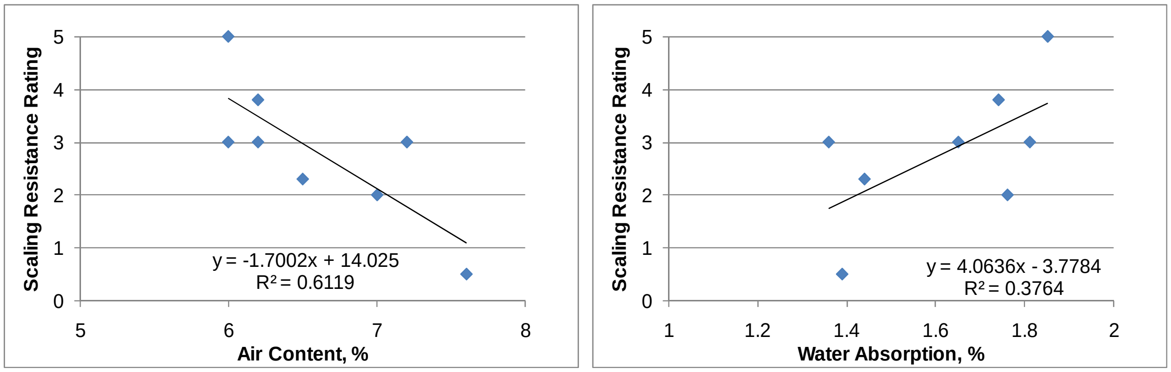
(c) (d)



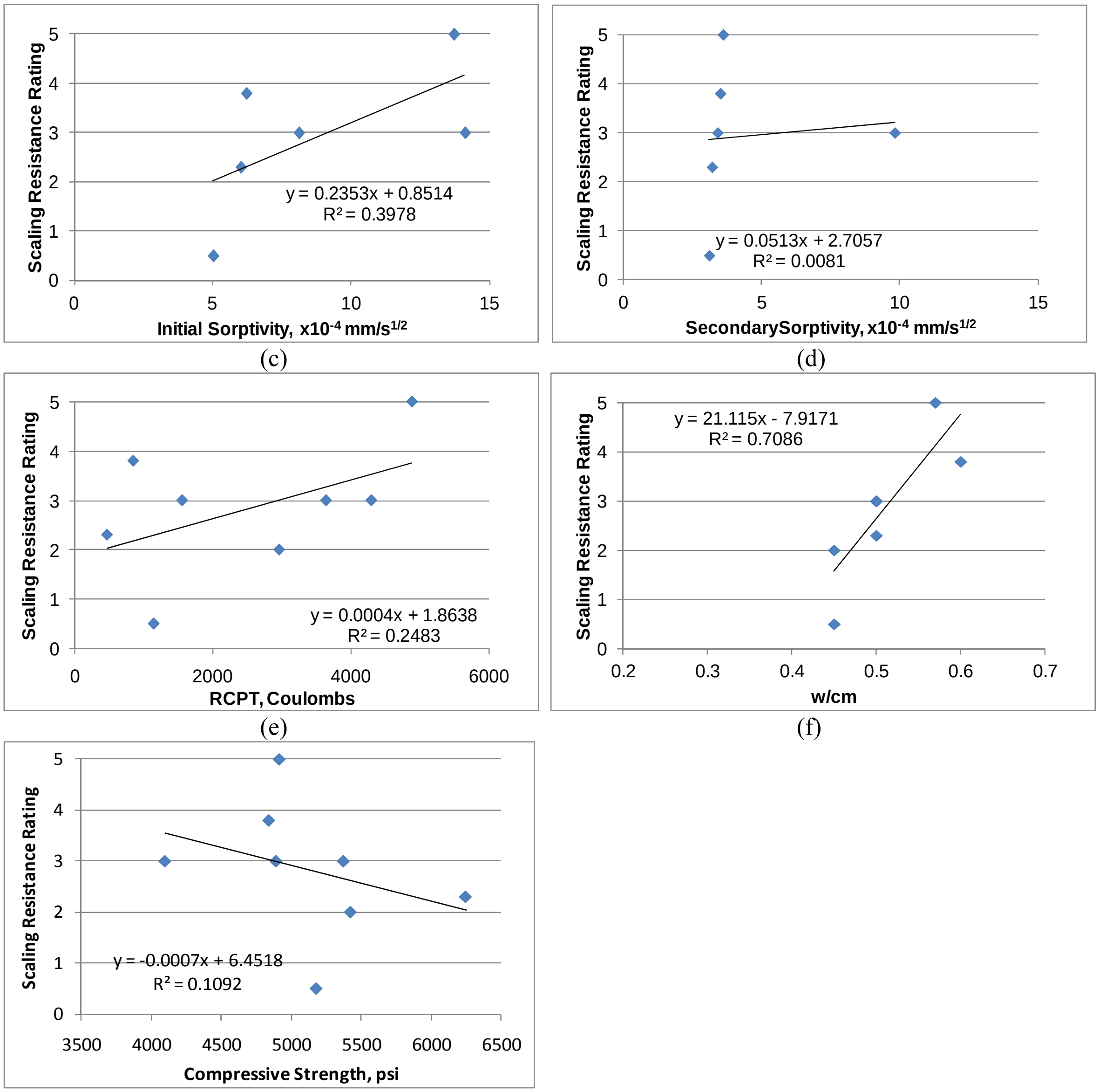
(e) (f)

(g)

Figure 3.4 (a) – (g) Correlation Between Mass Loss After 3200 Cycles and Fresh Air Content, W/CM, Compressive Strength and Various Rapid Index Tests



(a) (b)

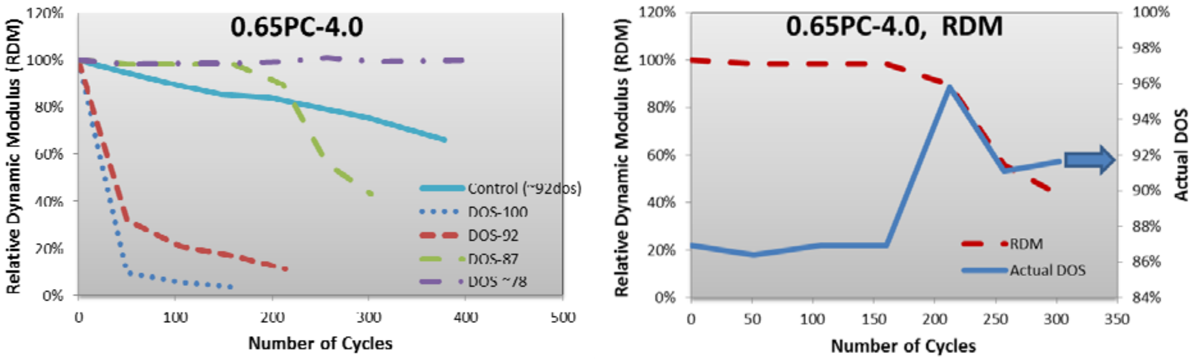


(c) (d)

(e) (f)

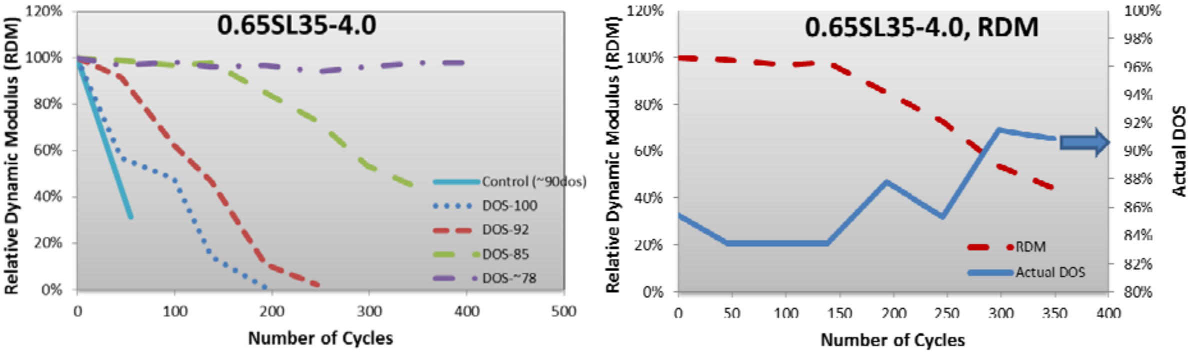
(g)

Figure 3.5 (a) – (g) Correlation Between the Visual Ratings After 50 Cycles and Fresh Air Content, W/CM, Compressive Strength and Various Rapid Index Tests



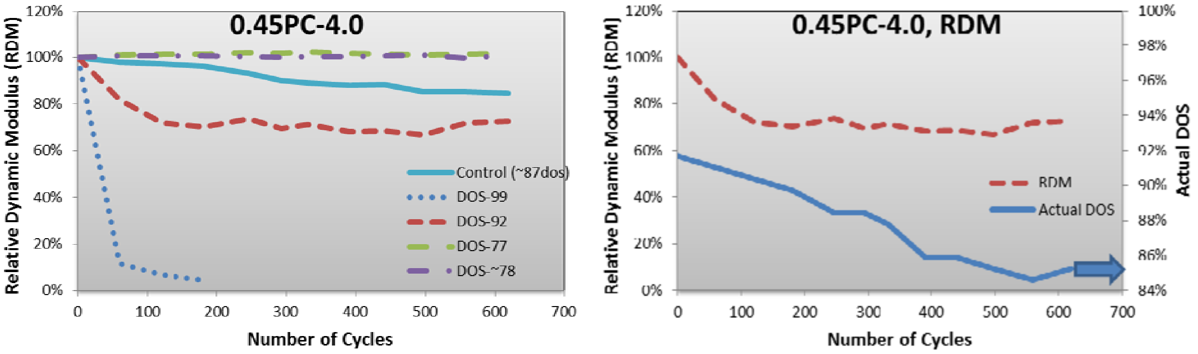
(a) (b)

Figure 3.6 Mixture 065PC-4.0 ASTM C666 Results vs. Number of Cycles (a) RDM (b) RDM, DOS of One of the Specimens



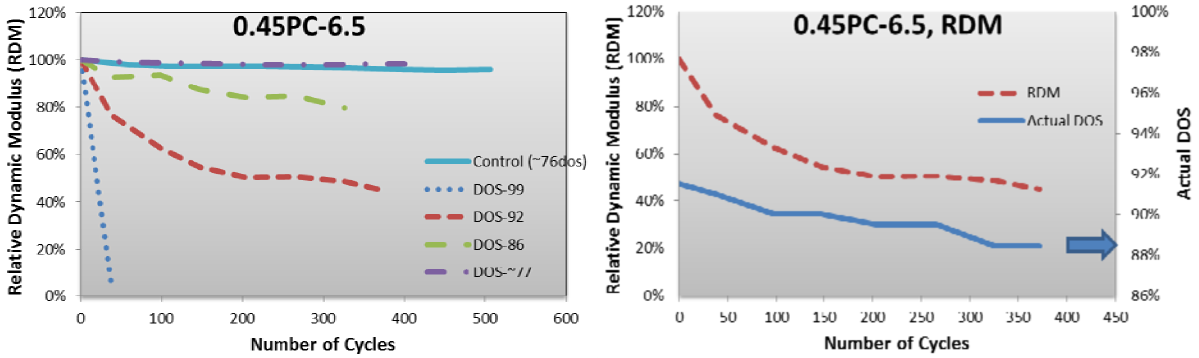
(a) (b)

Figure 3.7 Mixture 065SL35-4.0 ASTM C666 Results vs. Number of cycles (a) RDM (b) RDM, DOS of One of the Specimens



(a) (b)

Figure 3.8 Mixture 0.45PC-4.0 ASTM C666 Results vs. Number of cycles (a) RDM (b) RDM, DOS of One of the Specimens



(a) (b)

Figure 3.9 Mixture 0.45PC-6.5 ASTM C666 Results vs. Number of cycles (a) RDM (b) RDM, DOS of One of the Specimens

4. Exposure to Sulfates

Exposure to water-soluble sulfates 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 sulfates to form 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 are also reported to cause distress (Haynes et al. 2010) and therefore this type of attack is typically referred to as physical salt attack. The same terminology is used in this report.
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).

Note: The thaumasite sulfate attack mechanism is less common and is not addressed in this test program.

Resistance of concrete to chemical sulfate attack is governed by two factors (ACI 201.2R 2008; Lamond and Pielert 2006; Neville 2004):

1. Cementitious type – Increasing tri calcium aluminate in the portland cement portion in concrete decreases its sulfate resistance. Aluminate phases from SCMs can also sometimes contribute to this effect – more likely in some Class C fly ashes (Thomas et al. 1999) or some higher alumina content slag cements (Ogawa et al. 2012).
2. Low permeability – Water soluble sulfates penetrate concrete by a combination of capillary sorption and diffusion. Low w/cm and use of SCMs can reduce the rate of penetration of sulfates into the concrete.

Resistance of concrete to physical salt attack is primarily governed by the permeability of concrete.

The ACI 318 Building Code defines three classes of sulfate exposure in increasing severity based on concentration of water soluble sulfates in soil or water – S1, S2, and S3 and establishes the minimum requirements (Table 4.1) for concrete mixtures for adequate sulfate resistance. These requirements are relevant to chemical sulfate attack, but if the permeability of concrete is kept low, by designing to a low w/cm and or the use of SCMs, it is expected to minimize the potential for physical salt attack also.

Calcium chloride admixture is not permitted for S2 and S3 exposure classes. ASTM C595, C1157 cement types that have been qualified for moderate (MS) or high (HS) sulfate resistance are options for cementitious materials in ACI 318-11.

As an alternative to the cementitious material types, ACI 318-11 permits a cementitious materials combination that has been qualified to meet expansion criteria when tested by ASTM C1012. It also permits service records of acceptable performance to be used.

The objective of this portion of the research project was to develop test and performance criteria as an alternative to the maximum w/cm requirement. The maximum w/cm limit is invoked as a prescriptive requirement to reduce the permeability of concrete that controls the rate of penetration of water-soluble sulfates from external sources into the concrete. Besides w/cm, however, the permeability of concrete is also impacted by the composition of the cementitious materials used in the mixture. Viscosity modifiers and internal curing has been found to help reduce sulfate ingress (Bentz et al. 2014) and clearly a prescriptive set of criteria cannot possibly encompass all such options towards improved performance to sulfate attack.

In this study, the sulfate resistance of concrete was evaluated by a modified USBR 4908 test (1992). The USBR 4908 test was standardized by the US Bureau of Reclamation as part of their research work on sulfate resistance. It is a long term test on concrete and is not conducive to pre-qualification and acceptance of concrete on projects. In this part of the research project it was examined whether sulfate resistance of concrete, as determined by a modified USBR 4908 test, was better correlated with ASTM C1012; and a rapid index permeability indicator test as an alternative to w/cm criteria. So mixtures could then be categorized based on their resistance to sulfate attack and physical salt attack entirely from performance tests and criteria.

4.1 Materials and Mixture Proportions

The same materials used in the chloride ingress testing program were used. In addition the following materials were used for the concrete mixtures:

- ASTM C150 Type I portland cement (PC) with C_3A = 12%, Lot 8331;
- ASTM C150 Type V portland cement (PC) with C_3A = 3%, Lot 8390;
- ASTM C150 Type V portland cement (PC) with C_3A = 5%, Lot 8391;

The physical and chemical characteristics of the cementitious materials are shown in Table 4.2. The fly ash is an ASTM C618 Class F fly ash with low CaO content and is expected to demonstrate good sulfate resistance (Dhole et al. 2011). The slag cement has a moderate alumina content and should also provide acceptable sulfate resistance (Ogawa et al. 2012; Hooton and Emery 1990).

Twenty two concrete mixtures were made at varying w/cm, cement types, SCM types and dosages as shown in Table 4.3. The mixtures were selected covering a range of w/cm between 0.40 and 0.60 and varying SCM quantities as a percentage of the cementitious materials. The mixtures were designed to attain different levels of sulfate resistance. To achieve this, Type I cements were combined with low SCM dosages while Type V cements where combined with high SCM dosages. Mixtures containing no SCMs (PC mixtures) were also tested. The portland cements had different levels of sulfate resistance. All concrete mixtures were non-air-entrained. The mixtures were generally categorized to be resistant to the four different exposure classes in ACI 318 as indicated in Table 4.3.

Mixture designations are similar to those used in the chloride ingress testing program with one exception in that the cement type was noted at the end. For example 0.5SL35-II refers to mixture with a w/cm of 0.5, 35% slag cement, and Type II cement. Mixtures without SCM use 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. A 3 oz/cwt. dosage of an ASTM C494 Type A water-reducing admixture was used for all concrete mixtures. The dosage of ASTM C494 Type F high-range water-reducing admixture was varied to attain a target slump of 4 to 7 in. Mixture proportions and test results are provided in Table 4.4 and Table 4.5. Table 4.4 includes two PC mixtures containing Type I and Type II cements and six mixtures containing SCMs prepared with Type I cement. Table 4.5 includes two

PC mixtures containing two brands of Type V cement and 12 mixtures containing SCMs, six of which were prepared with Type II cement, and six with Type V cement.

4.2 Procedures

Mortar mixtures with some of the cementitious combinations of the concrete mixtures were tested in accordance with ASTM C1012 – expansion of mortar bars immersed in sodium sulfate solution. The sulfate exposure duration was extended to 36 m. Mixture proportions and test results are provided in Table 4.6.

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 by the pressure method (C231), and density (C138). The gravimetric air content was also calculated in accordance with ASTM C138.

Tests on hardened concrete included compressive strength (C39) measured on two 4x8 in. cylindrical specimens at an age of 28 days.

For the permeability-related rapid index tests, the two curing procedures discussed in the chloride ingress testing program were used. 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) and were conducted at the following ages – after 28 day accelerated curing; and after 56 days and 52 weeks of standard curing. All the durability tests involved casting two 4x8 in. cylindrical specimens. Before the test the specimens were cut and the top 2 in. from the finished surface was subjected to the test.

4.2.1 USBR 4908 Test

The USBR 4908 test was standardized by the US Bureau of Reclamation. The test describes three methods. Method A involves immersion of 3x6 in. concrete cylinders in a 2.1 % sodium sulfate solution at room temperature; Method B involves immersion of the cylinders in a 10 % sodium sulfate solution at room temperature; and Method C involves alternate immersion in a 2.1 % sulfate solution and drying. Failure is defined as 0.5% expansion and it has been found to correlate with about 40% loss in dynamic modulus of elasticity (Kalousek et al. 1976). The time of exposure to failure was designated “life expectancy” (Kalousek et al. 1972). Method C required only about one eighth the time to attain an expansion equal to that obtained in Method A (Kalousek et al. 1972). Method B was also found to be as rigorous as Method C (Dikeou 1976). Method B was also found to have no apparent irregularities in the mechanisms of sulfate attack. In spite of being accelerated tests the USBR 4908 Methods B and C were found (Kalousek et al. 1976; Stephens and Carrasquillo 2000) to require more than two years before any significant results can be obtained.

In this project, Method B was chosen with some modifications. Instead of cylinders 3x3x11 ¼ in. concrete prisms were used. Sulfate exposure was started after 28 days of moist curing followed by 28 days of air drying. Two exposure conditions were evaluated: full immersion and partial immersion (for some of the mixtures) in 10% sodium sulfate solution. Two prisms were tested for each mixture and exposure condition and the average results were reported. All concrete mixtures were subjected to sulfate exposure for a period of 36 m and some of the mixtures are still being evaluated after a period of 48 m.

Specimens subjected to immersion were expected to deteriorate primarily due to chemical sulfate attack due to the inwards migration of the sulfate ions from the specimen surface. For specimens subjected to immersion - length change, change in mass, and visual deterioration ratings were obtained at different ages.

For some of the mixtures, specimens were subjected to partial immersion to a depth of 5 in. in a laboratory environment of 70°-75°F and 44-72% RH. With partial immersion, the primary deterioration mechanism was expected to be due to physical salt attack (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. Salt crystals occupy a larger volume causes scaling and cracking. This is specifically observed with crystallization of sodium sulfate.

The exposed specimen near the solution surface is most prone to 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. 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 4.1 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 physical salt attack, and specific to sodium sulfate, is a crystalline phase change between thenardite (Na_2SO_4) and mirabilite ($Na_2SO_4.10H_2O$) (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 4.2 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).

For the partially immersed specimens, 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 and 44-72% RH for one week followed by one week in an environment of 98°-100°F and 21-34% RH. The cycling was initiated at 15 m for Mixtures 1-8 and at 12 m for Mixtures 9-22. Temperature and RH were measured at a height of 1 in. above the solution surface. After a period of cycling it was noted that due to the lower RH in the lab environment the desired humidity levels for the mirabilite phase was attained only in one out of 10 cycles; for the rest of the period the conditions for the thernardite phase was attained (Figure 4.3). To increase the RH the container in the lab environment was covered with a perforated plastic lid. The modification was made at 27 m for Mixtures 1-8 and at 23 m for Mixtures 9-22. After the modification the desired temperature and humidity levels for the formation of the mirabilite phase was attained on a regular basis (Figure 4.3).

4.3 Discussions on Sulfate Test Results

4.3.1 ASTM C1012 Mortar test Results

Table 4.6 summarizes the ASTM C1012 mortar test results for 10 mortar mixtures. ASTM C1012 expansion results up to 36 m are reported. Based on the selected cementitious materials composition, the expected sulfate exposure class that these mixtures would satisfy relative to the ACI 318 expansion criteria is also indicated. Based on the measured C1012 expansion results, six mixtures conformed to the anticipated exposure class. For the remaining four mixtures (the low and mid SCM fly ash and slag cement mixtures), the expansion results indicate that the mixtures comply with a more severe exposure class, i.e. these mixtures had better sulfate resistance than expected. As expected, expansions decreased when the SCM dosage increased and/or the C_3A content of the cement decreased. SCMs even at a low dosage (15% fly ash or 25% slag cement) in conjunction with a Type I cement had equal or better sulfate resistance than mortar mixtures with Type V cement.

4.3.2 USBR 4908 - Fully Immersed Specimens

For the eight concrete mixtures evaluated in the first part of the study (Table 4.4), the length change is plotted as a function of age in Figure 4.4. Expansion measurements were continued for at least 44 months. In some cases, the measurements had to be terminated earlier due to excessive deterioration.

The expansion of the concrete mixtures increased with an increase in w/cm. This is observed for the mixtures containing slag cement and fly ash. For the mixtures with a w/cm of 0.60, the expansion exceeded 0.05% in 16 m. The expansion was less than 0.05% for both the mixtures with a w/cm of 0.40 even after 48 m of immersion in sodium sulfate solution. For the portland cement mixtures at a w/cm ratio of 0.50, the effect of C_3A is observed. The expansion level exceeded 0.05% in 9 m for the 0.50 PC-I mixture, containing cement with the higher C_3A content. For the 0.5PC-II mixture containing cement with the lower C_3A content, this expansion level was exceeded at 15 months. At later ages, the expansion of the 0.5PC-II mixture increased rapidly. By comparison, the SCM mixtures with a w/cm of 0.50 performed better than the PC mixtures but the expansions were higher than the SCM mixtures with a w/cm of 0.40.

The mass change as a function of duration of exposure is plotted in Figure 4.5. Initially, an increase in mass was observed for all mixtures due to absorption of the sulfate solution. Mixtures with a higher w/cm absorbed more solution as observed by the higher mass increase. Concrete mixtures at w/cm of 0.60 containing slag cement and fly ash as well as the 0.5PC-I mixture show significant decrease in mass at later ages resulting from deterioration of the specimens. After this point, the test was terminated for those mixtures. The mixtures at a w/cm of 0.50 containing slag cement or fly ash show a modest decrease in mass after 36 m indicating an initiation of deterioration. Mass loss was primarily due to the corners of the prisms breaking off. Specimen conditions for these mixtures at 48 m are shown in Figure 4.6. The mixtures containing slag cement and fly ash at a w/cm of 0.40 show cracking parallel to the longitudinal axis near the specimen finished surface and minor cracks near the corners without any spalling. For the six mixtures at a higher w/cm, all specimens displayed substantial cracking along the longitudinal axis near the specimen surface. It was also observed that a length change of 0.05% approximately corresponded to the time when the decrease in mass was noted. One exception was the 0.5PC-II mixture which shows very high expansion without any decrease in mass.

For the 14 concrete mixtures evaluated in the second part of the study (Table 4.5), length change and mass change is plotted as a function of exposure duration in Figure 4.7 and Figure 4.8. After about 30 months of immersion, the expansions of mixtures 0.6SL35-II and both 0.45PC-V mixtures exceeded 0.05%. None of the specimens were deteriorated to a point that resulted in a decrease in mass even though cracking initiated. This can be observed from the condition of the specimens shown in Figure 4.9, taken at 44 m of immersion in the solution. Specimens from mixtures 0.6SL35-II and both 0.45PC-V mixtures show corner damage and considerable amount of cracking along the longitudinal axis at the specimen surface. All mixtures in the second part of the study had substantial mass gain. Similar mass increases for mixtures in the first part (Table 4.4) resulted in increased expansion and corners breaking off, but this was not observed for the mixtures in the second part. The mixtures in the second part (Table 4.5) contained cements with lower C_3A content (Type II and Type V) and included higher amounts of SCMs. As might be expected, these concrete mixtures were more resistant to chemical sulfate attack. While a given level of mass change due to solution absorption may not indicate that the specimen has undergone sulfate attack; length change exceeding 0.05% is more likely indicative of progressing chemical sulfate attack. The six mixtures containing Type II cement with fly ash and slag cement at all w/cm tested showed faint cracking along the longitudinal axis near the specimen surface and visual corner damage. The six mixtures containing Type V cement (V-1) with SCMs at all w/cm tested showed the lowest deterioration in terms of cracking or corner damage, indicating better chemical sulfate resistance.

Typically, the specimen deterioration progressed as follows: faint cracking appeared very near to the specimen finished surface along the specimen longitudinal axis. The crack occurred through the width and gradually this crack width increased with time. This was followed by corner damage of the specimen in the form of cracking. With increasing corner damage there was spalling and measureable mass loss. The 22 concrete mixtures tested were categorized based on their resistance to chemical sulfate attack as in Table 4.7. The criteria for categorization of the concrete mixtures were as follows:

1. USBR expansions;
2. Measured loss of concrete mass;
3. Visual appearance of corner damage; and
4. Extent of cracking.

The mixtures are also matched with the anticipated performance in the four different ACI 318 sulfate exposure classes in column one. The rationale being that mixtures with excellent resistance to chemical sulfate attack can be used for ACI 318 exposure class S3, mixtures with high resistance to chemical sulfate attack can be used for ACI 318 exposure class S2 and so on.

After 48 months of immersion in 10% sodium sulfate solutions two 3x3 in. cubes were cut from a single prism. The cubes were testing in compression and the measured average strengths were modified by a strength reduction factor of 0.75 to provide an estimate of the strength as measured on cylinders. In addition strengths of concrete cylinders for some of the Table 4.5 mixtures that had been moist cured continuously for 43 months were measured. These strengths as well as the 28 day standard cured cylinder strengths are plotted in Figure 4.10. The strength of specimens immersed for

48 m for the 0.5PC-II, 0.45PC-V1 and 0.5SL25-I mixtures were 12% to 30% lower than their 28 day strengths. The 0.45PC-V2 mixture had about the same strength at both ages. If these four mixtures are excluded strengths of the remaining 11 mixtures immersed in sulfate solution for 48 m were on average 39% higher than the 28 day strengths. When the strength of specimens immersed for 48 m is compared to the strength of cylinders moist cured for 43 m, the strengths are about the same or slightly higher except for the two 0.45PC-V mixtures – these two mixtures had about 23% lower strengths. This suggests that mixtures with a high sulfate resistance had no loss in strength.

4.3.3 USBR 4908 - Partially Immersed Specimens

Mass change data was not useful in evaluating failure due to physical salt attack. Mass loss occurred both due to surface scaling from physical salt attack 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 are plotted for the different mixtures in Figure 4.11 and Figure 4.14. 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 4.11) and 12 m for mixtures in the second part (Figure 4.14). However, the rate of scaling did not necessarily increase further when the humidity for the lower temperature cycle was increased (27 m for mixtures in Figure 4.11 and 23 m for mixtures in Figure 4.14) to approach the conditions for mirabilite formation. One reason is that by the time this change in exposure condition was initiated, most of the damage had already occurred.

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_3A contents (8% and 12%) did not result in a different rate of deterioration. This tends to validate that the deterioration is due to physical salt attack. For the mixtures containing fly ash and slag cement, the scaling distance was less for the mixtures with a lower w/cm.

The condition of the specimens after about 26 months of exposure in sulfate solutions is shown in Figure 4.13 and Figure 4.16. Average (of all specimen surfaces) visual scaling ratings for each mixture after about 26 m of exposure in sulfate solution are reported in Table 4.4 and Table 4.5. The scaling ratings are based on those in ASTM C672. Figure 4.13 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.

By comparing Figure 4.6, Figure 4.9, Figure 4.13 and Figure 4.16 the specimen failure due to chemical sulfate attack (full immersion) and physical salt attack (partial immersion) can be compared. In the case of chemical sulfate attack the specimens undergo no surface scaling; there is expansion and mass gain and after a period of immersion there is cracking along the specimen longitudinal axis; continued immersion results in corners of the specimens breaking off resulting in mass loss. In the case of physical salt attack, the specimens clearly show surface scaling similar to deicer salt scaling that extends from the solution surface and progresses upwards with time. Continued partial immersion results in substantial scaling and mass loss. The scaling loss, 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).

Comparison between PC and SCM mixtures: The comparison of the scaling distances between the PC and SCM mixtures is shown in Figure 4.11 and Figure 4.15. From Figure 4.11 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. After 19 m exposure, the two SCM mixtures with w/cm of 0.40 had scaling distances less than 1.6 in., whereas the other four mixtures had scaling distances exceeding 3.8 in. From Figure 4.15 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. after 16 m 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 physical salt attack as these materials are improving resistance to chemical sulfate attack. This can be expected because porosity and sorptivity of concrete play a larger role in physical salt attack than does the composition of the cementitious materials.

Scaling distances at 19 months for mixtures listed in Table 4.4 and 16 months for mixtures listed in Table 4.5 are considered. At these exposure ages all specimens had been subjected to four months of temperature and RH cycling. The resistance to physical salt attack for all these mixtures is categorized on the basis of scaling distance in Table 4.8.

Visual scaling ratings were recorded at 28 months of exposure for mixtures in Table 4.4 and at 24 months of exposure for mixtures in Table 4.5. At these ages all the mixtures were subjected to 12 months of temperature and RH cycling. The values are provided in Table 4.4 and Table 4.5. The scaling ratings at this exposure age would result in the same categorization of mixtures for resistance to physical salt attack as in Table 4.8.

The specimens were examined petrographically with a stereomicroscope and by thin section analysis at various locations along the specimens. Lesser amounts of secondary gypsum deposits were noticed 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 since gypsum was only observed in the interior uncarbonated section of the immersed area it is likely that the scaling on the exposed surfaces was initiated by PSA and subsequently there was chemical sulfate attack. Further, the aggregate particles within the scaled areas of the specimens were generally cracked and degraded which is symptomatic of PSA.

4.4 Rapid Index Test Results Related to USBR 4908 Performance

4.4.1 Fully Immersed

Chemical sulfate attack requires ingress of sulfate ions into the concrete and a cementitious system that is vulnerable to chemical sulfate attack. Therefore, a combination of compressive strength, rapid index test for transport characteristics and ASTM C1012 expansion are considered to classify mixtures based on their resistance to chemical sulfate attack observed in USBR 4908 test for fully immersed specimens (Table 4.7).

Results in Table 4.7 indicate that some mixtures with a w/cm of 0.60 demonstrate excellent resistance to chemical sulfate attack whereas some mixtures with a w/cm of 0.45 demonstrate moderate resistance. Further, it is evident that mixtures with w/cm varying between 0.40 and 0.60 demonstrate similar sulfate resistance. These observations call into question the ACI 318 approach of using w/cm as the sole permeability-related requirement for sulfate resistance. It is well recognized that transport characteristics in concrete are related to w/cm and the composition of the cementitious materials. The ACI 318 requirements do not consider the latter.

Table 4.9 classifies the 22 mixtures evaluated in this study relative to the ACI 318 sulfate exposure criteria. Column two lists mixtures as categorized in Table 4.7 based on the performance in chemical sulfate attack as evaluated by full immersion in USBR 4908 test. The ACI 318 criteria for concrete exposed to sulfates are reproduced in Columns 3, 4, 5. Column 6 lists the mixtures that meet the ACI 318 criteria. Recognize that the cement type and C1012 expansion limits are alternate criteria in ACI 318. The mixtures that meet the ACI 318 criteria (Column 6) but may not be considered to be in the same category based on the performance criteria stated in Table 4.7 for full immersion in the USBR test (Column 2) are shown in different color format. Out of the 22 mixtures, nine fall in the same category of sulfate resistance based on the ACI 318 criteria and the criteria for USBR 4908 stated in Table 4.7. Of the 13 mixtures that fell in different performance categories, the ACI 318 criteria categorized eight mixtures conservatively, in that the performance of these mixtures in USBR 4908 was superior for the stated ACI 318 exposure class. The remaining five mixtures did not perform well in the USBR 4908 test as intended by the ACI 318 criteria.

The sulfate resistance of concrete depends on both the permeability of the concrete to sulfates as well as the chemical resistance of the cementitious material to sulfates. As a result, a concrete mixture with lower permeability and lower chemical resistance may have similar sulfate resistance as a concrete mixture with a higher permeability and higher chemical resistance. This has been observed by other researchers (Khatri et al. 1997). So for a given ACI 318 exposure classes it is logical to allow different levels of permeability contingent on the chemical resistance of the cementitious material.

Based on the observed performance of concrete mixtures in USBR 4908 immersed condition, the following recommendations are made in Table 4.10 to revise the ACI 318 criteria and the rationale is discussed below:

Exposure Class S3 – Mixtures 0.4SL25-I, 0.4FA20-II, 0.4SL35-II, 0.4FA30-V1 and 0.4SL50-V1 meet the ACI 318 criteria for this exposure class. In this study, Mixtures 0.4SL35-II, 0.4FA30-V1 and 0.4SL50-V1 had superior sulfate resistance compared to mixtures 0.4SL25-I and 0.4FA20-II (Column 2 of Table 4.9). If Type I cement is restricted for concrete assigned to Exposure Class S3, mixture 0.4SL25-I will be eliminated from this category. Mixtures 0.5SL50-V1 and 0.5FA30-VI would qualify only for Exposure Class S1 in accordance with ACI 318 despite performance in this study showing superior sulfate resistance (Column 2 of Table 4.10). To permit mixtures 0.5SL50-V1 and 0.5FA30-VI for Exposure Class S3 the following optional criteria for Exposure Class S3 are suggested as follows:

- Minimum specified strength = 4000 psi,
- Maximum w/cm = 0.50,
- C1012 expansion limit of 0.05% at 18 m.
  (restriction to Type I)

Exposure Class S2 – Mixtures 0.45PC-V1 and 0.45PC-V2 meet the ACI 318 criteria for this exposure class but did not perform well for this category in USBR 4908 (Column 2 of Table 4.10). Mixtures 0.5FA20-II and 0.5SL35-II would qualify only for Exposure Class S1 in accordance with ACI 318 despite performance in this study showing superior sulfate resistance (Column 2 of Table 4.10). To permit mixtures 0.5FA20-II and 0.5SL35-II for Exposure Class S2 the following optional criteria for Exposure Class S2, based on the sulfate resistance of mixtures in this study, are suggested as follows:

- Minimum specified strength = 4000 psi,
- Maximum w/cm = 0.50,
- C1012 expansion limit of 0.05% at 12 m.

These criteria, however, will categorize the 0.5SL25-I mixture acceptable for use in Exposure Class S2 despite that mixture showing only moderate sulfate resistance (Column 2 of Table 4.10). This mixture would be eliminated if Type I cement is restricted for us in concrete assigned to Exposure Class S2.

Exposure Class S1 – Mixture 0.5PC-II met the ACI 318 criteria for this exposure class despite showing poor sulfate resistance (Column 2 of Table 4.10). Mixtures containing SCMs with w/cm of 0.60 had similar or better sulfate resistance than the 0.5PC-II mixture (Column 2 of Table 4.10). The following optional criteria for Exposure Class S1, based on the sulfate resistance of mixtures in this study, are suggested:

- Minimum specified strength = 3500 psi,
- Maximum w/cm = 0.55,
- C1012 expansion limit of 0.05% at 6 m,
- Mixture should contain SCMs.

Based on these proposed criteria, Table 4.10 re-categorizes the 22 mixtures in this study. Of these mixtures, 12 mixtures fall in the appropriate sulfate resistant exposure class; six mixtures were categorized conservatively; and four mixtures did not perform well for the assigned exposure class. Of these four mixtures, three were made with portland cement and no SCM. The proposed modifications to ACI requirements in Table 4.10 are however considered an improvement over the existing ACI 318 criteria.

These proposed alternative criteria for sulfate resistance are summarized below:

Exposure Class S1

- Type II cement and max w/cm of 0.50 (prescriptive and allowed by current ACI 318)
- Any cement with ASTM C1012 expansion <0.10% @6 m and max w/cm of 0.50 (performance and allowed by current ACI 318)
- Blended cement with (MS) designation or PC SCM combinations with ASTM C1012 expansion <0.05% @6 m and max w/c 0.55 (additional proposed performance option for ACI 318)

Exposure Class S2

- Type V cement and max w/cm of 0.45 (prescriptive and allowed by current ACI 318)
- Any cement with ASTM C1012 expansion <0.1 @12 m and w/c 0.45; Type I cement not permitted

- Blended cement with (HS) designation; or PC SCM combinations with ASTM C1012 expansion <0.05 @12 m and max w/c 0.50; Type I cement not permitted (additional proposed performance option for ACI 318)

Exposure Class S3

- Type V + SCM and max w/cm of 0.45 (prescriptive and allowed by current ACI 318)
- Any cement with ASTM C1012 expansion <0.1 @18 m and max w/c 0.45; Type I cement not permitted
- Any cement with ASTM C1012 expansion <0.05 @18 m and max w/c 0.50; Type I cement not permitted (additional proposed performance option for ACI 318)

4.4.2 Partially Immersed

The correlation between scaling distance and rapid index test results, w/cm, or strength for all the mixtures are provided in Figure 4.17. Scaling distances at 19 months for mixtures listed in Table 4.4 and at 16 months for mixtures in Table 4.5 were considered. These were the same periods used for mixture categorization in Table 4.8. The correlation between visual ratings and same test and mixture indicators are provided in Figure 4.18. Visual scaling ratings at 28 months for mixtures listed in Table 4.4 and at 24 months for mixtures listed in Table 4.5 were considered. The intent of these charts is to evaluate which of these test or mixture indicators best correlate with the deterioration trend observed by scaling distance or scaling rating. Of these, compressive strength and w/cm provide the best predictors for mixtures with high resistance to physical salt attack. Other options such as absorption and initial sorptivity appear to have a reasonable correlation; however, choosing limits result in inaccurate categorization of mixtures for resistance to physical salt attack. A concrete mixture compressive strength of 6600 psi at 28 days or a maximum w/cm of 0.45 captures all the mixtures that had low scaling distance (<3.0 in.), and visual rating (<3.0). The 0.4SL50-V1 mixture seems to meet the strength and w/cm requirement but it has a high scaling rating suggesting that high SCM content mixtures need to be tested. For air-entrained concrete the corresponding compressive strength criterion can be set at 80% of this value or 5300 psi. The average strengths can be converted to specified strengths based on an NRMCA survey of average strengths and reported standard deviations. Converting these average strength levels to specified strength requirements translates to 5500 psi for non-air-entrained concrete and 4500 psi for air-entrained concrete. Therefore, strength or a w/cm requirement seems to be sufficient to categorize mixtures with high resistance to physical salt attack. A w/cm requirement of 0.45 has also been suggested in the literature to prevent concrete deterioration from physical salt attack (Haynes et al. 1996). The proposed criteria are stated in Table 4.11.

4.5 Proposed Test Procedure for Resistance to Physical Salt Attack

Mixtures were tested by the following test procedure, modified from USBR 4908, to evaluate their resistance to physical sulfate attack.

The 14 mixtures from Table 4.5 were evaluated by this method. The specimens used were 4x8 in. concrete cylinders. Since this evaluation was performed later in the program, these specimens had been standard cured for about 32 months prior to subjecting them to partial immersion in the sodium sulfate solution. The specimens were partially submerged to a height of 3 in. in 10% sodium sulfate solution and subjected to daily cycling. The specimens were kept in lab environment of 70°-75°F and 77-85% RH for 16 h followed by 8 h in an environment of 98°-100°F and 21-34% RH. Temperature and RH were measured at a height of 1 in. above the solution surface. This cycling was to attempt to promote alternate cycles of conversion between thenardite and mirabilite every day. 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 as follows: The cylinders were washed under water above a large pan so that both water and debris could be collected. Most of the water was carefully decanted and the remaining debris with a small amount of water was transferred to a small pan and oven dried. The oven dried mass was measured and was recorded as the scaled mass after every 10 cycles. The specimens were given a visual rating on the degree of deterioration. The results are provided in Table 4.12 and Figure 4.19.

The accumulated scaled mass with number of cycles, shown in Figure 4.19a, 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 accumulated scaled mass (between 7.6 and 12.3 g after 50 cycles). In contrast, the other nine concrete mixtures had significantly lower amounts of accumulated scaled mass (between 0.0 and 2.1 g). The four SCM mixtures with a w/cm of 0.40 had very low amounts of accumulated scaled mass (between 0.0 and 0.6 g). The 0.40 SCM mixtures had similar or lower accumulated scaled mass than the 0.45PC mixtures (0.1 and 1.6 g) while the 0.50 SCM mixtures had higher accumulated scaled mass (three of them ranged between 1.7 to 2.1 g) than the 0.45PC mixtures. This indicates that SCM mixtures did not improve the performance of concrete subjected to physical salt attack when compared to PC mixtures. From Figure 4.19b it can be seen that the SCM mixtures with Type V cement did not have lower accumulated scaled mass when compared to the SCM mixtures with Type II cement – in some instances it was higher. These data indicate that concrete's resistance to physical salt attack is primarily a function of porosity and absorption capacity and not dependent on the type and composition of cementitious materials used.

The visual rating and scaling distance plots (Figure 4.19c, d) support the conclusions drawn from the accumulated scaled mass results. The plot on visual rating shows that the four SCM mixtures with a w/cm of 0.60 and the 0.50FA30-VI mixture had a visual rating of three or higher after 40 cycles. The plot on scaling distance shows the same mixtures and mixtures 0.50SL50-VI and 0.45PC-V2 had scaling distance of 1.5 in. or higher after 40 cycles. The four SCM mixtures with a w/cm of 0.40 again had the lowest visual rating and scaled distance.

The condition of the specimens after 50 cycles in sulfate solution is shown in Figure 4.20. The specimens are sequentially displayed based on the amount of accumulated scaled mass after 50 cycles. Mixtures with the most amount of scaling (7.6 to 12.3 g) are shown in Figure 4.20a and b, followed by mixtures with moderate amount of scaling (1.6 to 2.1 g) in Figure 4.20c and d; followed by mixtures with the least amount of scaling (0 to 0.6 g) in Figure 4.20e and f. The accumulated scaled mass after 50 cycles is plotted as a function of w/cm and 28 day compressive strength in Figure 4.21a and b respectively. A w/cm of 0.45 or a compressive strength of 6500 psi are suggested criteria to distinguish mixtures that have a low amount of scaling (< 2 g) due to physical salt attack. These are 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 about 33 months after casting. The strength results are reported in Table 4.12 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. Strength of standard cured cylinders of these mixtures at an age of 43 months is also reported in Table 4.12. All the three strengths are plotted in Figure 4.20. The results seem to suggest that the deterioration due to physical salt attack over the 50 cycle period did not adversely impact the compressive strength of these concrete mixtures. However, a one year period of partial immersion has been shown to lead to strength regression (Hartell et al. 2011).

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 physical salt attack within a 50 day period. A shorter defined initial curing period should be defined. The cycling should encompass 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 potassium sulfate or gypsum since 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 physical sulfate attack. It is possible that with lower concentration of sodium sulfate in soil or water, the probability of damage due to physical salt attack will be low.

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Table 4.1 ACI 318-11 Requirements for Concrete Exposed to Sulfates

Exposure Class (Concrete in contact with soluble sulfates in soil/sea water)	Max. w/cm	Minimum f'_c, psi	ASTM C150 Cementitious Type	ASTM C1012 expansion
S0 – Low sulfates*	N/A	2500	NA	
S1 - Moderate sulfates*	0.50	4000	Type II	0.10% at 6 m
S2 - Severe sulfates*	0.45	4500	Type V	0.05% at 6 m or 0.10% at 12 m
S3 – Very severe sulfates*	0.45	4500	Type V+pozzolan or slag	0.10% at 18 m

*Sulfate concentration is provided in ACI 318-11

Table 4.2 Chemical and Physical Characteristics of Portland Cements, Slag Cement, and Fly Ash Used in Sulfate Program

Item	Type I	Type II	Type V	Type V	Slag Cement	Fly Ash	Silica Fume
Cement Type	**I**	**II**	**V-1**	**V-2**	**SL**	**FA**	**SF**
Silicon oxide (SiO_2), %	19.34	20.6	22.2	20.7	-	60.5	93
Aluminum oxide (Al_2O_3), %	5.95	5.0	3.7	4.4	11.79	29.1	0.7
Iron oxide (Fe_2O_3), %	1.94	3.2	4.1	4.0	-	2.9	0.7
Calcium oxide (CaO), %	62.3	62.8	64.7	64.8	-	0.7	0.7
Magnesium oxide (MgO), %	2.93	3.9	1.2	1.6	-	-	0.7
Sulfur trioxide (SO_3), %	3.89	2.9	2.1	2.5	2.40	0	-
Loss of Ignition, %	1.46	1.1	0.9	1.1	-	1.3	6
Fineness 45μm sieve, % retained	-	-	-	-	-	27.2	1.5
Blaine (Specific Surface) m$^{2/}$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_2O eq), %	0.94	0.53	0.41	0.30	0.49	0.54	0.99
Tricalcium Silicate (C_3S), %	53	53	58	64	-	-	-
Dicalcium silicate (C_2S), %	16	-	20	11	-	-	-
Tricalcium Aluminate (C_3A), %	12	8	3	5	-	-	-
Tetracalcium Aluminoferrite (C_4AF), %	6	-	12	12	-	-	-

Table 4.3 Selected Mixture Conditions

Exposure Class	w/cm	Cement	PC	15% FA	20% FA	30% FA	25% SL	35% SL	50% SL
S0	0.50	Type I	1						
S1	0.50	Type II	1						
	0.40, 0.50, 0.60	Type I		Yes			Yes		
S2	0.45	Type V	2						
	0.40, 0.50, 0.60	Type II			Yes			Yes	
S3	0.40, 0.50, 0.60	Type V				Yes			Yes

Table 4.4 Yield Adjusted Mixture Proportions and Test Results – First Series

Mixture Designation	**0.4SL25-I**	**0.5SL25-I**	**0.6SL25-I**	**0.5PC-I**	**0.4FA15-I**	**0.5FA15-I**	**0.6FA15-I**	**0.5PC-II**
Mix #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Calculated Batch Quantities								
Cement Type	I	I	I	I	I	I	I	II
Type II cement, lb/yd^3	457	419	378	559	519	476	413	557
Slag, lb/yd^3	152	140	126					
Fly ash, lb/yd^3					92	84	73	
SCM, %	25	25	25	0	15	15	15	0
Coarse Agg. (No.57), lb/yd^3	2060	2055	2079	2056	2062	2061	2068	2050
Fine Aggregate, lb/yd^3	1302	1247	1260	1256	1277	1277	1272	1253
Mixing Water, lb/yd^3	244	279	283	279	244	280	291	279
w/cm	0.40	0.50	0.56	0.50	0.40	0.50	0.60	0.50
ASTM C494 Type A, oz/cwt	3	3	3	3	3	3	3	3
ASTM C494 Type F, oz/cwt	9.15	5.64	0	3	10.29	3.3	2	2.41
Fresh Concrete Properties								
ASTM C143, Slump, in.	5.50	6.50	6.50	7.00	4.00	4.00	7.00	5.25
ASTM C231, Air, %	1.6	1.7	1.2	1.4	1.6	1.4	1.2	2.0
ASTM C138, Air, %	2.0	2.3	2.3	2.2	1.9	2.0	1.7	2.5
ASTM C138, Density, lb/ft^3	156.9	154.1	153.7	154.5	156.1	153.7	153.3	154.1
ASTM C1064, Temperature, °F	72	72	72	73	72	72	72	72
Hardened Concrete Properties								
ASTM C39, Compressive Strength, psi								
28 days	9,540	7,700	5,710	5,690	8,400	5,980	4,630	6,440
Draft ASTM Standard, Water Absorption Test at 50 °C, %								
28d accelerated cure	0.62	0.79	1.34	1.33	0.61	0.88	1.13	1.31
56d standard cure	0.63	0.75	1.17	1.04	0.61	0.83	1.01	1.23
52w standard cure	0.55	0.65	0.87	0.72	0.38	0.64	0.86	0.73
ASTM C1202, Rapid Chloride Permeability, Coulombs								
28d accelerated cure	728	1104	1842	3132	509	968	1849	3459
56d standard cure	704	1161	1947	2947	913	1593	2627	3610

Mixture Designation	**0.4SL25-I**	**0.5SL25-I**	**0.6SL25-I**	**0.5PC-I**	**0.4FA15-I**	**0.5FA15-I**	**0.6FA15-I**	**0.5PC-II**
52w standard cure	649	1004	1253	2365	353	526	963	3132
ASTM C 1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/$s^{1/2}$								
28d accelerated cure (Initial/Secondary)	$2^*/1.1^*$	$2.8^*/1.7^*$	$4.2^*/2.2^*$	$6.3^*/4.8$	$1.8^*/1.3^*$	$2.5^*/1.9^*$	$5.2^*/3.1^*$	$7.2/3.8^*$
56d standard cure (Initial/Secondary)	$3.1^*/2$	$5/2.6^*$	$8.1/3^*$	$5.8^*/3.3^*$	$4^*/2.4^*$	$5.7/2.6^*$	$7.4/4.2^*$	6.2/4.3
52w standard cure (Initial/Secondary)	$4.6^*/1.4$	$4.9^*/1.6^*$	$7.7^*/2.5$	$6.8^*/3.8$	**	$7.2^*/1.9^*$	$9.9^*/2.8^*$	$4^*/4.8$
USBR 4908 Fully Immersed Method B (10% solution)								
Length Change, %								
12 m	0.021	0.030	0.040	0.096	0.028	0.038	0.043	0.044
19 m	0.024	0.034	0.194	NA	0.028	0.039	0.058	0.059
24 m	0.025	0.036	NA	NA	0.029	0.041	0.082	0.088
26 m	0.025	0.038	NA	NA	0.030	0.043	0.098	0.111
33 m	0.027	0.039	NA	NA	0.031	0.046	0.390	0.297
36 m	0.030^{++}	0.039	NA	NA	0.031	0.049^{++}	NA	0.41^{++}
39 m	0.030	0.039	NA	NA	0.031	0.051	NA	0.65
48 m	0.034	0.044	NA	NA	0.032	0.071	NA	1.3
Change in Mass, %								
12 m	0.6	1.0	0.7^+	1.4	0.8	1.4	1.3^+	1.6
19 m	0.6	1.0	-2.5	-22.2^+	0.8	1.4	0.8	1.8
24 m	0.7	1.0	NA	NA	0.9	1.4	0.7	2.1
26 m	0.7	1.0	NA	NA	0.9	1.2	-0.7	2.1
33 m	0.8	0.9^+	NA	NA	1.0	1.2	-2.4	2.6
36 m	0.8^{++}	0.3	NA	NA	1.0	1.3^{++}	NA	3.0^{++}
39 m	0.8	0.3	NA	NA	1.0	0.6^+	NA	3.1
48 m	0.8	0.5	NA	NA	1.1	-1.1	NA	4.8
USBR 4908 Partially Immersed (10% solution),								
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
28 m	2.46	-	NA	NA	3.50	-	6.00	6.00
Visual Rating @ 28 m								
	2.1	-	5.0(est)	5.0(est)	2.2	-	3.8	5.0

[*] A correlation coefficient less than 0.98 indicating that the rate cannot be determined according to ASTM C1585

[**] No correlations were found, so data is unavailable

[++] Specimen 1 of the mix has been removed for petrographic analysis.

[+] Both ends corners of the specimen crumbled and fell off resulted in mass reduction instead of mass gain.

Note. Type I cement had C_3A content of 12% whereas Type II cement had C_3A content of 8%.

Table 4.5 Yield Adjusted Mixture Proportions and Preliminary Test Results – Second Series

Mixture Designation	0.4FA20-II	0.5FA20-II	0.6FA20-II	0.4SL35-II	0.5SL35-II	0.6SL35-II	0.4FA30-V1	0.5FA30-V1	0.6FA30-V1	0.4SL50-V1	0.5SL50-V1	0.6SL50-V1	0.45PC-V1	0.45PC-V2
Mix #	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Calculated Batch Quantities														
Cement Type	II	II	II	II	II	II	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-2
Type II cement, lb/yd^3	487	448	387	391	361	316								
Type V cement, lb/yd^3							429	392	343	300	281	245	577	581
Slag cement, lb/yd^3				210	195	170				300	281	245		
Fly ash, lb/yd^3	122	112	97				184	168	147					
SCM, %	20	20	20	35	35	35	30	30	30	50	50	50	0	0
Coarse Agg. (No.57), lb/yd^3	2057	2061	2062	2030	2046	2073	2069	2062	2088	2028	2070	2086	2049	2065
Fine Aggregate, lb/yd^3	1262	1216	1259	1279	1238	1267	1245	1194	1256	1271	1247	1270	1286	1296
Mixing Water, lb/yd^3	244	280	290	240	278	302	245	280	294	240	281	304	260	262
w/cm	0.40	0.50	0.60	0.40	0.50	0.62	0.40	0.50	0.60	0.40	0.50	0.62	0.45	0.45
ASTM C494 Type A, oz/cwt	3	3	3	3	3	3	3	3	3	3	3	3	3	3
ASTM C494 Type F, oz/cwt	4.67	1.8	0	5.84	2.16	0	4.58	0	0	1.17	0.72	0	2.5	2.5
Fresh Concrete Properties														
ASTM C143, Slump, in.	4.5	6.75	5	7	5	4.5	4.75	6.75	7	7	5.5	6	4.5	6.5
ASTM C231, Air, %	1.6	1.8	1.7	3.2	2.1	1.7	2	1.5	1	1.7	1.8	1.3	1.9	1.6
ASTM C138, Air, %	2.2	2.0	1.9	3.5	2.7	1.4	1.6	2.0	0.7	3.6	1.6	0.8	2.5	1.8
ASTM C138, Density, lb/ft^3	155.3	153.3	152.5	154.5	153.3	153.7	155.3	152.5	153.7	154.1	154.9	154.5	155.3	156.5
ASTM C1064, Temperature, °F	74	75	75	72	72	72	70	70	70	71	70	70	72	74
Hardened Concrete Properties														
ASTM C39, Compressive Strength, psi														
28 days	7,490	5,310	3,990	10,020	6,740	5,730	7,610	4,870	3,590	7,500	7,500	6,200	8,800	7,720
Water Absorption Test (drying at 122 °F), % change in mass														
28d accelerated cured	0.96	1.45	1.81	0.69	1.02	1.14	0.91	1.46	1.98	1.08	1.09	1.30	1.12	1.30
56d standard cured	0.92	1.38	1.65	0.78	1.08	1.29	0.93	1.47	1.86	1.07	1.12	1.52	1.14	0.96
364d standard cured	0.59	0.93	1.18	0.60	0.84	0.97	0.65	0.99	1.29	0.94	1.09	1.32	0.75	1.14
ASTM C1202, Rapid Chloride Permeability, Coulombs														
28d accelerated cured	1147	1776	3081	576	789	1143	592	1434	2618	470	487	586	2845	3437
56d standard cured	1848	2662	3856	705	943	1790	1543	3731	4772	593	887	1077	3456	3905
364d standard cured	354	660	1080	441	621	889	362	554	759	393	447	535	2861	3184
ASTM C 1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$														

Mixture Designation	**0.4FA20-II**	**0.5FA20-II**	**0.6FA20-II**	**0.4SL35-II**	**0.5SL35-II**	**0.6SL35-II**	**0.4FA30-V1**	**0.5FA30-V1**	**0.6FA30-V1**	**0.4SL50-V1**	**0.5SL50-V1**	**0.6SL50-V1**	**0.45PC-V1**	**0.45PC-V2**
28d accelerated cured (Initial/Secondary)	$1.8^*/1.6$	$2.1^*/2.9$	$3.8^*/4$	**	$4.2^*/2.3$	$5^*/2.4^*$	$3.2^*/1.3^*$	$7.8^*/2.5$	$15.2^*/4.4^*$	**	$5.3^*/1.5^*$	$6.2^*/1.6^*$	$5.4^*/2$	$8.6^*/3.3^*$
56d standard cured (Initial/Secondary)	$6/2.8^*$	$8.3^*/4.1$	$22/11.1^*$	$5.4^*/1.7^*$	$7.1^*/2.2^*$	$12.9/2.2^*$	$6.4/2.6^*$	$6.7^*/1.7^*$	9.4/4	**	$4.3/1.4^*$	$6.9/1.8^*$	$6.5^*/2.9$	10.3/4.9
364d standard cured (Initial/Secondary)	3.4/1.7	$3.4^*/2$	$6^*/4.4^*$	$2.3^*/0.8^*$	6.4/2	**	$1.2^*/1.1^*$	**	$5.8^*/1.5^*$	**	$2.4^*/1^*$	$3.8^*/1.1^*$	$2.1^*/-$	$3.7^*/^{**}$
USBR 4908 Fully Immersed Method B														
Length Change, %														
9 m	0.028	0.031	0.035	0.026	0.028	0.042	0.032	0.031	0.034	0.028	0.028	0.031	0.033	0.027
20 m	0.029	0.032	0.036	0.029	0.030	0.044	0.032	0.031	0.034	0.029	0.029	0.032	0.039	0.031
22 m	0.031	0.033	0.037	0.029	0.033	0.049	0.037	0.036	0.035	0.029	0.029	0.034	0.044	0.036
29 m	0.032	0.034	0.037	0.030	0.033	0.049	0.037	0.036	0.036	0.029	0.029	0.035	0.047	0.036
32 m	0.032	0.034	0.037	0.031	0.033^{++}	0.049	0.037	0.036	0.036^{++}	0.029	0.029	0.035	0.051^{++}	0.036
36 m	0.032	0.034	0.037	0.031	0.033	0.049	0.037	0.036	0.036	0.029	0.030	0.035	0.062	0.041
44 m	0.036	0.034	0.039	0.034	0.035	0.054	0.037	0.036	0.036	0.031	0.030	0.035	0.138	0.069
Change in Mass, %														
9 m	1.2	1.8	2.4	0.7	1.1	1.5	1.2	2.3	3.0	1.0	1.2	1.6	1.2	1.2
20 m	1.3	1.8	2.5	0.8	1.2	1.6	1.2	2.4	3.0	1.1	1.3	1.6	1.4	1.4
22 m	1.3	1.8	2.5	0.8	1.2	1.6	1.2	2.4	3.0	1.1	1.3	1.6	1.5	1.4
29 m	1.3	1.8	2.5	0.8	1.2	1.6	1.2	2.4	3.0	1.1	1.3	1.6	1.7	1.6
32 m	1.3	1.8	2.5	0.8	1.2^{++}	1.6	1.2	2.4	3.0^{++}	1.1	1.3	1.6	1.8^{++}	1.6
36 m	1.3	1.8	2.5	0.8	1.2	1.6	1.2	2.4	3.0	1.1	1.3	1.6	1.9	1.8
44 m	1.3	1.9	2.6	0.8	1.3	1.7	1.2	2.4	3.0	1.1	1.3	1.7	2.2	2.1
USBR 4908 Partially Immersed (10% solution)														
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

* A correlation coefficient less than 0.98 indicating that the rate cannot be determined according to ASTM C158

** No correlations were found, so data is unavailable

Note. Type II, V-1, and V-2 cements had C_3A content of 8%, 3%, and 5%, respectively.

$^{++}$ Specimen 1 of the mix has been removed for petrographic analysis.

Table 4.6 ASTM C1012 Mortar Mixture Proportions and Test Results

Mix No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Cement Type	I	II	V-1	V-2	I	II	V-1	I	II	V-1
C_3A (Cement mill cert.), %	12	8	3	5	12	8	3	12	8	3
Slag cement, %					25	35	50			
Fly ash, %								15	20	30
Batch Quantities										
Cement, g	500	500	500	500	375	325	250	425	400	350
Slag cement, g					125	175	250			
Fly ash, g								75	100	150
Graded Standard Sand, g	1375	1375	1375	1375	1375	1375	1375	1375	1375	1375
Water, g	243	243	243	243	243	243	243	243	243	243
w/cm	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Fresh Mortar Properties										
ASTM C1064, Temperature, °F	74	75	75	75	75	75	72	77	74	73
ASTM C1437, Flow, %	92	111	122	116	108	108	118	89	107	121
ASTM C109, At Immersion into Sulfate Solution										
Age, days	1.9	1.8	1.3	1.9	1.8	2.0	5.8	6.8	3.8	6.0
Compressive strength, psi (est)	2,850	3,381	2,925	3,169	2,894	2,931	4,019	2,850	2,850	2,856
ASTM C1012, Sulfate Expansions										
6 m, %	0.45	0.06	0.02	0.03	0.03	0.04	0.02	0.03	0.04	0.02
12 m, %	NA	0.16	0.05	0.04	0.04	0.04	0.02	0.09	0.04	0.02
18 m, %	NA	0.51	0.20	0.16	0.05	0.05	0.03	0.34	0.06	0.03
27 m, %	NA	1.07	0.38	0.33	0.08	0.05	0.03	0.61	0.12	0.04
36 m, %	NA	1.56	0.49	0.44	0.20	0.07	0.06	0.93	0.24	0.05
Expected sulfate class based on cementitious composition (ACI 318-11)	S0	S1	S2	S2	S1	S2	S3	S1	S2	S3
Actual sulfate class based on measured expansions (ACI 318-11)	S0	S1	S2	S2	S3	S3	S3	S2	S3	S3

Note. Type I cement had C_3A content of 12% whereas Type II cement had C_3A content of 8%.

Table 4.7 Mixture Categorization Based on Resistance to Chemical Sulfate Attack (USBR 4908 Full Immersion)

Resistance to Chemical Sulfate Attack	Basis for Categorization	Mixtures
Low – Acceptable for 318 EC S0	Expansions > 0.05% in 18 m; High cracking; Loss of concrete mass due to corner damage	0.6SL25-I, 0.6FA15-I, 0.5PC-I, 0.5PC-II
Moderate – Acceptable for ACI 318 EC S1	Exp. > 0.05% in 44-48 m; High cracking; Loss of concrete mass/visual appearance of corner damage	0.45PC-V1, 0.45PC-V2, 0.5SL25-I, 0.5FA15-I, 0.6SL35-II
High– Acceptable for use in ACI 318 EC S2	Exp. < 0.04% in 44-48 m; Some cracking; Some visual corner damage but no loss of concrete mass	0.4FA15-I, 0.4SL25-I, 0.4FA20-II, 0.5FA20-II, 0.6FA20-II, 0.5SL35-II
Excellent – Acceptable for use in ACI 318 S3	Exp. < 0.04% in 44-48 m; Low cracking; Low visual corner damage but no loss of concrete mass	0.4SL35-II, 0.4FA30-V1, 0.5FA30-V1, 0.6FA30-V1, 0.4SL50-V1, 0.5SL50-V1, 0.6SL50-V1

*except 0.5SL25-I

Table 4.8 Categorization Based on Resistance to Physical Salt Attack (USBR 4908 Partial Immersion)

Resistance to Physical Salt Attack	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

Basis for Categorizing Mixtures:
Low - >3.0 in.
High – scaling distance ≤ 3.0 in.

Table 4.9 Mixtures Categorized by ACI 318 (ASTM C1012 + Strength + W/CM) for Sulfate Resistance

Exposure Class (Concrete in contact with soluble sulfates in soil/sea water)	Table 4.7 mixtures that can be used in the exposure class based on USBR 4908 full immersion	Minimum f'_c, psi	w/cm	ASTM C1012 expansion limit	Mixtures that meet the strength, w/cm and C1012 expansion criteria of ACI 318
S0 – Low	0.6SL25-I, 0.6FA15-I, 0.5PC-I, 0.5PC-II	2500	NA	NA	0.6SL25-I, 0.6FA15-I, 0.5PC-I, **0.6FA20-II, 0.6SL35-II, 0.6FA30-V1, 0.6SL50-V1**
S1 - Moderate	0.45PC-V1, 0.45PC-V2, 0.5SL25-I, 0.5FA15-I, 0.6SL35-II	4000	0.50	0.10% at 6 m	0.5SL25-I, 0.5FA15-I, **0.5PC-II, 0.5SL35-II, 0.5SL50-V1, 0.5FA20-II, 0.5FA30-V1**
S2 - Severe	0.4FA15-I, 0.4SL25-I, 0.4FA20-II, 0.5FA20-II, 0.6FA20-II, 0.5SL35-II	4500	0.45	0.05% at 6 m or 0.10% at 12 m	**0.45PC-V1, 0.45PC-V2,** 0.4FA15-I
S3 – Very severe	0.4SL35-II, 0.4FA30-V1, 0.5FA30-V1, 0.6FA30-V1, 0.4SL50-V1, 0.5SL50-V1, 0.6SL50-V1	4500	0.45	0.10% at 18 m	**0.4SL25-I, 0.4FA20-II,** 0.4SL35-II, 0.4FA30-V1, 0.4SL50-V1

Table 4.10 Mixtures Categorized by Modified ACI 318 (ASTM C1012 + Strength + W/CM) for Sulfate Resistance

Exposure Class (Concrete in contact with soluble sulfates in soil/sea water)	Table 4.7 mixtures that can be used in the exposure class based on USBR 4908 full immersion	Minimum f'_c, psi	w/cm	ASTM C1012 expansion limit	Mixtures that meet the modified ACI 318 strength, w/cm and C1012 expansion criteria
S0 – Low	0.6SL25-I, 0.6FA15-I, 0.5PC-I, 0.5PC-II	2500	NA	NA	0.6FA15-I, 0.5PC-I, 0.6SL25-I, **0.6FA20-II, 0.6SL35-II, 0.6FA30-V1, 0.6SL50-V1**
S1 - Moderate	0.45PC-V1, 0.45PC-V2, 0.5SL25-I, 0.5FA15-I, 0.6SL35-II	4000/3500	0.50/ 0.55	0.10% at 6 m/0.05% at 6 m+SCMs	0.5FA15-I , 0.5SL25-I, **0.5PC-II, 0.4FA15-I, 0.4SL25-I**
S2 - Severe	0.4FA15-I, 0.4SL25-I, 0.4FA20-II, 0.5FA20-II, 0.6FA20-II, 0.5SL35-II	4500/ 4000	0.45/ 0.50	No Type I 0.10% at 12m/0.05% at 12m	**0.45PC-V1, 0.45PC-V2,** 0.5SL35-II, 0.5FA20-II
S3 – Very severe	0.4SL35-II, 0.4FA30-V1, 0.5FA30-V1, 0.6FA30-V1, 0.4SL50-V1, 0.5SL50-V1, 0.6SL50-V1	4500/4000	0.45/ 0.50	No Type I 0.10% at 18m/0.05% at 18m	**0.4FA20-II**, 0.4SL35-II, 0.4FA30-V1, 0.4SL50-V1, 0.5SL50-V1, 0.5FA30-V1

Table 4.11 Performance Criteria for Physical Salt Attack

Resistance to Physical Salt Attack	Prescriptive option	Performance Option
High	w/cm ≤ 0.45	Compressive Strength ≥ 4500*

*for air-entrained concrete. For non-air-entrained concrete it is 5500 psi.

Table 4.12 New Test Procedure for Resistance to Physical Salt Attack

Mixture Designation	0.4FA20-II	0.5FA20-II	0.6FA20-II	0.4SL35-II	0.5SL35-II	0.6SL35-II	0.4FA30-V1	0.5FA30-V1	0.6FA30-V1	0.4SL50-V1	0.5SL50-V1	0.6SL50-V1	0.45PC-V1	0.45PC-V2
Mix #	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Scaling Measurements														
Scaled Length, in.														
10 cycles	0	0	0	0	0	1	0	0	1	0	0	1	0	0
20 cycles	0	0.5	2.5	0	1	1.5	0	1.5	1.5	0.5	1	1.5	0	0
30 cycles	0.5	1	2.5	0	1	1.5	0.5	1.5	2	1	1.5	2	0.5	1
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
Scaled Mass, g														
10 cycles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.4	0.0	0.0
20 cycles	0.1	0.4	2.7	0.0	0.3	2.3	0.0	2.3	2.2	0.1	0.3	1.9	0.0	0.0
30 cycles	0.0	0.2	3.9	0.0	0.7	2.7	0.0	2.2	4.0	0.2	0.3	3.1	0.0	0.3
40 cycles	0.0	0.2	1.2	0.0	0.5	1.4	0.0	1.5	3.4	0.2	0.4	2.0	0.0	0.9
50 cycles	0.1	0.9	1.3	0.0	0.6	1.6	0.1	1.6	2.5	0.1	0.7	2.4	0.1	0.4
50 cycles, cumulative	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														
10 cycles	0	0	0	0	0	1	0	0	1	0	0	1	0	0
20 cycles	1	1	2	0	1	2	0	2	2	1	1	2	0	0
30 cycles	1	2	3	0	2	3	1	3	3	1	2	3	1	1
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 Strength														
After the Test, psi	10810	7840	5970	12690	8580	7360	11640	8960	6150	9470	9960	8090	10880	10540
Factor of 28 day Strength	1.44	1.48	1.50	1.27	1.27	1.28	1.53	1.84	1.71	1.26	1.33	1.30	1.24	1.37
44 months standard cured, psi	10125	7290	5700	11860	8205	7250	11570	7800	6635	9675	10510	8305	10680	9565

Figure 4.1 USBR Partially Immersed Specimens in the Container

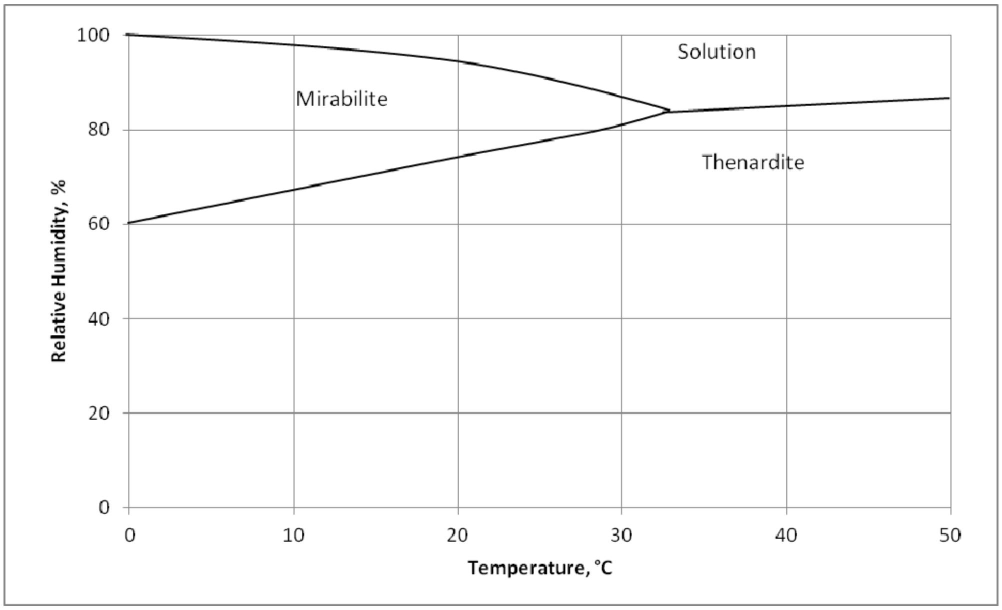


Figure 4.2 Sodium Sulfate Conversions Under Different Environmental Conditions (Flatt)

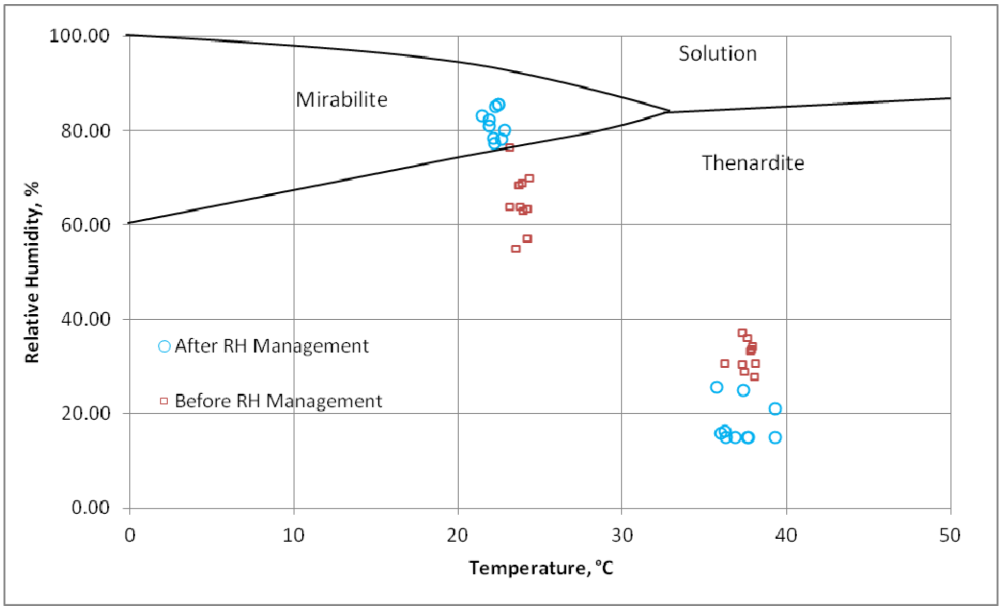
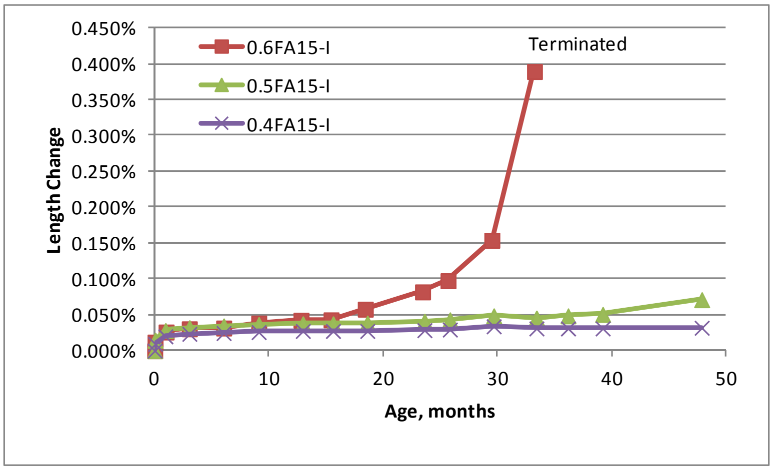
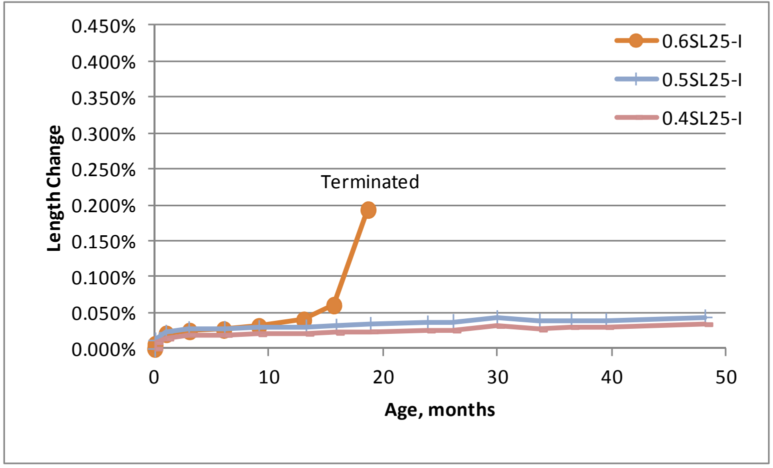


Figure 4.3 Temperature/RH Management Profile Before & After Modification



(a)



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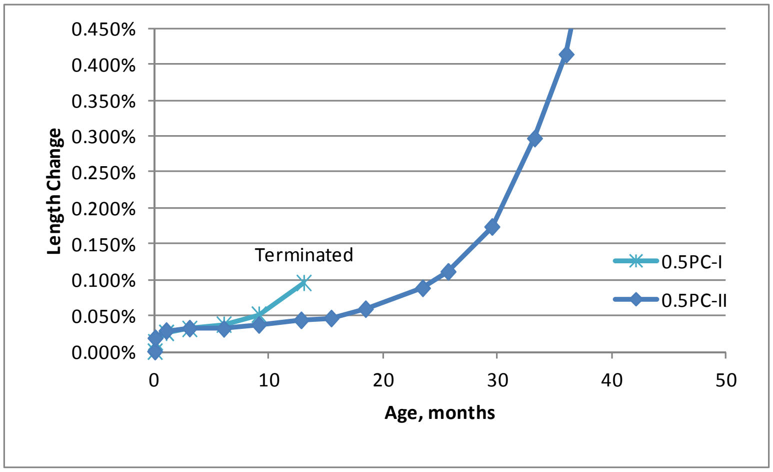
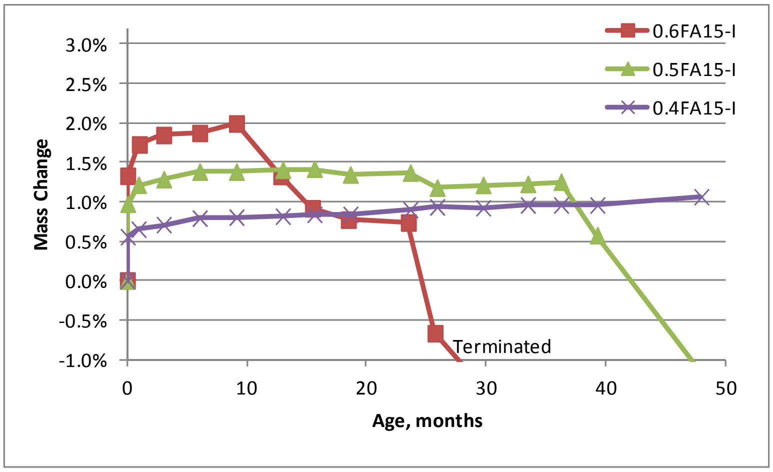


(c)

Figure 4.4 USBR Fully Immersed Condition Length Change (Mixtures 1-8)
(a) 15% fly ash mixtures, (b) 25% slag cement mixtures, and (c) portland cement mixtures (I C_3A=12%, II C_3A=8%)



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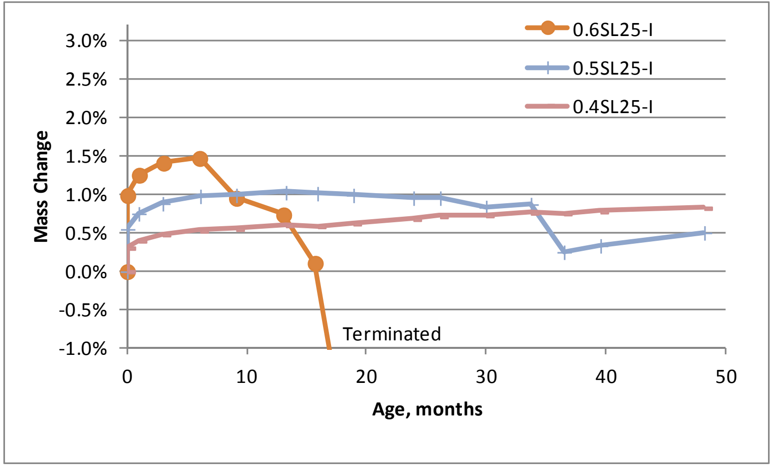

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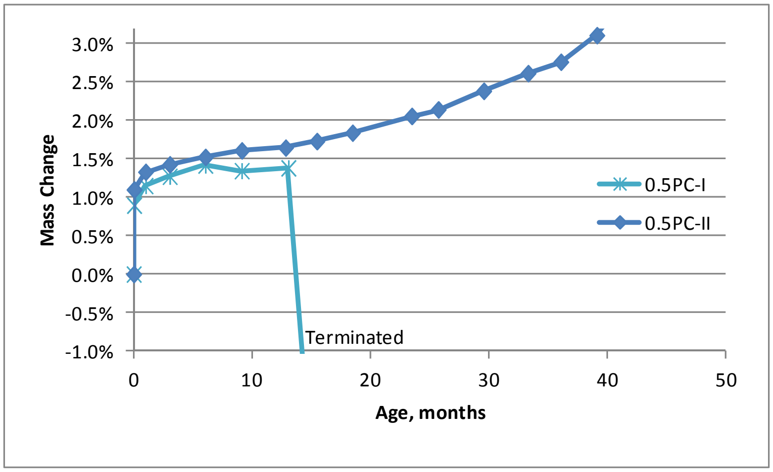
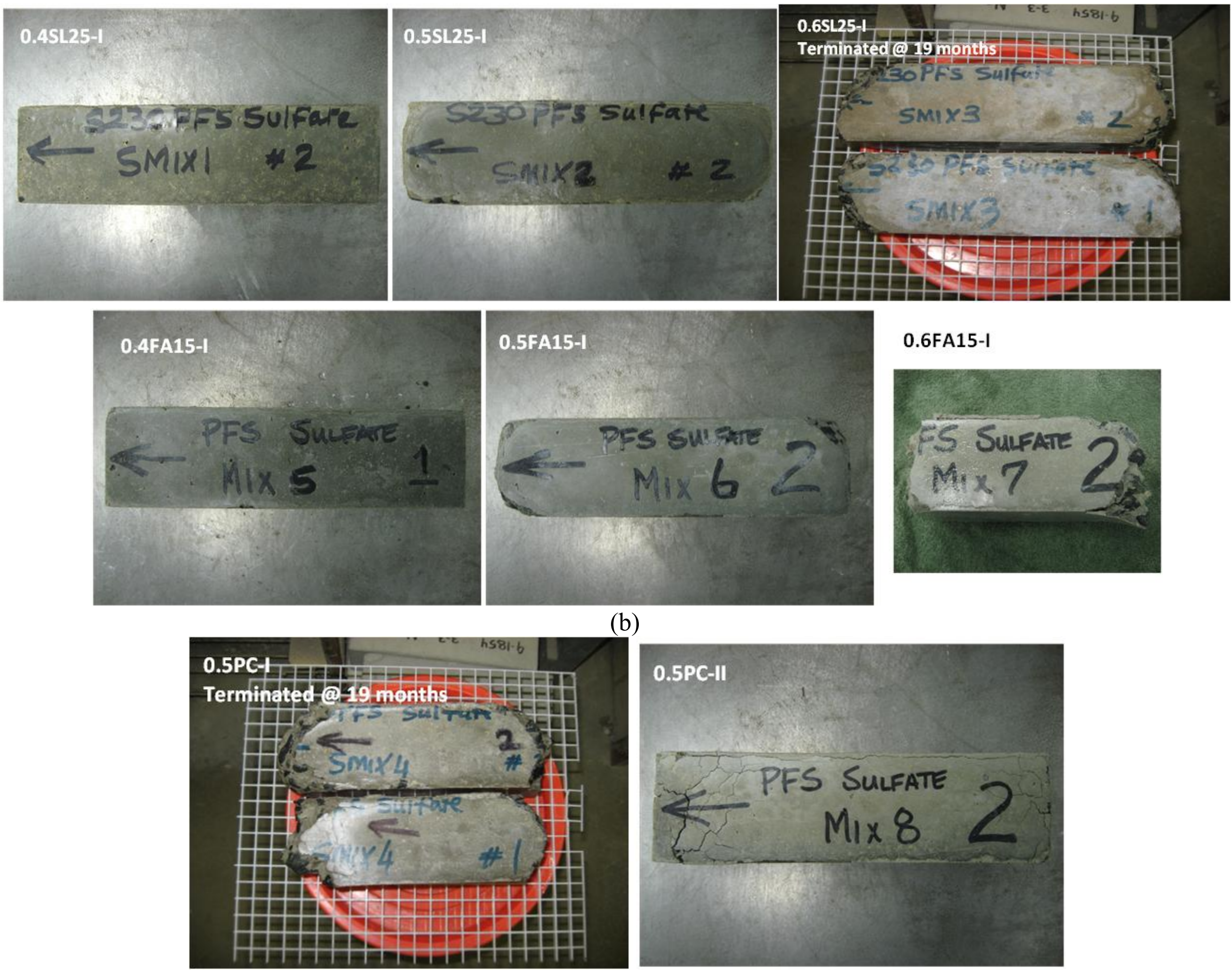


(c)

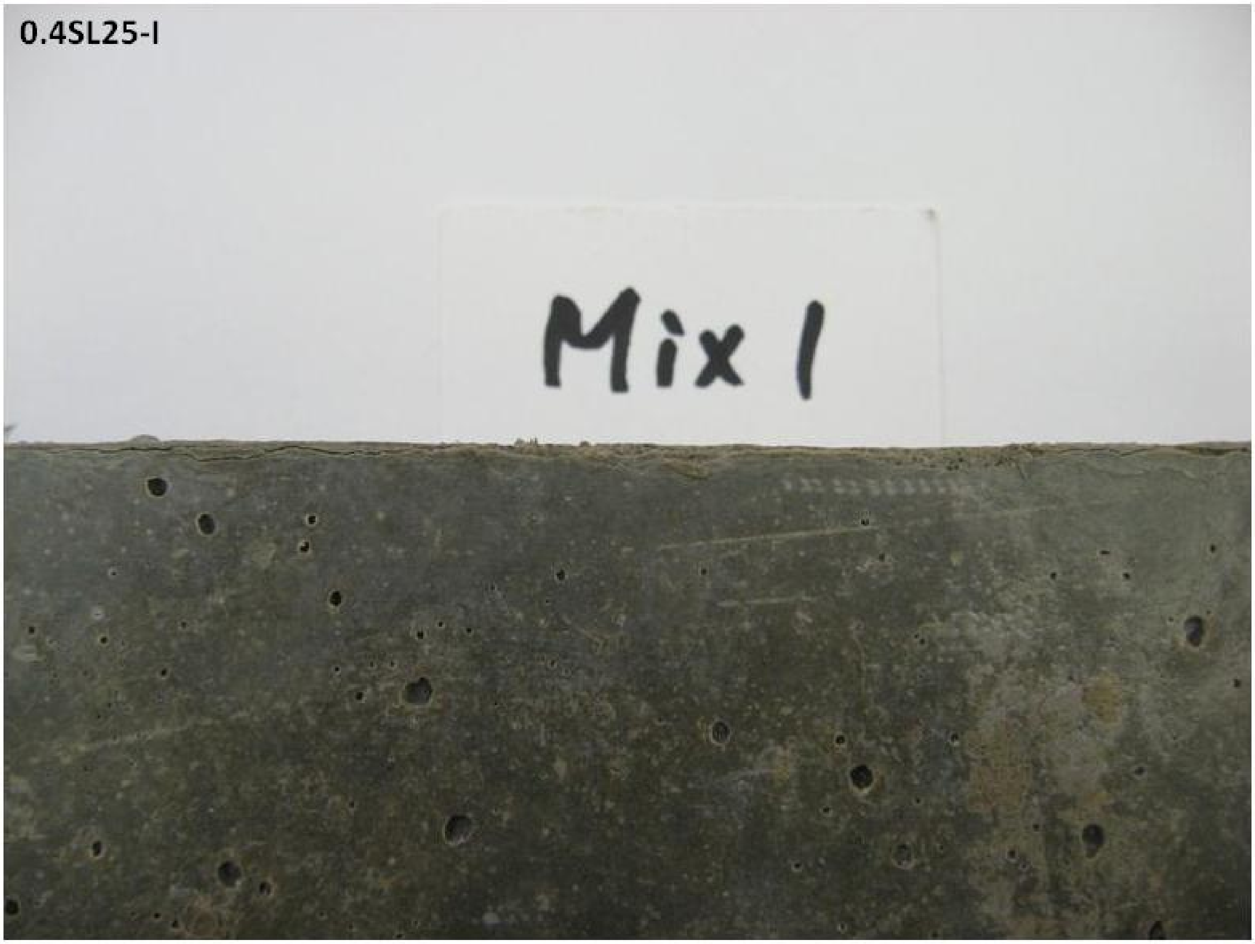
Figure 4.5 USBR Fully Immersed Condition Mass Change (Mixtures 1-8)
(a) 15% fly ash mixtures, (b) 25% slag cement mixtures, and (c) portland cement mixtures (I C_3A=12%, II C_3A=8%)



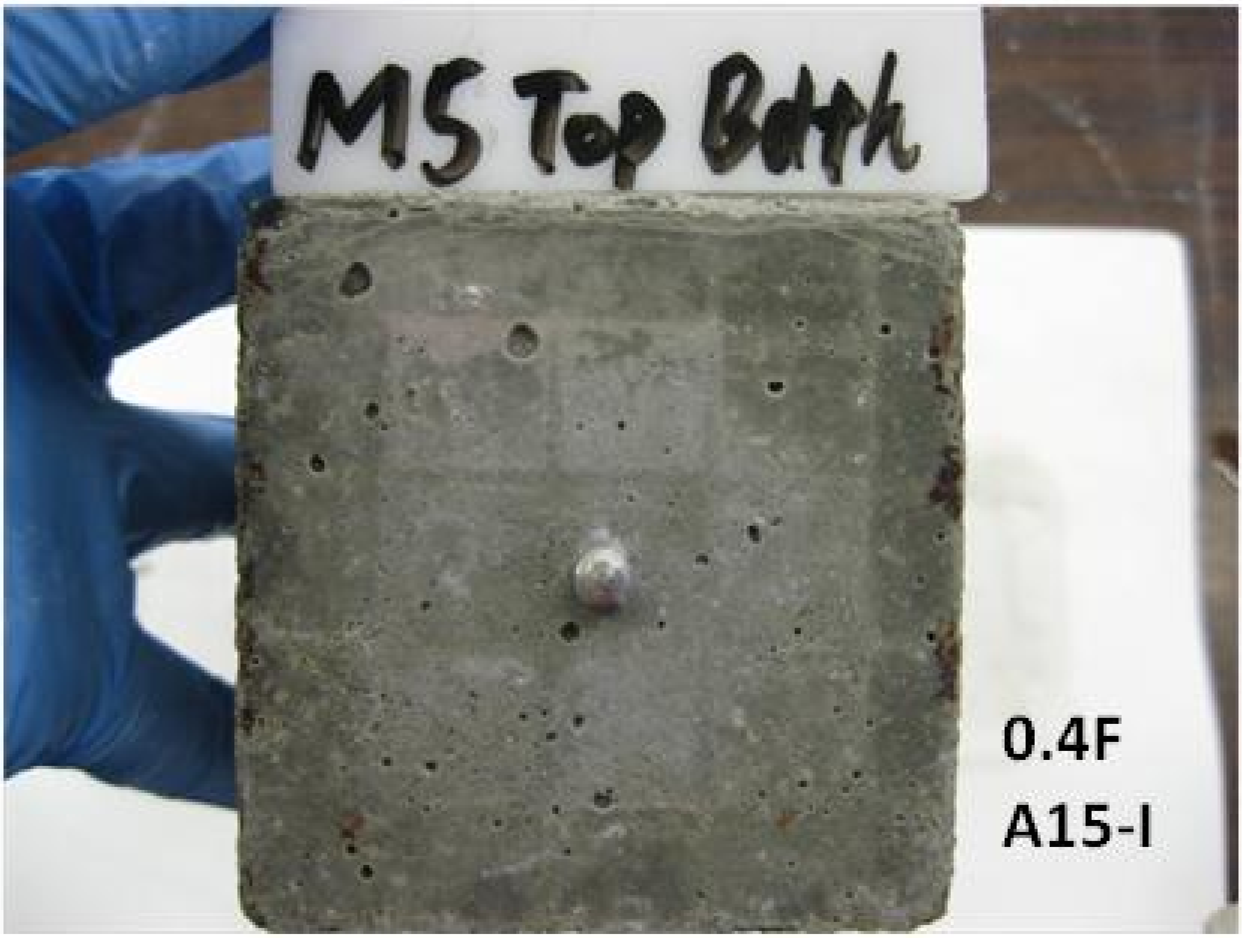
(a)

(b)

(c)

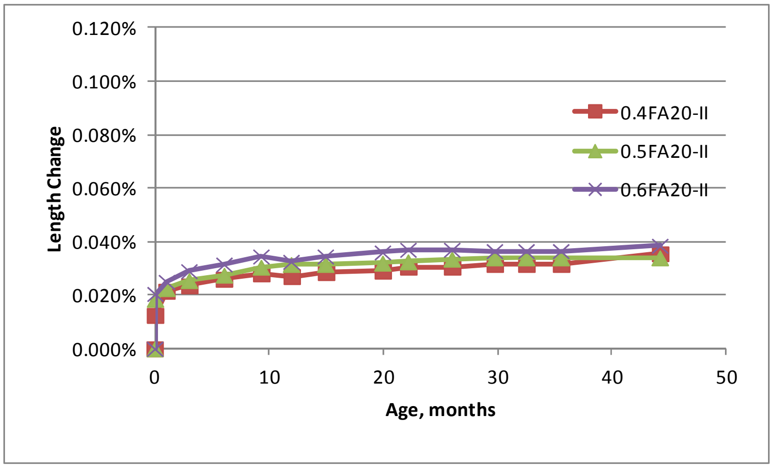


(d)

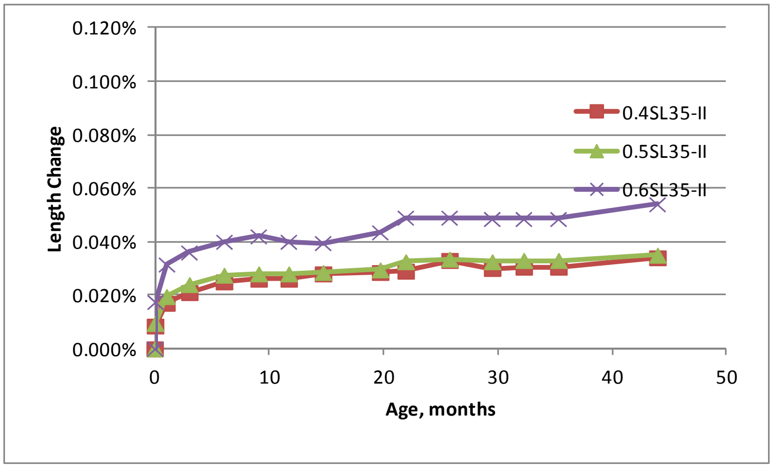


(e)

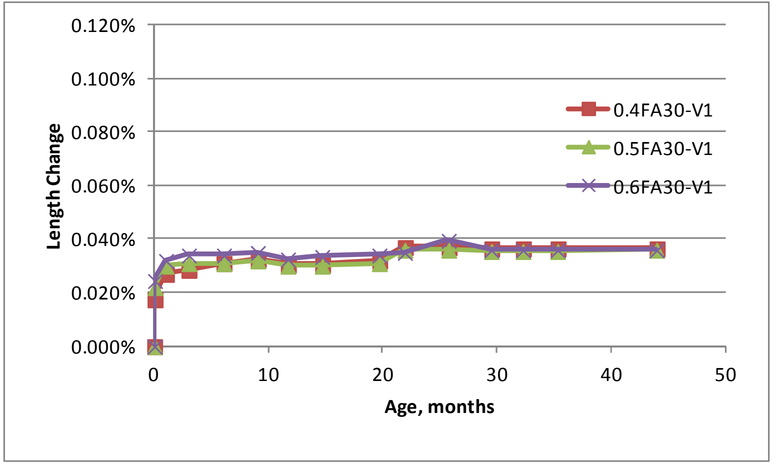
Figure 4.6 USBR Fully Immersed Sample Pictures After 48 m (Mixtures 1-8)
(a) 15% fly ash mixtures at various w/cm ratios, (b) 25% slag cement mixtures at various w/cm ratios, (c) portland cement mixture, (d) and (e) Close up images showing cracking – Mixture IDs are provided in the figures



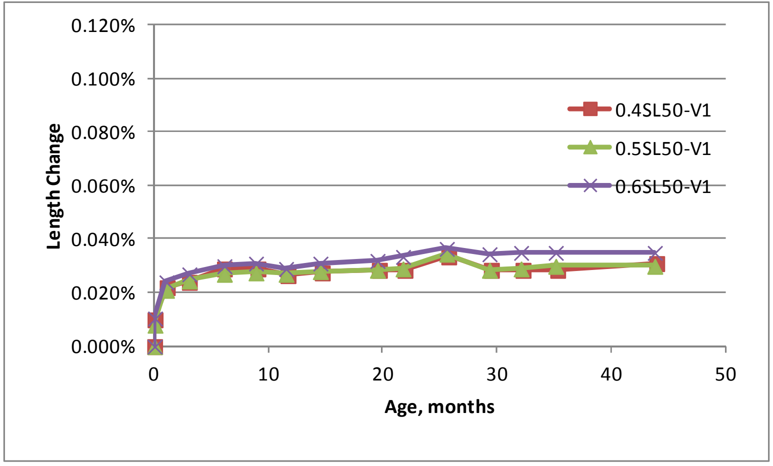
(a)


0.120%
0.100%
0.080%
0.060%
0.040%
0.020%
0.000%
Length Change
0
10
20
30
40
50
Age, months
0.4SL35-II
0.5SL35-II
0.6SL35-II

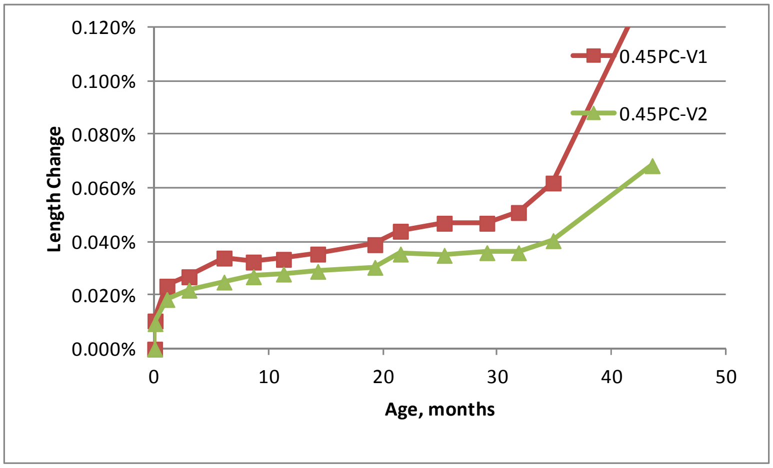
(b)


0.120%
0.100%
0.080%
0.060%
0.040%
0.020%
0.000%
Length Change
0
10
20
30
40
50
Age, months
0.4FA30-V1
0.5FA30-V1
0.6FA30-V1

(c)


0.120%
0.100%
0.080%
0.060%
0.040%
0.020%
0.000%
Length Change
0
10
20
30
40
50
Age, months
0.4SL50-V1
0.5SL50-V1
0.6SL50-V1

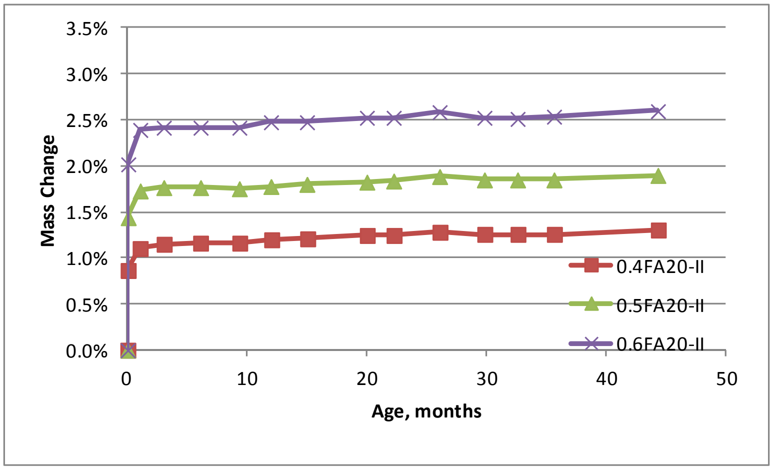
(d)



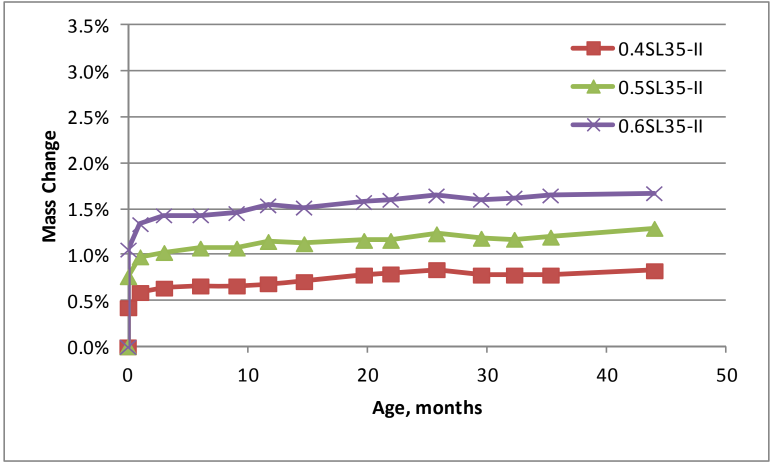
(e)

Figure 4.7 USBR Fully Immersed Condition Length Change (Mixtures 9-22)

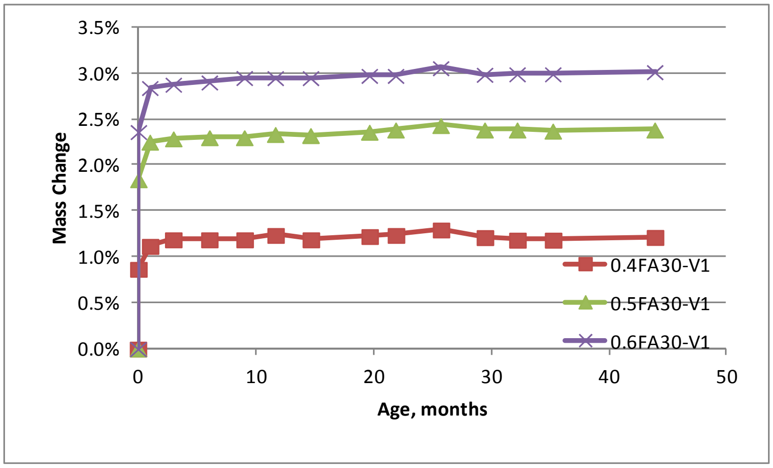
(a) 20% fly ash mixtures, (b) 35% slag cement mixtures, (c) 30% fly ash mixtures, (d) 50% slag cement mixtures, and (e) portland cement mixtures (PC-V1 C3A=3%, PC-V2 C3A=5%)



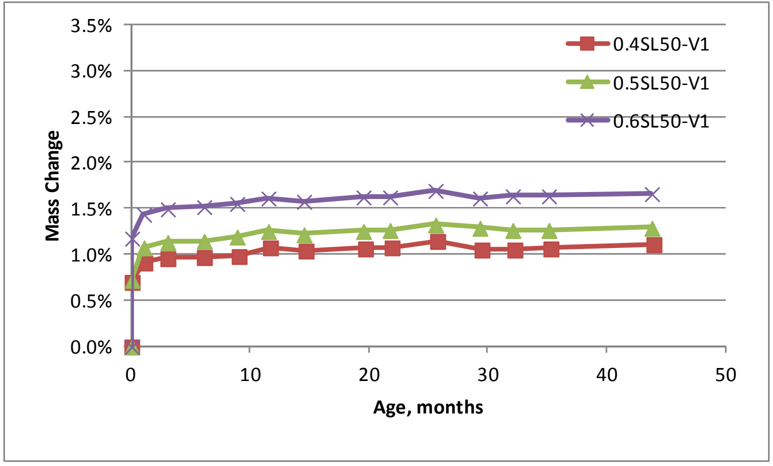
(a)



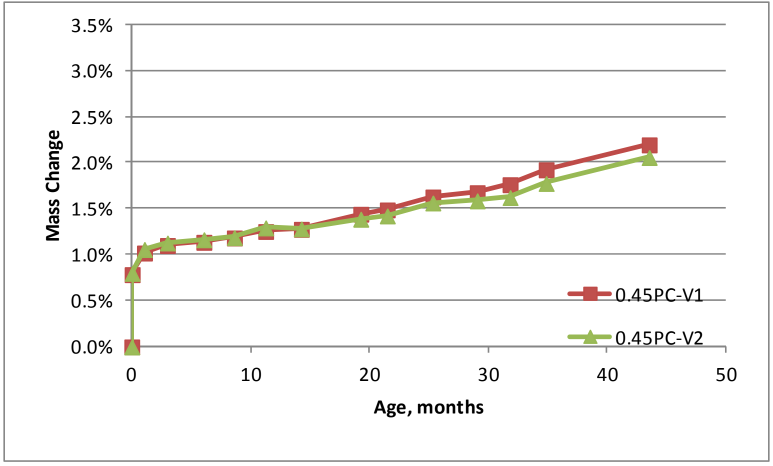
(b)



(c)

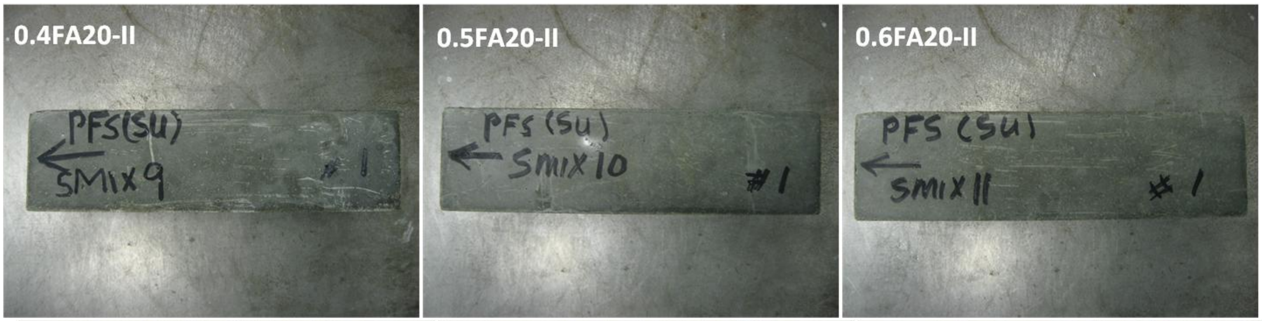


(d)

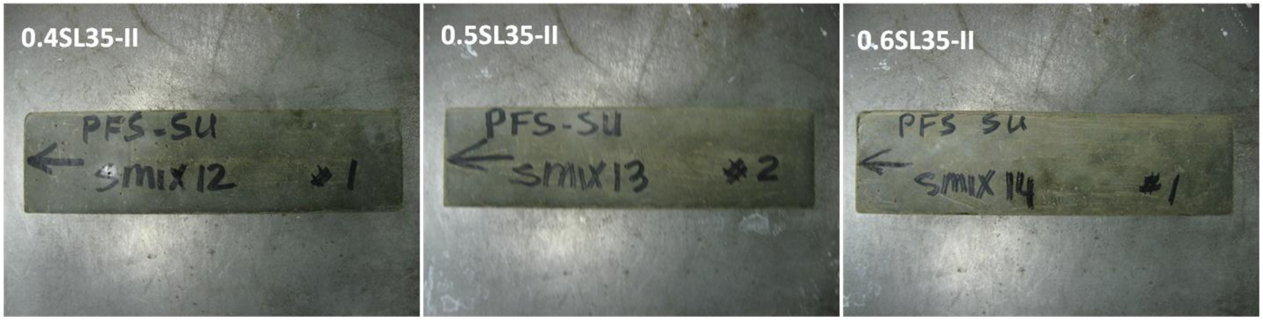


(e)

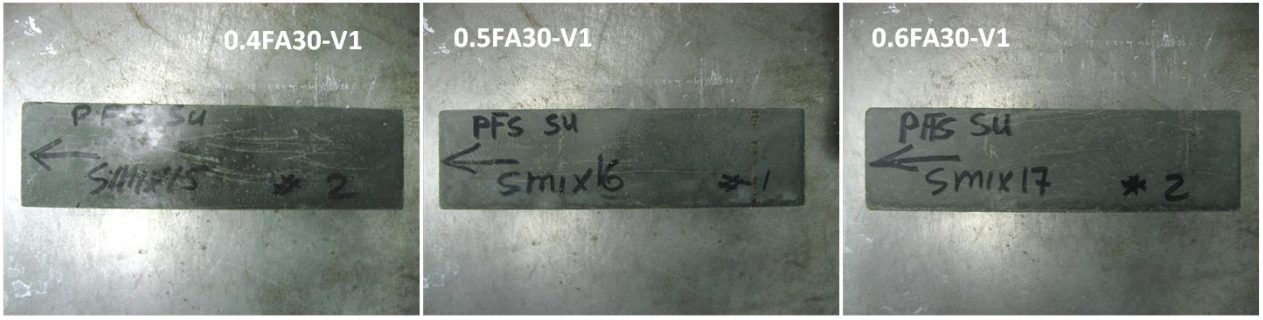
Figure 4.8 USBR Fully Immersed Condition Mass Change (Mixtures 9-22)
(a) 20% fly ash mixtures, (b) 35% slag cement mixtures, (c) 30% fly ash mixtures, (d) 50% slag cement mixtures, and (e) portland cement mixtures (PC-V1 C_3A=3%, PC-V2 C_3A=5%)


0.4FA20-II
PFS(SU)
SMIX9
#1
0.5FA20-II
PFS (SU)
SMIX10
#1
0.6FA20-II
PFS (SU)
SMIX11
#1

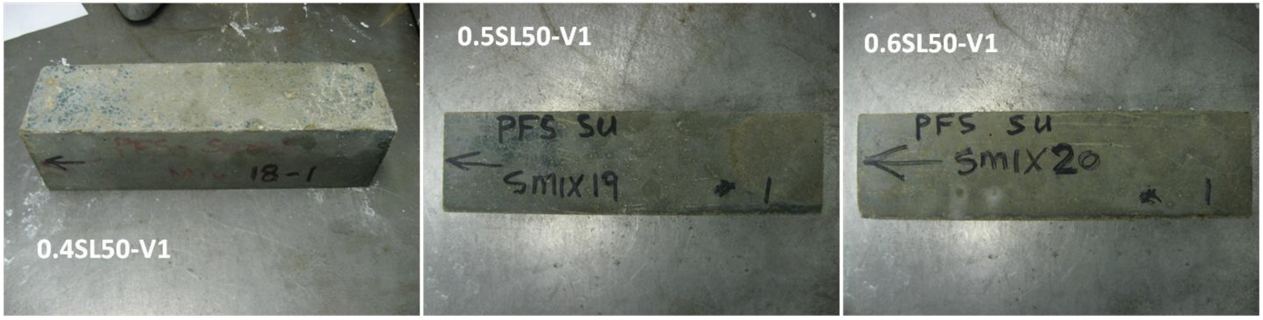
(a)


0.4SL35-II
PFS-SU
SMIX12
#1
0.5SL35-II
PFS-SU
SMIX13
#2
0.6SL35-II
PFS SU
SMIX14
#1

(b)


0.4FA30-V1
PFS SU
SMIX15
#2
0.5FA30-V1
PFS SU
SMIX16
#1
0.6FA30-V1
PFS SU
SMIX17
#2

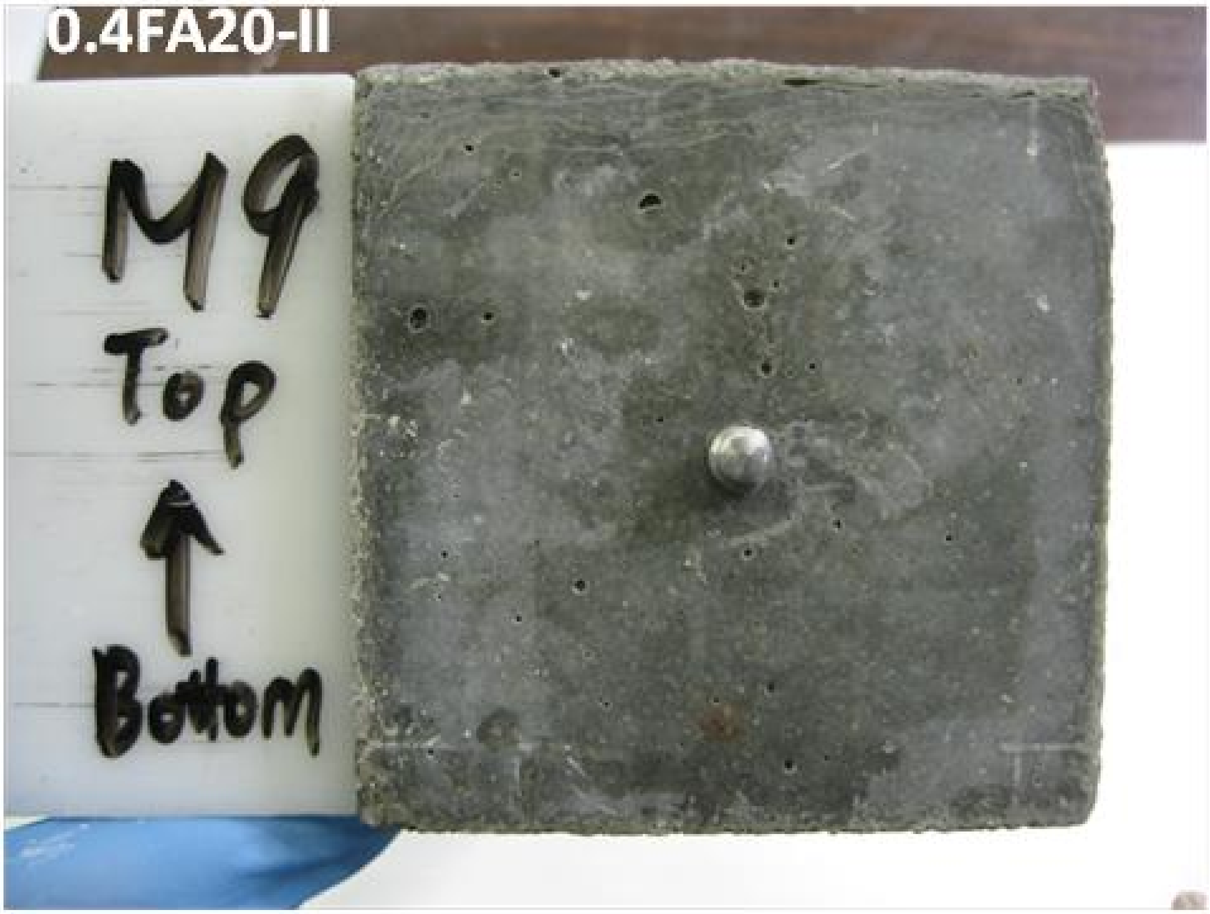
(c)


Mix 18-1
0.4SL50-V1
0.5SL50-V1
PFS SU
SMIX19
#1
0.6SL50-V1
PFS SU
SMIX20
#1

(d)

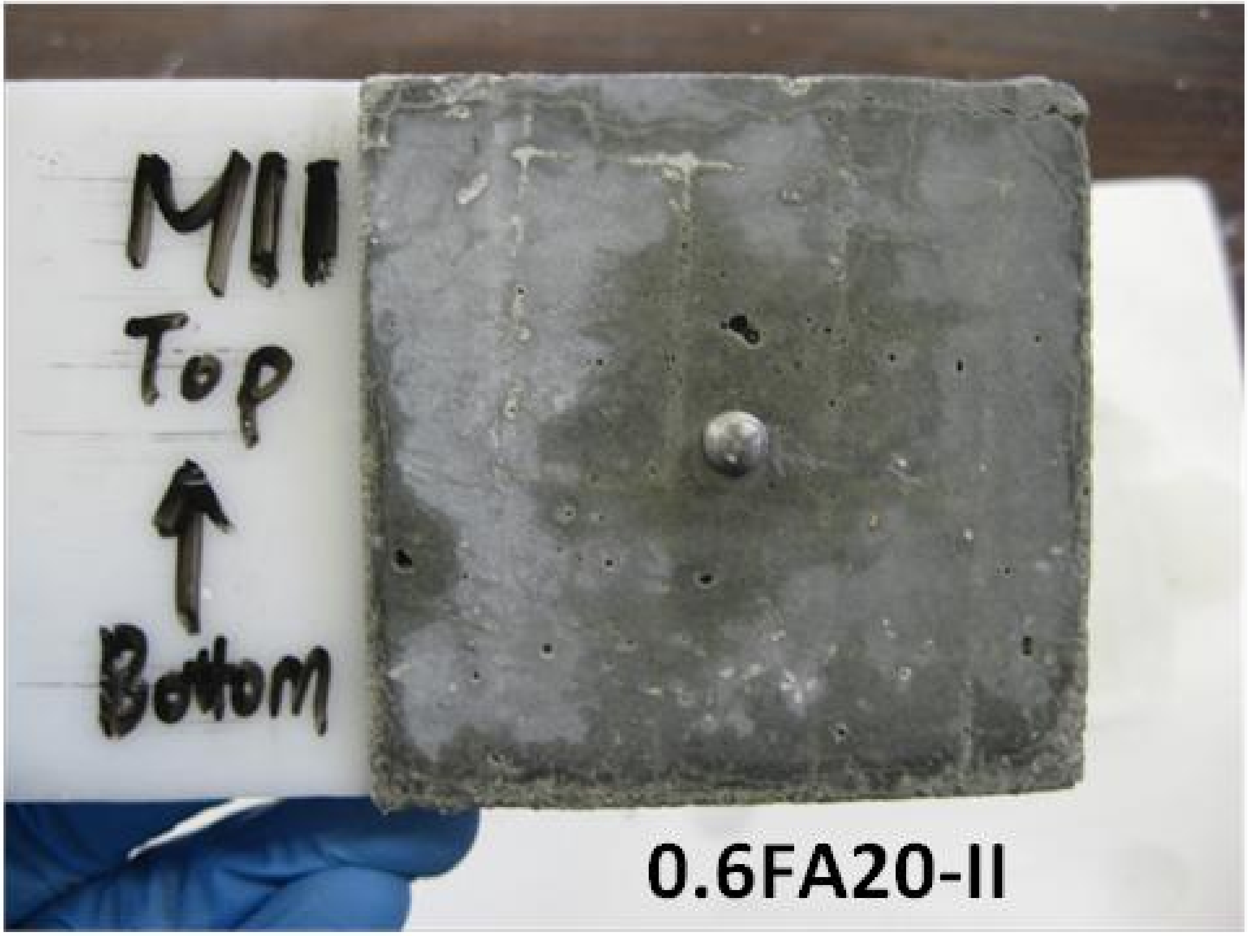

PFS SULFATE
Mix 21-2
0.45PC-V1
PFS SULFATE
Mix 22-1
0.45PC-V2

(e)



(f)

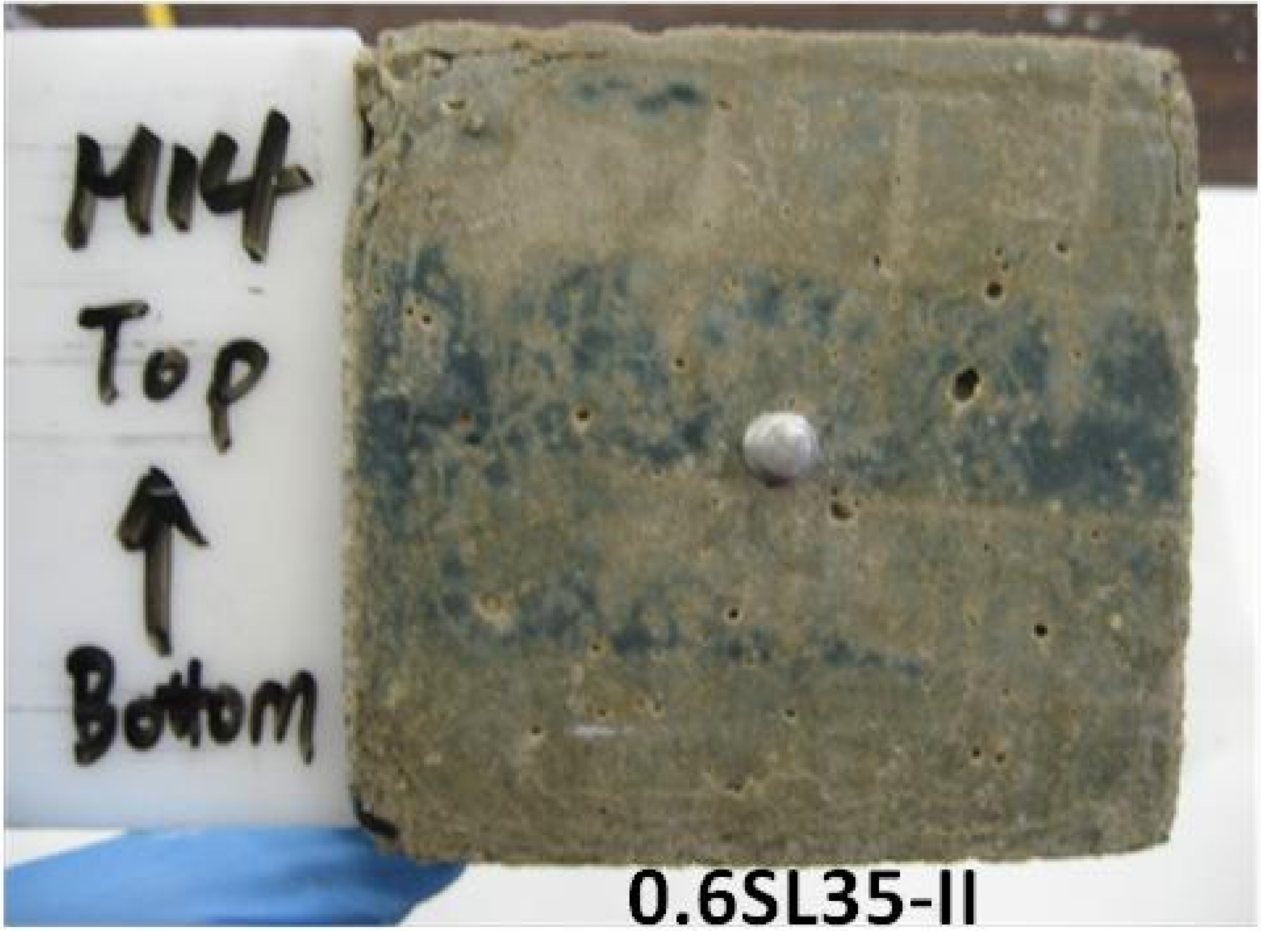
(g)



(h)

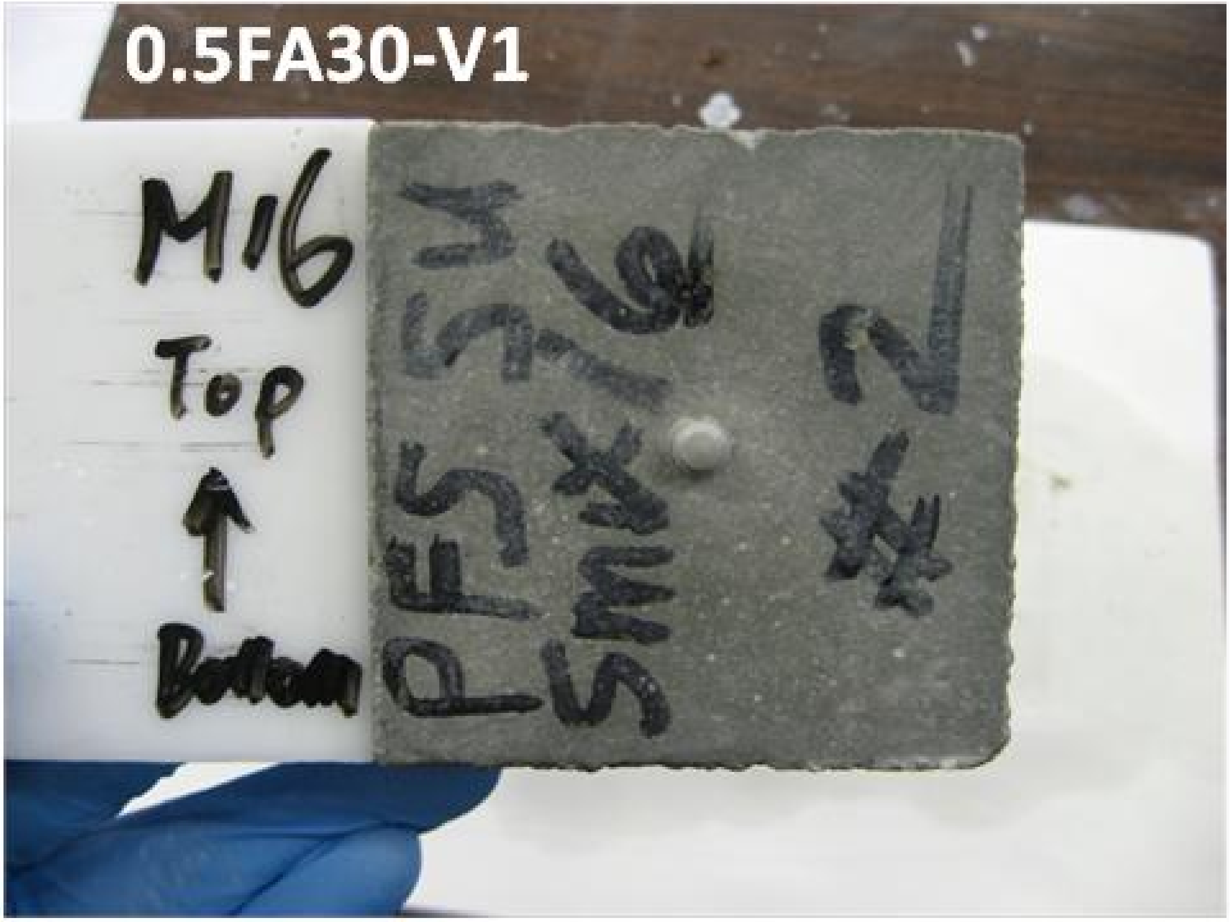
(i)

(j)



(k)

(l)



(m)

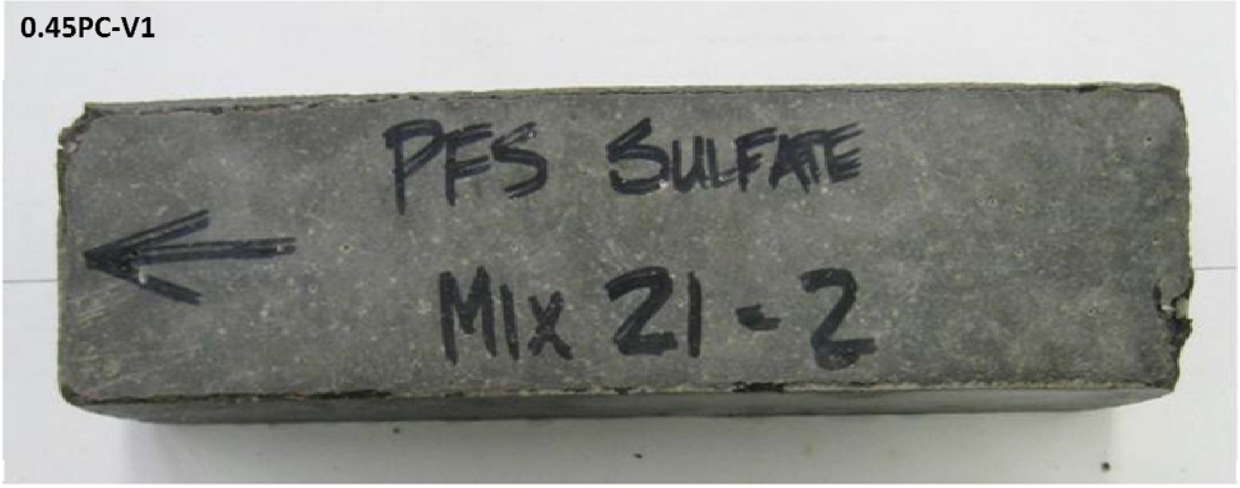
(n)

(o)

(p)


0.6SL50-V1
M20
Top
Bottom
PFS SULFATE MIX 20-2

(q)


0.45PC-V1
PFS SULFATE
MIX 21-2

(r)

(s)

Figure 4.9 USBR Fully Immersed Sample Pictures After 44 m (Mixtures 9-22)
(a) 20% fly ash mixtures, (b) 35% slag cement mixtures, (c) 30% fly ash mixtures, (d) 50% slag cement mixtures, (e) portland cement mixtures (PC-V1 C_3A=3%, PC-V2 C_3A=5%), and (f) – (m) Close up images showing cracking – Mixture IDs are provided in the figures

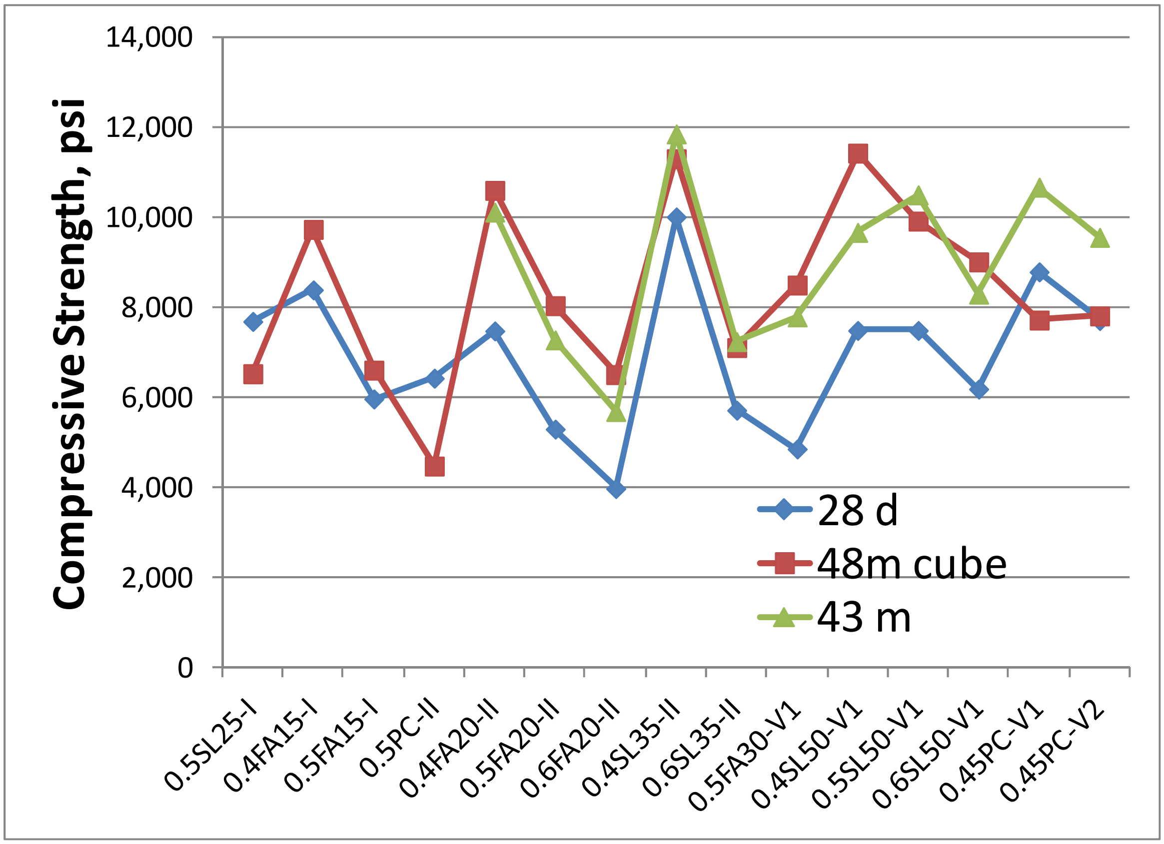


Figure 4.10 Specimens Showing Negligible Strength Deterioration After Long Term Immersion in Sodium Sulfate Solution (48 m results are average of two 3x3 in. cubes cut from a single prism modified by a strength reduction factor of 0.75)

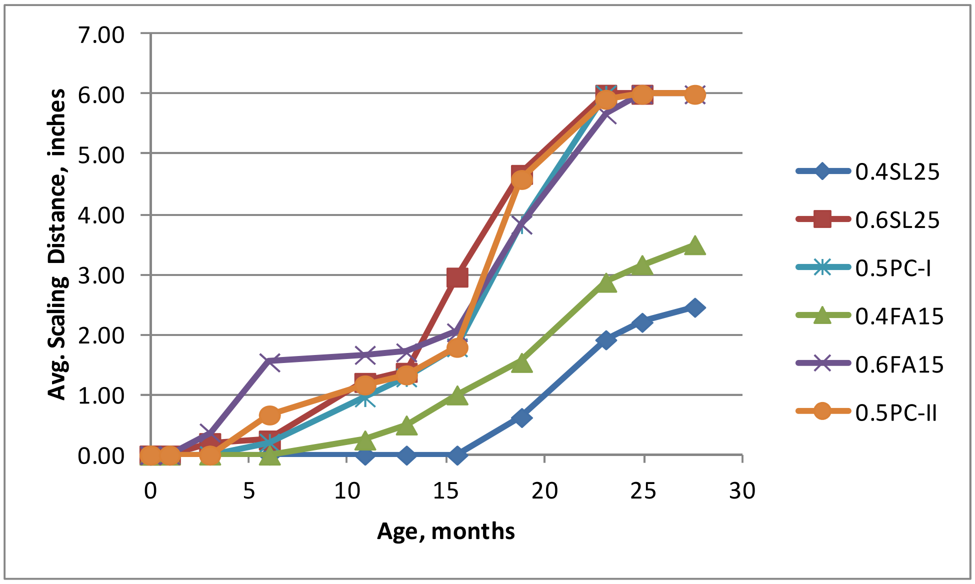


Figure 4.11 USBR 4908 Partially Immersed Specimens - Scaling Distance From Immersion Line vs Exposure Age

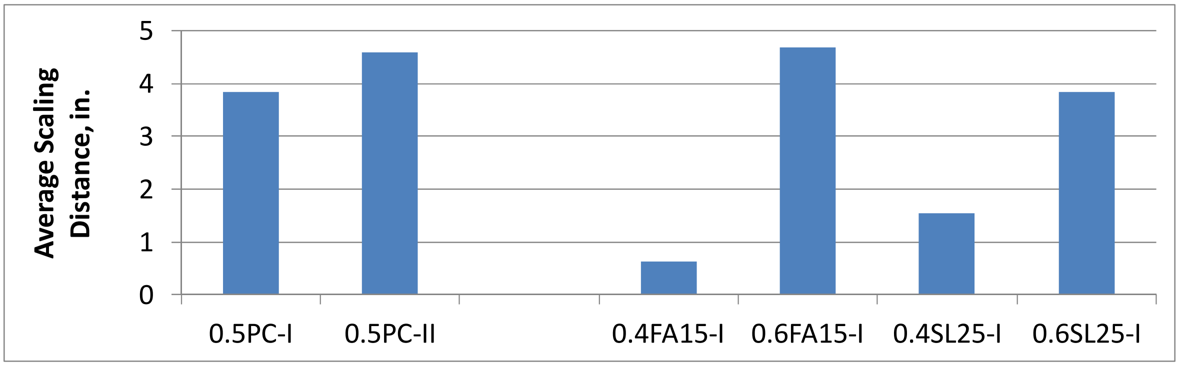
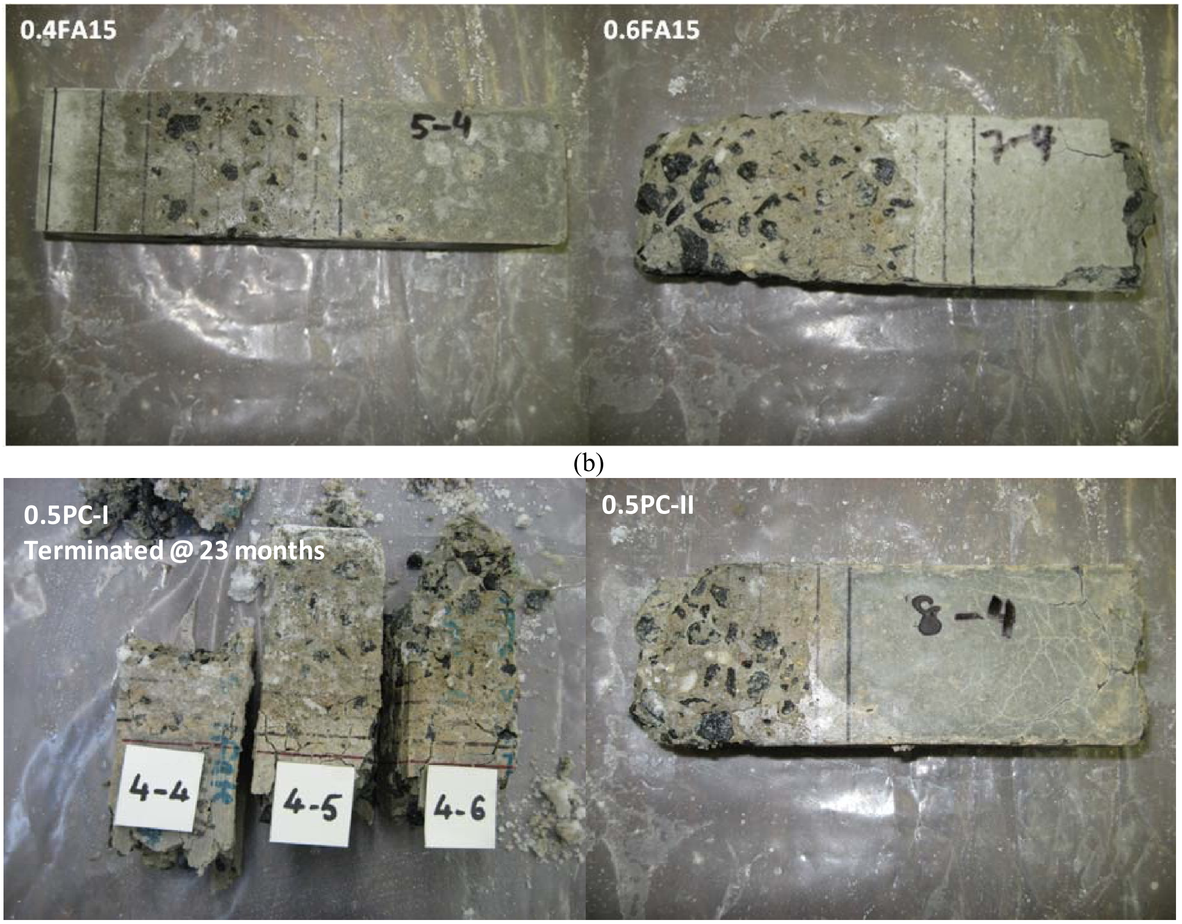


Figure 4.12 USBR 4908 Partially Immersed Specimens – 19 m Scaling Distance Comparison Between PC and SCM Mixtures at Similar W/CM

(a)

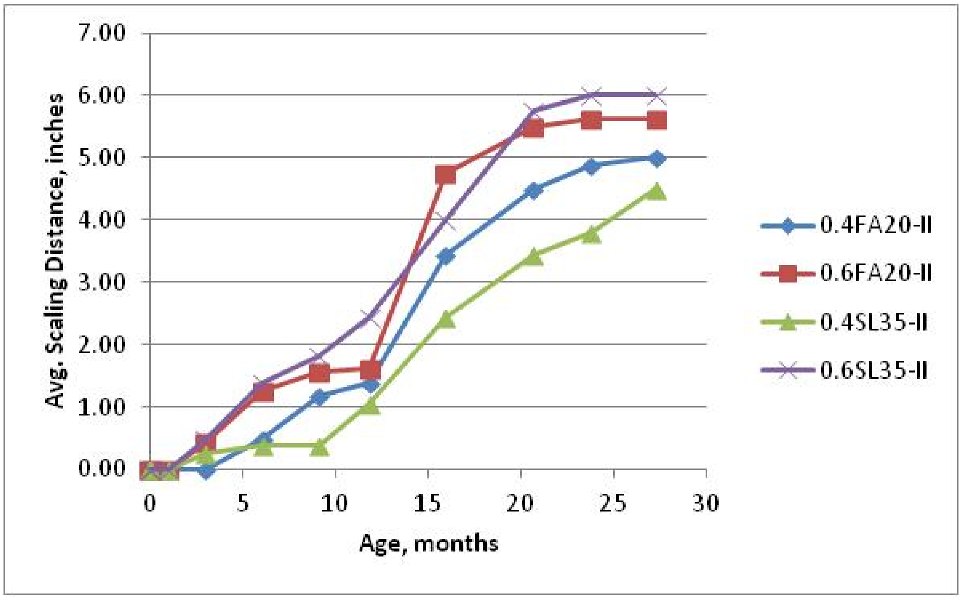


(b)

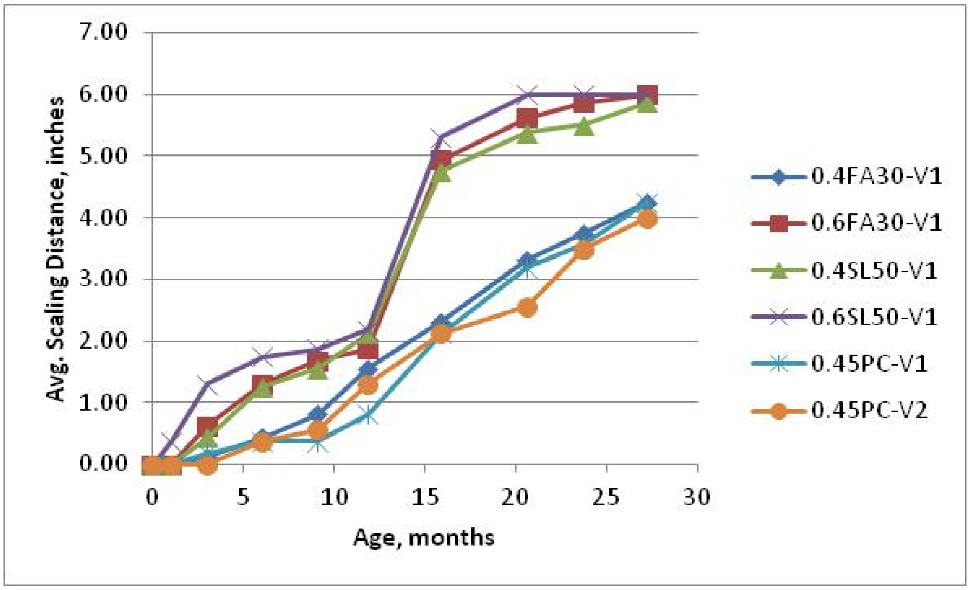
(c)

Figure 4.13 USBR Half Immersed Sample Pictures After 28 m

(a) 25% slag cement mixtures, (b) 15% fly ash mixtures, and (c) portland cement mixtures



(a)



(b)

Figure 4.14 USBR 4908 Partially Immersed Specimens - Scaling Distance From Immersion Line vs Exposure Age (a) SCM Mixtures with Type II Cement (b) Mixtures with Type V Cements

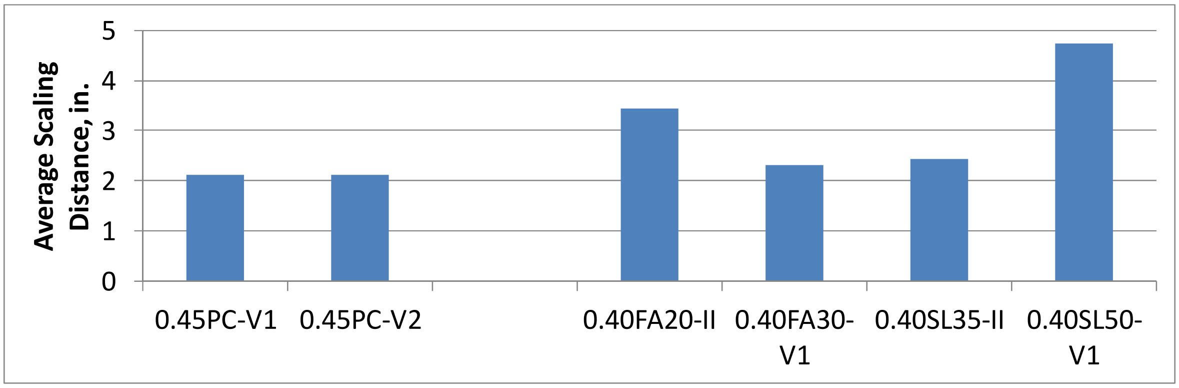


Figure 4.15 USBR 4908 Partially Immersed Specimens – 16 m Scaling Distance Comparison Between PC and SCM mixtures at Similar W/CM


0.4FA20-II
9-3
0.6FA20-II
11-4

(a)


0.4SL35-II
12-4
0.6SL35-II
14-3

(b)


0.4FA30-V1
#3
0.6FA30-V1
17-4

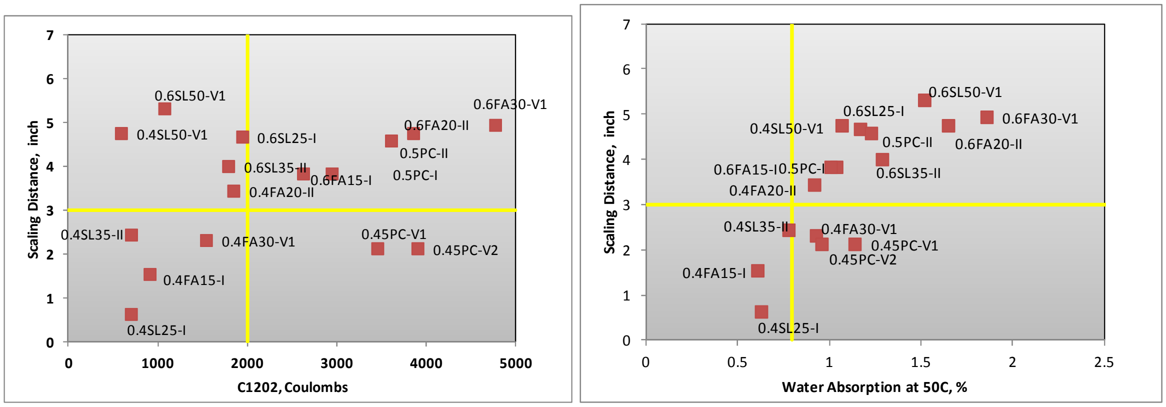
(c)

(d)

(e)

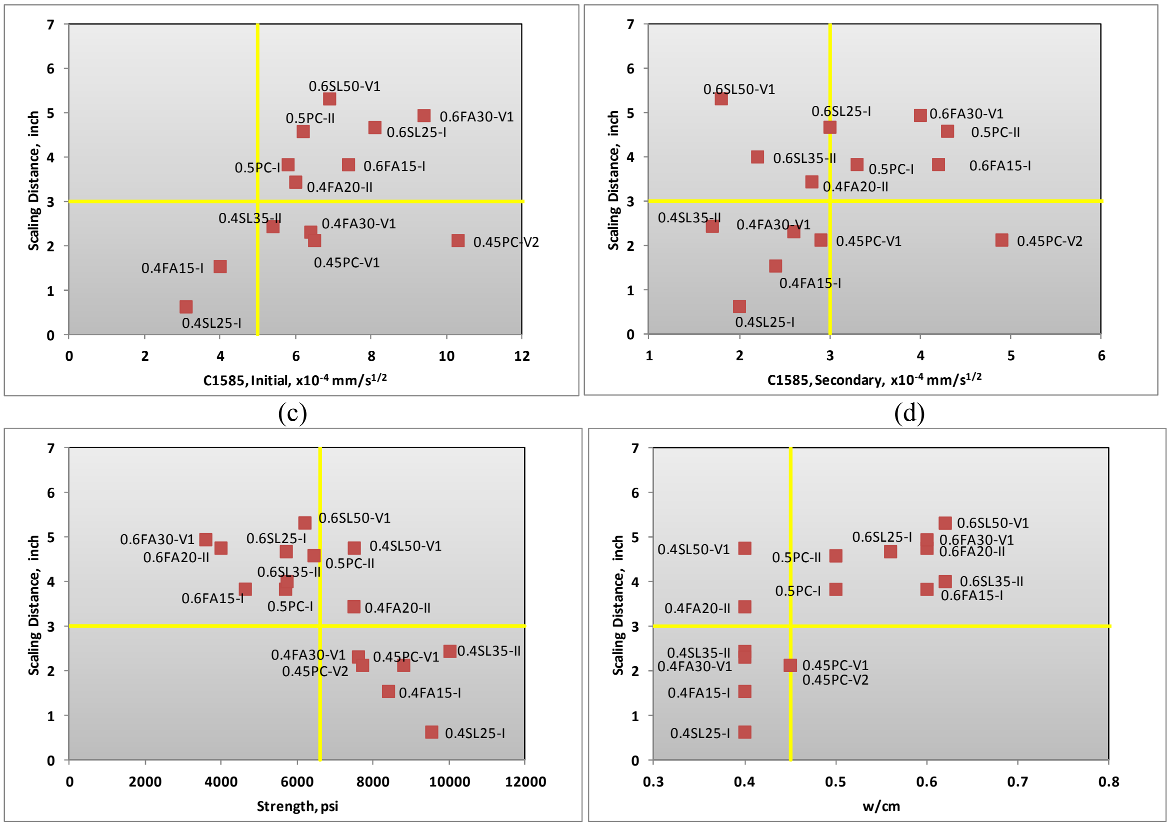
Figure 4.16 USBR Half Immersed Sample Pictures After 24 m

(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



(a)

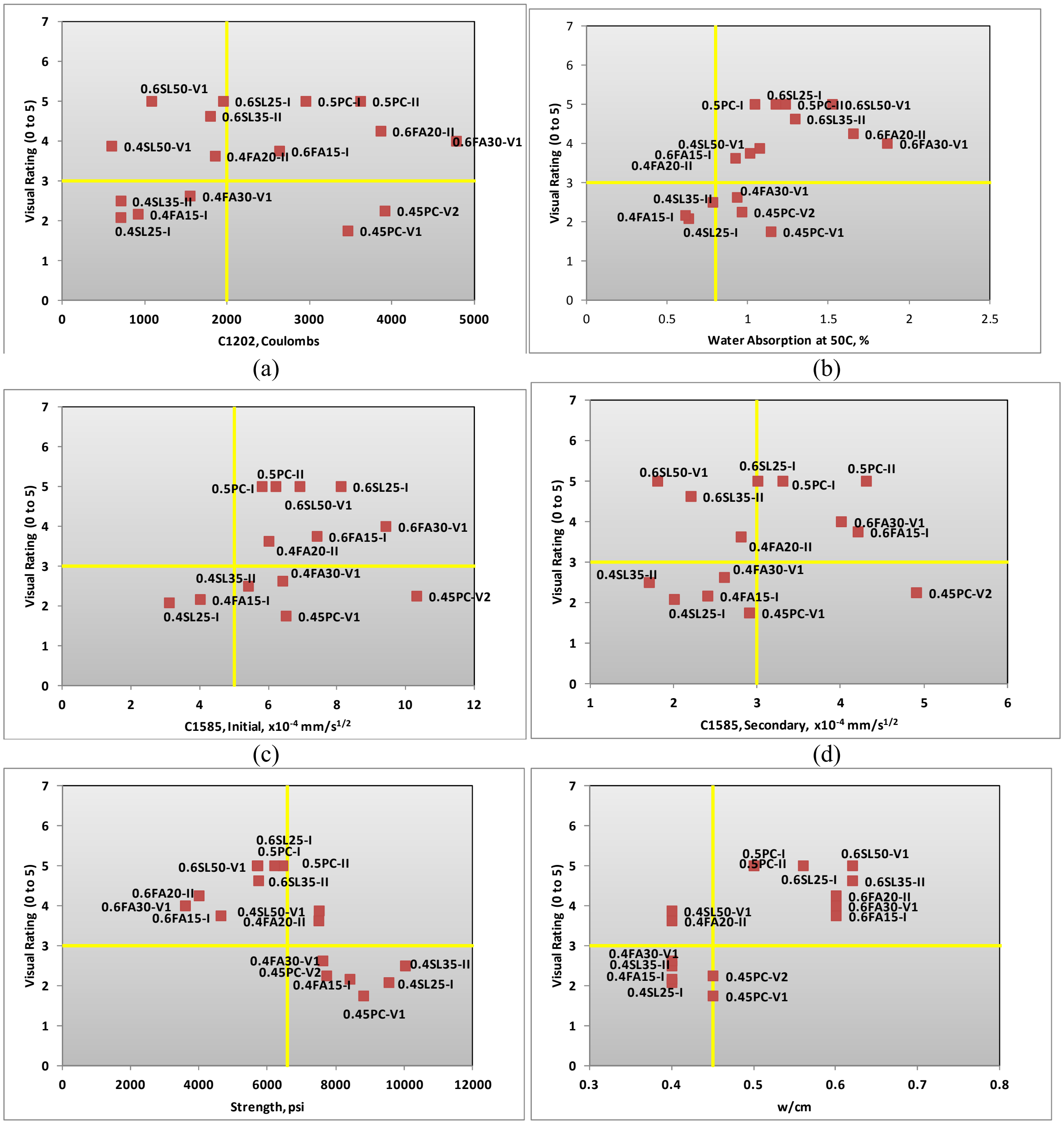
(b)



(c) (d)

(e) (f)

Figure 4.17 USBR 4908 Partially Immersed (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

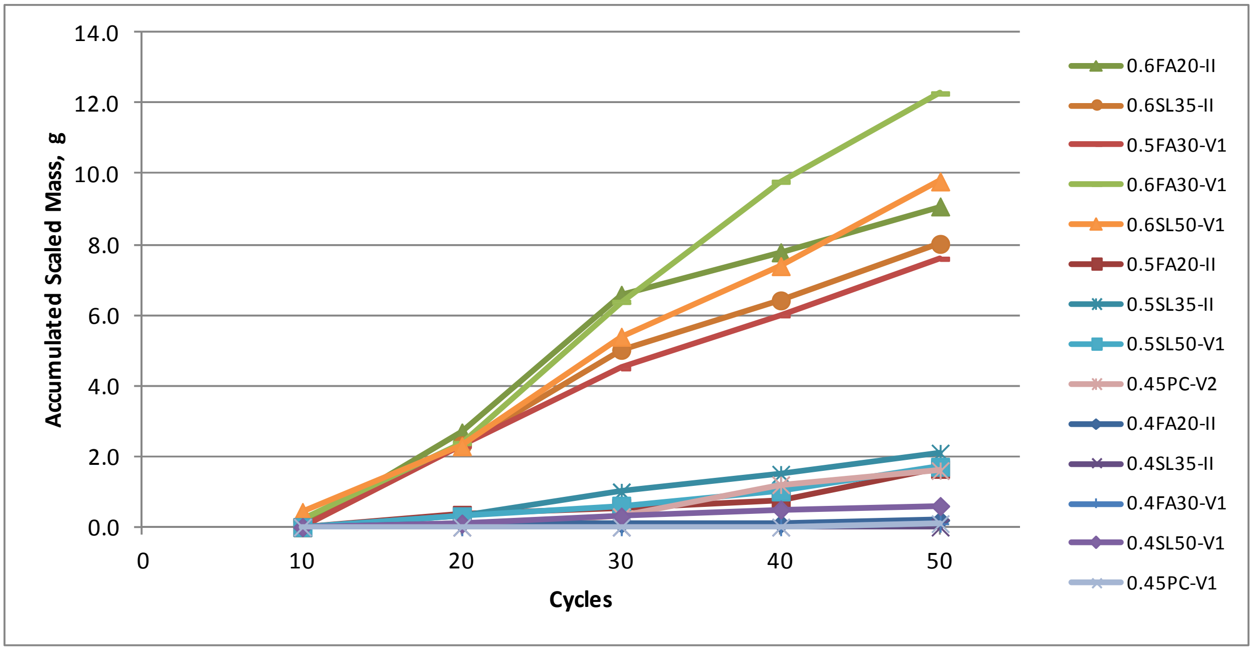


(a) (b)

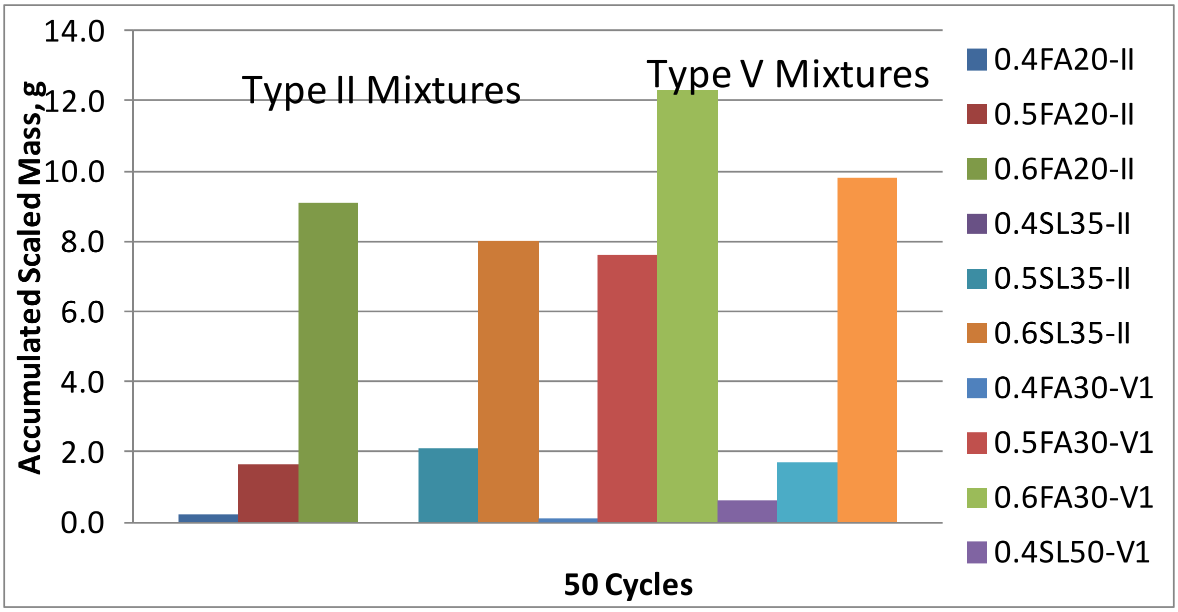
(c) (d)

(e) (f)

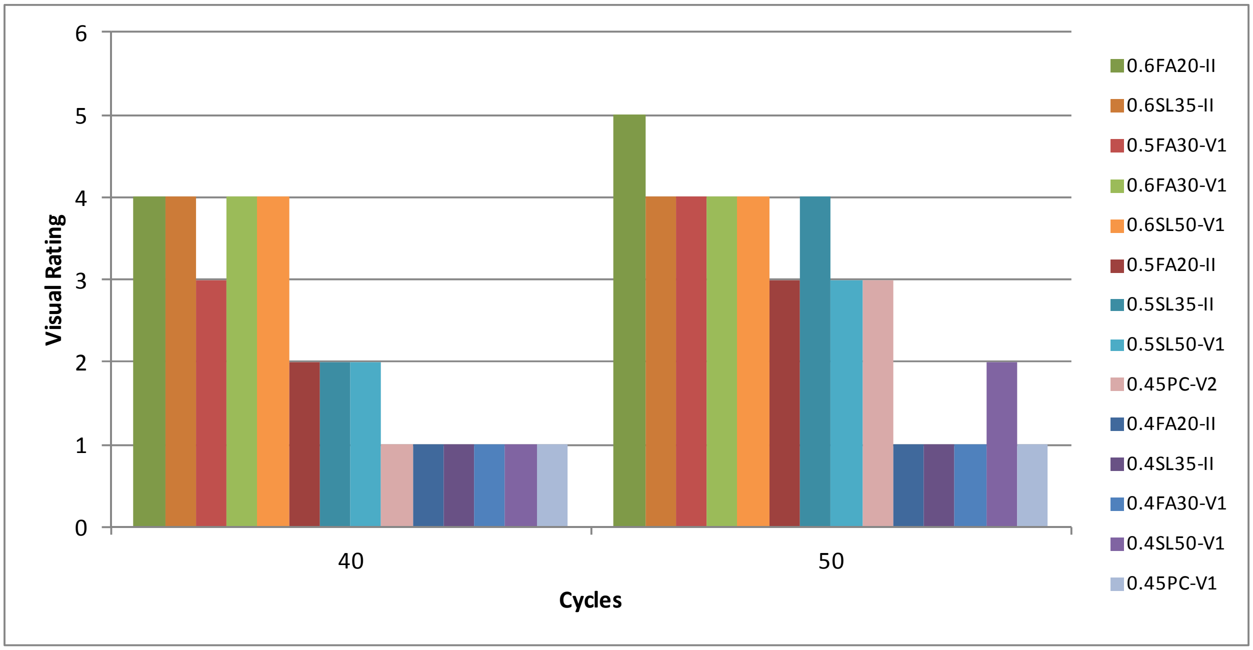
Figure 4.18 USBR 4908 Partially Immersed (a) – (d) Correlation Between Visual Rating and 56d Standard Cured Rapid Index Test Results, (e) – (f) Correlation Between Visual Rating and 28d Compressive Strength, W/CM Respectively



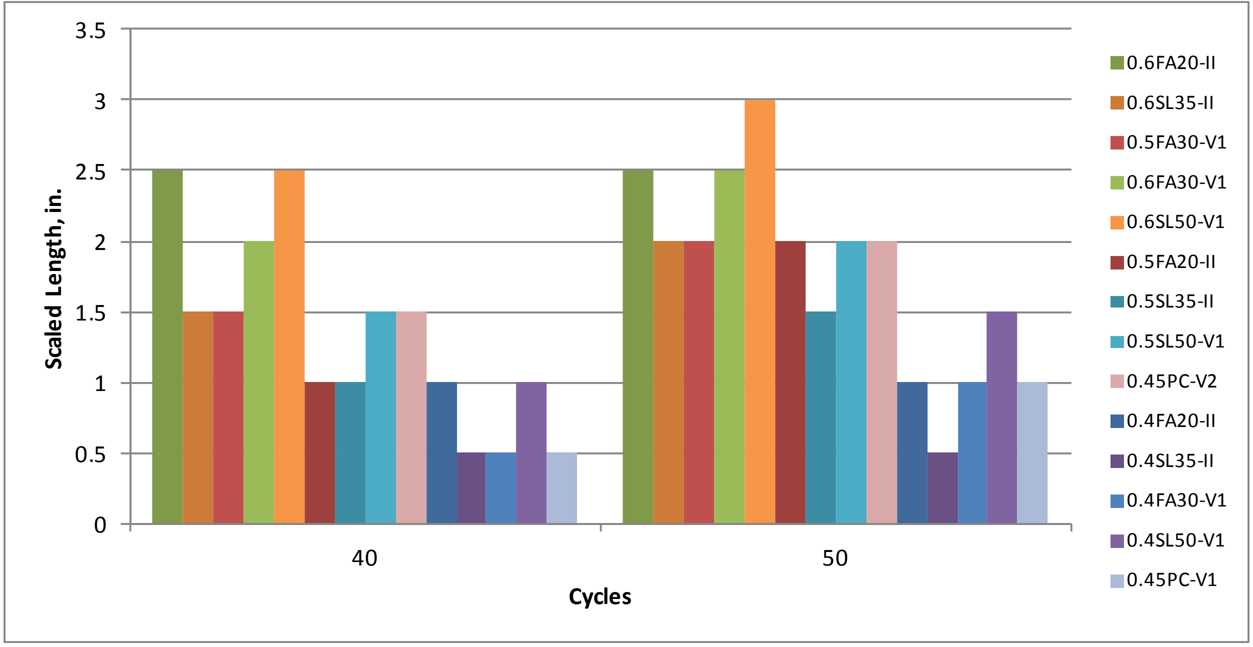
(a) Accumulated Scaling



(b) Accumulated Scaling After 50 cycles

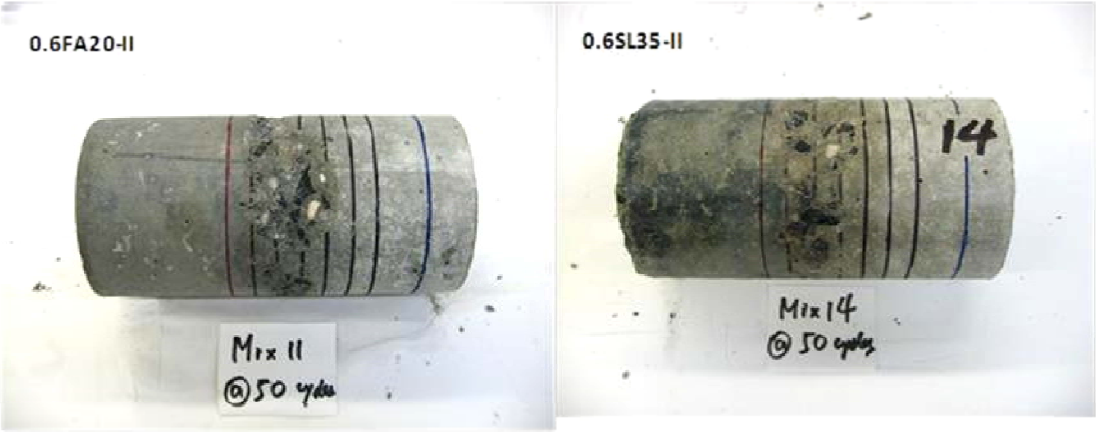


(c) Visual Rating



(d) Scaled Length

Figure 4.19 Observed Deterioration Due to Physical Salt Attack in the New Test Procedure


0.6FA20-II
Mix 11
@50 cycles
0.6SL35-II
14
Mix 14
@50 cycles

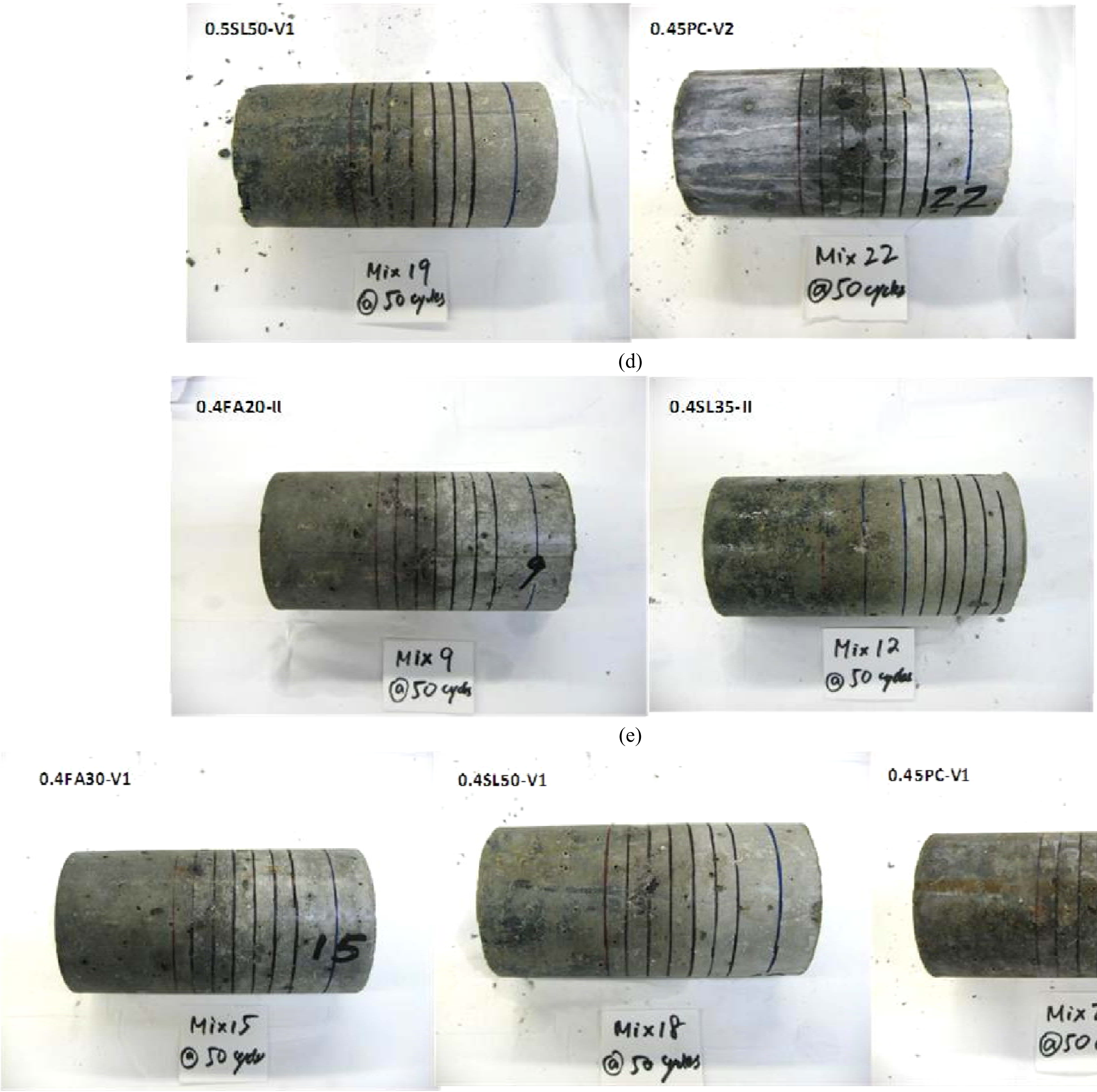
(a)


0.5FA30-V1
Mix 16
@50 cycles
0.6FA30-V1
Mix 17
@50 cycles
0.6SL50-V1
Mix 20
@50 cycles

(b)


0.5FA20-II
Mix 10
@50 cycles
0.5SL35-II
13
Mix 13
@50 cycles

(c)

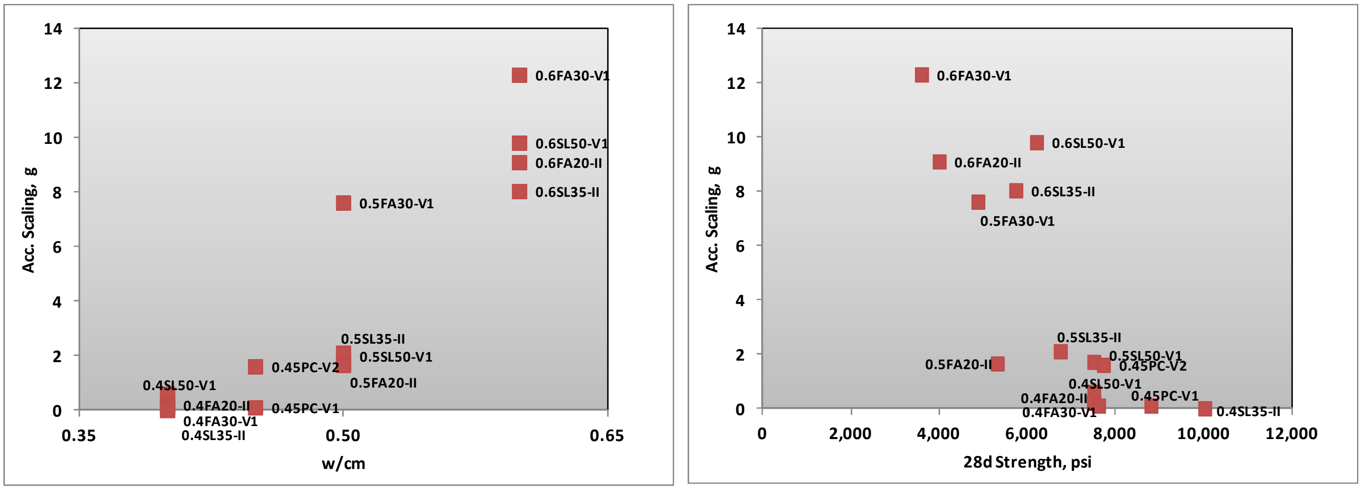


(d)

(e)

(f)

Figure 4.20 Sample Pictures of Physical Salt Attack in the New Test Procedure After 50 Cycles (a) and (b) Total Accumulated Scaling (7.6 to 12.3 g); (c) and (d) Total Accumulated Scaling (1.6 to 2.1 g); (e) and (f) Total Accumulated Scaling (0 – 0.6g)



(a) (b)

Figure 4.21 Physical Salt Attack in the New Test Procedure After 50 Cycles (a) Correlation Between Accumulated Scaling and W/CM, (b) Correlation Between Accumulated Scaling and 28d Compressive Strength

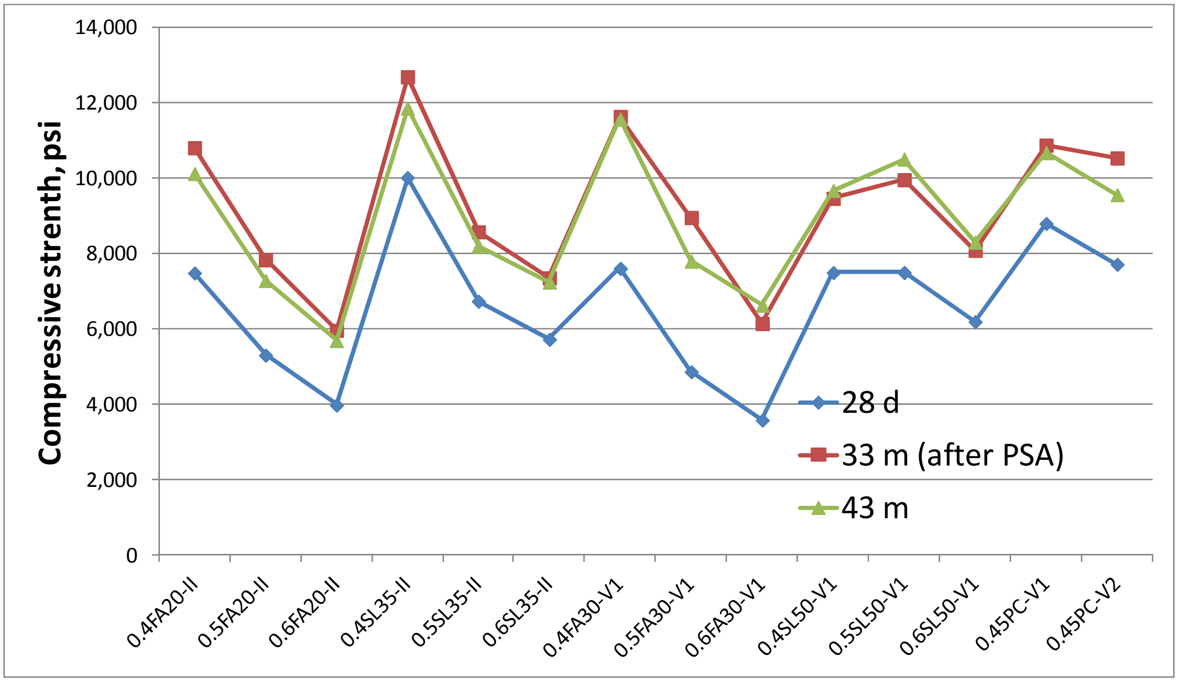


Figure 4.22 Specimens Showing Negligible Strength Deterioration After the New Rapid Physical Salt Attack Test