Criteria for Concrete Mixtures Resistant to Chemical Sulfate Attack

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SYNOPSIS:
This paper presents research on the sulfate resistance of concrete mixtures as it relates to ACI 318 Code requirements for sulfate resistance. The study evaluates the provisions of ACI 318 for various concrete mixtures containing sulfate resisting portland cements and supplementary cementitious materials with w/cm varying between 0.40 and 0.60. The sulfate resistance of concrete mixtures was evaluated using prolonged exposure in a concentrated sulfate solution in accordance with USBR Test 4908. The results on the concrete evaluation reveal that the ACI requirements are considerably conservative for most concrete mixtures that contain a sulfate resisting cementitious system with supplementary cementitious materials. Sulfate resisting portland cements did not perform as well in the associated exposure class defined in ACI 318. While a performance-based alternative to the requirement for a maximum w/cm was attempted, no clear criteria could be achieved. The paper proposes alternative criteria to those in ACI 318 for sulfate resistance based on the performance of concrete mixtures evaluated in this study.

KEYWORDS:
ACI 318, chemical sulfate attack, Code requirements, specifications, sulfate resistance

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INTRODUCTION

Exposure of concrete members to water-soluble sulfates from external sources can be a significant cause of deterioration. This type of durability problem is typically prevalent where higher sulfate concentrations are present in soil or water in contact with concrete. It can also be an issue in facilities that generate sulfate bearing solutions that will come in contact with concrete. There are three types of phenomenon observed when concrete members are exposed to an external source of sulfates[1] – chemical sulfate attack[2]; physical sulfate attack resulting from crystallization of some salts of sulfate[3, 4, 5]; and thaumasite formation when concrete mixtures contain finely divided carbonates[6, 7].

This paper is limited to chemical sulfate attack, often referred to as *classical* sulfate attack. Chemical sulfate attack is governed by two factors[1, 8, 9]:

1. Type and characteristics of cementitious materials – Increased quantity of tri-calcium aluminate phase, C_3A, in portland cement decreases its sulfate resistance. Aluminate phases in some supplementary cementitious materials (SCM), such as in some Class C fly ash[10], or higher alumina content in slag cement[11], can contribute to sulfate attack.
2. Permeability of concrete – Water-soluble sulfates penetrate concrete by a combination of capillary sorption and diffusion. Concrete mixtures with a low w/cm and containing SCM reduce the rate of penetration of sulfates into the concrete.

The ACI 318 Building Code, ACI 318-14[12], limits its durability provisions to chemical sulfate resistance in the sulfate exposure category. It defines sulfate exposure classes based on the concentration of sulfate in soil or water concrete members will be exposed to. The requirements for concrete mixtures that will be exposed to these exposure classes are summarized in Table 1**.** ACI 318-14 also permits a cementitious materials combination that has been qualified when tested by ASTM C1012[13] with expansion criteria listed in Table 1. Service records of acceptable performance of concrete mixtures containing SCM are also permitted in lieu of ASTM C1012 tests.

The objective of this research project was to evaluate the current requirements for sulfate resistance in ACI 318 and to evaluate whether a rapid index test that provides an indicator of the permeability of concrete could be proposed as an alternative to the maximum w/cm. 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 and this benefit from using SCMs is not accounted for in the current provisions.

The sulfate resistance of concrete was evaluated by a long-term immersion test used by the US Bureau of Reclamation (USBR) in their research work on sulfate resistance. A modified version of USBR 4908[14] test was used in this study. The level of sulfate resistance of concrete in USBR 4908 was related to the performance of cementitious materials in ASTM C1012 and other mixture characteristics. Based on these comparisons alternative requirements for chemical sulfate resistance are proposed.

MATERIALS AND MIXTURES

The following materials were used:

- ASTM C150[13] Type I portland cement (PC-I) with C_3A = 12%;
- ASTM C150 Type II portland cement (PC-II) with C_3A = 8%;
- ASTM C150 Type V portland cement (PC V-1) with C_3A = 3%,
- ASTM C150 Type V portland cement (PC V-2) with C_3A = 5%,
- ASTM C618[15] Class F fly ash (FA) – CaO = 0.7%
- ASTM C989[15] Grade 120 Slag Cement – Al_2O_3 = 11.8%
- ASTM C778[13] standard graded sand for C1012 tests
- ASTM C33[15] natural sand, fineness modulus 2.88
- ASTM C33 No. 57 crushed stone coarse aggregate
- ASTM C494[15] Type A polycarboxylate-based water reducing admixture and Type F polycarboxylate-based high range water reducing admixture

ASTM C1012 was conducted on mortar mixtures with selected combinations of cementitious materials as indicated in Table 2.

Twenty two non air-entrained concrete mixtures were made with ASTM C150 Types I, II and V portland cements, varying quantities of slag cement and Class F fly ash, and with w/cm varying between 0.40 and 0.60. The mixtures were evaluated in two separate series. Mixture parameters were selected for different levels of sulfate resistance and to attempt to characterize mixture performance within the four ACI 318 exposure classes for sulfate resistance. Mixture designations were provided to denote the type of mixture: "w/cm; SCM type; SCM quantity: and portland cement type". Mixtures with only portland cement are denoted with "PC". Mixture designations and parameters are provided in Table 3.

TEST PROCEDURES

Several cementitious material combinations were tested for sulfate resistance in accordance with ASTM C1012. Mortar bars were immersed in 5% sodium sulfate solution after achieving the minimum strength required by the test method. This method uses a fixed w/cm of 0.485 and its purpose is to evaluate the cementitious materials for sulfate resistance. Expansion criteria in ACI 318 extend to 18 months for the more severe exposure class. In this study, the duration of immersion in sulfate solution was extended to 36 months. Mixture parameters and test results for ASTM C1012 are provided in Table 2.

The concrete mixtures were mixed in a revolving drum laboratory mixer in accordance with ASTM C192[15]. A dosage of 3 oz/cwt. (195 mL/100 kg) of the Type A water-reducing admixture was used for all concrete mixtures. The dosage of the Type F high-range water-reducing admixture was varied to attain a target slump between 4 and 7 in. (100 and 175 mm).

Fresh concrete was tested for slump in accordance with ASTM C143[15], temperature in accordance with ASTM C1064[15], air content by the pressure method in accordance with ASTM C231[15], and density in accordance with ASTM C138[15]. The gravimetric air content was also calculated in accordance with ASTM C138.

Compressive strength of test specimens from the concrete mixtures was tested in accordance with ASTM C39[15]. The strength reported is the average of two 4 × 8 in. (100 × 200 mm) cylindrical specimens at an age of 28 days.

From the concrete mixtures, samples were prepared to measure the transport properties of concrete mixtures. Only results of the rapid chloride permeability tests, ASTM C1202[15], are reported here. For these tests 4 × 8 in. (100 × 200 mm) cylindrical specimens were cast. Specimens were subjected to three curing procedures and durations:

- Accelerated curing, in accordance with ASTM C1202, and tested at an age of 28 days;
- Moist cured and tested at an age of 56 days; and

- Moist cured and tested at an age of 1 year.
- The top 2 in. (50 mm) from the finished surface of the cylinder was tested. Results reported are the average from two specimens.

The sulfate resistance of concrete mixtures was evaluated using USBR 4908. Method B involves immersion of test specimens in 10% sodium sulfate solution. Method B was used with some variations on the specimen type and pre-conditioning prior to immersion. 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. In this study 3 × 3 × 11¼ in. (75 × 75 × 280 mm) concrete prism specimens were used. The specimens were moist cured for 28 days followed by air drying for 28 days before immersion in the solution. The specimens were immersed in the sulfate solution for 48 months or until it had experienced significant expansion or deterioration. The USBR has used a failure criterion as expansion that exceeds 0.5% and this was found to correlate with about 40% loss in dynamic modulus of elasticity[16]. The USBR test uses 3 × 6 in. (75 × 150 mm) cylinders as opposed to the prismatic specimens used in this study. Periodic measurements of length change, mass change, and visual rating of specimen condition were performed. For each condition, results reported are the average of two specimens.

At the termination of the immersion period of the concrete specimens in the sulfate solution, visual rating of specimen condition was observed by three laboratory personnel with the following guidelines:

- 0 – considerable cracking and spalling of concrete at corners and edges
- 1 – Moderate cracking; some loss of concrete due to spalling; and damage at edges
- 2 – Moderate cracking and edge damage but no loss of concrete due to spalling
- 3 – Minor cracking and no loss of concrete.

The impact of sulfate attack on the strength for some of the concrete mixtures was also evaluated. After the immersion period two 3 × 3 in. (75 × 75 mm) cubes were obtained from a single prism for each mixture. The cubes were tested in compression and the measured average strengths were modified by a correction factor of 0.75 to estimate the cylinder strength from that measured on the cubes. Additionally, strength of cylinders moist cured for 43 months was also measured.

Additional details of concrete mixture proportions, fresh concrete and other transport indicator tests are reported elsewhere[17].

RESULTS AND DISCUSSION

Results of ASTM C1012 Tests

The cementitious material combinations and the expansion results for the 10 mortar mixtures tested in accordance with ASTM C1012 tests reported in Table 2 and illustrated in Figure 1. The mixture parameters were selected to reflect a range of sulfate resistance of the cementitious materials used. These results are consistent with expectations for sulfate resistance. ACI 318 criteria for C1012 expansion extend to up to 18 months for the most severe exposure class (S3). These tests were continued for 36 months to observe if any later age expansion occurred. As expected, expansion decreased when the SCM quantity increased and/or the C_3A content of the portland cement decreased. Based on the expansion results, the ACI 318 Exposure Class applicable to these cementitious combinations is indicated in Table 2. The expansion associated with the ACI 318 expansion criteria is highlighted in Table 2 and denoted in Figure 1.

Expansion of the mortars with portland cements conform to the applicable ACI 318 exposure classes for cement type. All mixtures with fly ash and slag cement had superior sulfate resistance within the 18-month period and qualify to be used for the most severe Exposure Class S3. One exception is the mixture with 15% fly ash with Type I portland cement, which barely passed the expansion criteria (0.10% at 12 months) for Exposure Class S2 with an expansion of 0.09% at 12 months. The rate of expansion increased after this period. With this exception, all other mixtures containing SCMs had equal to or better sulfate resistance than mixtures with the Type V portland cements used in this study.

Increasing later age expansion is observed for the three sulfate resisting portland cement mixtures. An increasing expansion trends at later ages is observed for mixtures with Type I cement and 15% fly ash and to a lesser extent for the mixtures with Type I cement with 25% slag cement and that with Type II cement with 20% fly ash.

ACI 318 does not permit a Type I portland cement with 12% C_3A to be used for sulfate resistance, unless a cementitious material combination complies with the C1012 expansion criteria. It does permit the use of portland cement with up to 10% C_3A for concrete in seawater exposure (Exposure Class S1) provided the w/cm of the concrete does not exceed 0.40. This recognizes that C_3A improves binding of chlorides from seawater that can beneficially impact corrosion of reinforcing steel.

Concrete Mixtures
The parameters of the concrete mixtures tested in two series and selected test results are provided in Table 3. The test results reported are the 28-day compressive strength, ASTM C1202 results for specimens moist cured for 56 days, and the expansion and visual deterioration ratings for specimens tested by USBR 4908 at the termination of the immersion period or when immersion was terminated due to specimen failure. Immersion of concrete specimens in the 10% sodium sulfate solution was terminated at 48 months.

Expansion—For specimens tested by USBR 4908 all the portland cement mixtures without SCMs had high expansions. Considering an expansion level of 0.05% as failure, the Type I portland cement mixture exceeded this limit at nine months; Type II at 15 months; Type V-1 (3% C_3A) at 30 months; and Type V-II (5% C_3A) at 40 months. These high expansions were associated with considerable deterioration as indicated by the visual rating in Table 3. The rate of deterioration was related to the C_3A content of the portland cement used in these mixtures.

In Series 1 the concrete mixtures contained lower quantities of SCM (15% fly ash and 25% slag cement) with Type I portland cement. The expansion and visual deterioration increased as the w/cm of the concrete mixtures increased. The expansion for the mixtures containing SCM in Series 1 at a w/cm of 0.60 exceeded the 0.05% expansion level at around 16 months. The mixtures containing SCM at a w/cm of 0.40 performed extremely well for the duration of the test.

In Series 2, with higher quantities of SCMs and sulfate resisting portland cement, the higher expansion and level of deterioration is evident with increase in w/cm but differences are not that significant, with one exception. Mixture 0.6SL35-II showed the highest expansion and level of deterioration. This mixture exceeded the 0.05% expansion limit at about 42 months and there was modest visual deterioration of the specimens. The six mixtures containing Type V cement (V-1) with SCMs at all w/cm tested showed the lowest level of visual deterioration.

These data indicate that the mixtures with SCMs and Type I portland cement in Series 1 were less sulfate resistant than those in Series 2 with the Type II and Type V portland cements, as expected. The exceptions are for the mixtures in Series 1 with w/cm at 0.40.

Change in Mass—The change in mass of concrete specimens immersed in the sulfate solution is not reported here. The specimens were air-dried for 28 days prior to immersion and an increase in mass was observed for all mixtures due to absorption of the sulfate solution. Mixtures with a higher w/cm had a higher gain in mass. When deterioration progressed to the point of significant cracking, the rate of mass gain increased and subsequent spalling resulted in a loss in mass. Mass loss was primarily due to the corners of the prisms breaking off. Qualitatively, the specimen deterioration and increase or loss of mass generally corresponded to when the specimens exceeded the expansion limit of 0.05%. One exception was the 0.5PC-II mixture which had high expansion without any spalling and an associated decrease in mass.

Exposure Classification—In Table 3, Exposure Classes are assigned to the different concrete mixtures. In column titled “C1012”, the Exposure Class for the cementitious materials are listed as indicated in Table 2. The Exposure Class in the column titled “318” is based on the requirements in ACI 318. These are based on the C1012 expansion and the w/cm of the concrete mixtures. Sulfate resistance of the concrete mixtures evaluated in this study are assigned Exposure Classes in column titled “4908” based on their performance in the prolonged immersion as tested by USBR 4908. The assigned Exposure Class is based on the expansion level and the visual condition of the specimens represented by the numerical visual rating. Concrete mixtures tested by USBR 4908 that were categorized in Exposure class S0 exceeded the expansion level of 0.05% in 18 months; while mixtures categorized in Exposure Class S1 exceeded this expansion after 44 months. Concrete mixtures categorized as Exposure Class S2 and S3 categories had expansions less than 0.04% at 48 months. This assignment of Exposure Class for the concrete mixtures permits a comparison of the requirements for concrete mixtures in ACI 318 and the sulfate resistance of concrete mixtures evaluated by USBR 4908. The mixtures where the exposure classification differs between ACI requirements and the performance of concrete mixtures in USBR 4908 are highlighted in the last two columns of Table 3.

In three cases the performance of the concrete mixtures in USBR 4908 was inferior to that expected by the ACI 318 requirements – the Exposure Class assigned from the USBR 4908 results suggest that these mixtures should be used in a less severe sulfate Exposure Class than what would be assigned in accordance with ACI 318. These were the portland cement mixtures (Types II, V-1, and V-2) without SCM.

In nine cases the performance of the concrete mixtures in USBR 4908 was superior to that expected by the ACI 318 requirements – the Exposure Class assigned from the USBR 4908 results suggest that these mixtures can be used at a more severe sulfate Exposure Class than what would be assigned in accordance with ACI 318. Eight of these nine mixtures contained supplementary cementitious materials and sulfate resistant cements (Type II and V). Of these, 4 cases are mixtures with a w/cm at 0.60 that likely will not be an acceptable requirement in ACI 318. However, the data illustrate that sulfate resistance is improved by the use of SCMs due to the increased sulfate resistance of cementitious material system (C1012 expansion) and an associated reduction of the permeability of concrete. The impact on the permeability of concrete can be surmised from the ASTM C1202 results in Table 3. In this regard, w/cm as a controlling requirement for sulfate resistance in ACI 318 may be lacking. These data suggest that a higher w/cm may be permitted with cementitious material system that is demonstrated to be more sulfate resistant and improves the permeability of concrete. In Series 2, the mixtures with a w/cm of 0.50 would comply with ACI 318 exposure class S1 but performed well enough to be used in exposure class S2 or even in S3 in one case. Mixture 0.40FA15-1 showed moderate sulfate resistance (S2) with the cementitious materials in ASTM C1012. This is a combination of the higher C_3A in the portland cement (12%) and the lower quantity of fly ash. However with a w/cm of 0.40, this mixture performed very well in the USBR 4908 test and could qualify to be used for Exposure Class S3.

It is noted that at this time ACI 318 provisions for sulfate resistance do not require concrete mixtures to comply with a maximum w/cm of 0.40. In this study, all concrete mixtures with a w/cm of 0.40 contained SCMs and performed very well to qualify to be used in Exposure Class S3 even when used with lower quantity of slag cement or fly ash and with the Type I portland cement (12% C_3A). There is a proposal in ACI 318, which would make it consistent with Canadian Standard CSA A23.1[18], to permit Type V portland cement and mixtures that meet the C1012 expansion criteria for Exposure Class S2 to be used for Exposure Class S3 with a maximum w/cm of 0.40. This study did not include a Type V portland cement concrete mixture without SCMs at a w/cm of 0.40. However, since both 0.45 w/cm Type V mixtures without SCMs performed only to a sulfate exposure level of S1 in the USBR 4908 test it is unlikely that a 0.40 w/cm Type V mixture without SCM would have performed to a sulfate exposure level of S3. But results of this study do support this revision for mixtures that contain SCMs.

<u>Permeability</u>—One of the goals of this research was to evaluate whether a rapid test that provides an indicator of the permeability of concrete could be used as an alternative to w/cm. The results of 56-day moist cured specimens tested by ASTM C1202 are reported in Table 3. This may be considered a limiting test age for mixture qualification. It also reflects the age of the specimens when they were immersed in the sulfate solution for USBR 4908 tests. No clear relationship could be established between the sulfate resistance of concrete mixtures in USBR 4908 and an indicator of permeability for ASTM C1202 results obtained at 56 days. For this reason, no performance-based test criterion is proposed as an alternative to the max w/cm.

Additional ASTM C1202 tests were performed on specimens that were subjected to the accelerated curing as defined in ASTM C1202 and specimens moist cured for 1 year. These results are illustrated in Figure 2. For the portland cement mixtures the change in the charge passed is not significant between 56 days and 1 year. The average reduction of the charge passed is about 15%. For the mixtures with slag cement the reduction in the charge passed between the same ages is about 35%. However, for the mixtures with fly ash, there is a considerable improvement in this permeability indicator – the reduction in charge passed is about 75% between 56 days and 1 year. In this regard fly ash mixtures may not demonstrate low permeability characteristics at early ages but this considerably improves with age and continued curing. In this evaluation, accelerated curing did not have as much of an impact on the C1202 result compared to a longer moist curing period. From a practical standpoint, it is likely that concrete will be subjected to sulfate exposure at the time of construction – such as a footing or foundation in sulfate soils. But the section size and water-soluble sulfate concentration is not likely to cause deterioration to the level observed in the

USBR test and the sulfate resistance of these concrete members will improve with age. In some cases, such as in environmental engineering structures, the exposure to sulfates may be at a later age, when the sulfate resistance of mixtures containing SCMs can be expected to be at a higher level.

Compressive Strength—A comparison of compressive strength of cylinders moist cured for 28 days and 43 months, and cubes extracted from USBR 4908 test prisms after 48 months of exposure are illustrated in Figure 3 for selected mixtures. The strength of USBR 4908 specimens for the 0.5PC-II, 0.45PC-V1 and 0.5SL25-I mixtures were between 12% and 30% lower than their 28 day strengths. The 0.45PC-V2 mixture had about the same strength at both ages. The strength of the remaining 11 mixtures immersed in sulfate solution for 48 m were on average 40% higher than the 28-day strength. When the strength of USBR 4908 specimens is compared to the strength of cylinders moist cured for 43 months, these are about the same or slightly higher except for the two 0.45PC-V mixtures – these two mixtures had about 23% lower strength. The reduction in strength is consistent with the excessive deterioration observed for these mixtures. For the mixtures with a high sulfate resistance no loss in strength is observed.

PROPOSED CRITERIA

Chemical sulfate attack requires ingress of sulfate ions into the concrete and a cementitious system that is vulnerable to chemical sulfate attack. The results in this study illustrate that using a maximum w/cm as a primary criterion discounts the benefits of using SCMs on the permeability characteristics of concrete. 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[19]. It further suggests that with a more sulfate resistant cementitious material combination with SCMs, a higher w/cm can be used and provide the necessary sulfate resistance for different Exposure Classes. Concrete mixtures at a higher w/cm and lower strength are typically used for footings and foundations of structures. Permitting concrete mixtures that are sulfate resistant with a higher w/cm affords a more economical mixture that will be easier to place for these applications. This change is proposed for concrete that will be assigned to Exposure Classes S1 and S2. To remain conservative, however, this recommendation is not extended to concrete members that will be assigned to Exposure Class S3. This is supported by the performance of concrete mixtures with w/cm of 0.50 in Series 2.

For Exposure Class S3, C1012 testing for 18 months is a considerably long period. Blended cements complying with ASTM C595 and C1157 are tested for a period of 12 months to achieve the HS designation. To shorten the testing period for evaluating cementitious materials, it is proposed that mixtures meeting the C1012 criteria for Exposure Class S2 (0.1% at 12 months) can be used for concrete mixtures assigned to Exposure Class S3 if the maximum w/cm is 0.40. The mixture should contain SCMs that improve the sulfate resistance. It is further recommended, based on this study, that mixtures with Type V portland cement without SCMs at a maximum w/cm of 0.40 not be permitted for Exposure Class S3.

Based on the results of this study, these criteria for sulfate resistance are proposed. These recommendations are summarized in Table 4.

Exposure Class S1

- Type II portland cement and max w/cm of 0.50 (current ACI 318)
- Blended cement with MS designation and max w/cm of 0.50 (current ACI 318)
- Cementitious materials with ASTM C1012 expansion <0.10% @ 6 m (S1) and max w/cm of 0.50 (current ACI 318)
- Cementitious materials with ASTM C1012 expansion <0.10% @ 12 m (or <0.05% @ 6 m) (S2) and max w/cm of 0.55. Cementitious materials permitted should be SCM with Type II or Type V portland cements; or blended cements with HS designation without additional SCM (alternative)

Note that in this study, the Type II portland cement mixture at a 0.50 w/cm did not perform well in the USBR 4908 test to be used in Exposure Class S1. However, in the field, the rate of deterioration at a considerably lower concentration of water soluble sulfates will likely reduce the rate of deterioration to provide acceptable service life. With successful past field service records, a Type II portland cement without SCMs could be used for Exposure Class S1. The use of SCMs that improve the sulfate resistance of the cementitious materials is strongly recommended.

Exposure Class S2

- Type V portland cement and max w/cm of 0.45 (current ACI 318)
- Blended cement with HS designation and max w/cm of 0.45 (current ACI 318)
- Cementitious materials with ASTM C1012 expansion <0.10% @ 12 m (or <0.05% @ 6 m) (S2) and max w/cm of 0.45 (current ACI 318)
- Cementitious materials with ASTM C1012 expansion <0.05% @ 12 m and max w/cm of 0.50. Cementitious materials permitted should include SCMs with Type II or Type V portland cements; or blended cement with HS designation with additional SCM (alternative)

It is also noted in this study that the Type V portland cement mixtures at a 0.45 w/cm did not perform well in the USBR 4908 test to be used in Exposure Class S2. With successful past field service records, a Type V portland cement without SCMs could be used for Exposure Class S2. The use of SCMs that improve the sulfate resistance of the cementitious materials is strongly recommended.

Exposure Class S3

- Type V + SCM and max w/cm of 0.45 (current ACI 318)
- Blended cement with HS designation + SCM and max w/cm of 0.45 (current ACI 318)
- Cementitious material with ASTM C1012 expansion <0.1 @ 18 m (S3) and max w/c 0.45; (current ACI 318)
- Cementitious material with ASTM C1012 expansion <0.1 @ 12 m (S2) and max w/c 0.40; (alternative)

An exception to the last provision that the concrete mixture should contain SCMs that improve the sulfate resistance of the system. Based on the results of this study, it is recommended that a Type V portland cement without SCMs should not be used. ACI 318 does not specifically permit the use of Type I portland cement for sulfate resistance. It can be used if a cementitious mixture qualifies to the ASTM C1012 expansion criteria. In this study, concrete mixtures with Type I portland cement with SCMs and with a w/cm of 0.40 performed well in USBR 4908. The cementitious mixtures complied with the C1012 expansion criteria for Exposure Class S2. The use of cementitous materials with Type I cement is thereby not restricted in these alternative criteria for Exposure Class S3.

In line with ACI 318, the following minimum specified strengths apply to the max w/cm: 0.40 / 5000 psi (35 MPa); 0.45 / 4500 psi (31 MPa); 0.50 / 4000 psi (28 MPa); and 0.55 / 3500 psi (24 MPa).

The alternative criteria for Exposure Classes S1, S2 and S3 are based on the performance of concrete specimens subjected to long term exposure in concentrated sulfate solution (USBR 4908) in this study. The proposed alternative criteria establishes more consistent assignment of Exposure Classes to concrete mixtures based on the performance in USBR 4908. Even with the proposed alternative criteria, concrete mixtures performed at a higher level sulfate of resistance in USBR 4908 test in five conditions and all these mixtures contained SCMs. Of these, four mixtures with Type II or V portland cement and SCMs were at a w/cm of 0.60 and the performance in USBR 4908 suggest that these could be assigned to Exposure Classes S1 or S2. This suggests some conservatism in the proposed alternative criteria. In three conditions, the concrete mixtures performed at a reduced level relative to that expected by the ACI 318 criteria. In these conditions, concrete mixtures were composed of sulfate resisting portland cement (Type II and V) without SCMs. It is however suggested that if past field service records indicate successful performance, these options could be permitted.

ASTM C1202

No definitive recommendations can be made to replace the maximum w/cm with a specified charge passed requirement determined in accordance with ASTM C1202. Based on Figure 2, even if a conservative specified value of 1000 coulombs was used as a performance-based alternative to w/cm for exposure class S3, it would permit some of the mixtures with slag cement with a w/cm of 0.50 or higher. These mixtures did not perform well enough for exposure class S3 in the USBR 4908 test.

CONCLUSIONS

1. Expansion results on the evaluation of cementitious materials by ASTM C1012 for sulfate resistance was consistent with expectations and ACI 318 provisions.
2. Concrete mixtures evaluated for sulfate resistance with extended exposure in a 10% sodium sulfate solution in USBR 4908 suggest that ACI 318 provisions are conservative for mixtures containing SCMs with good sulfate resistance as determined by ASTM C1012. The mixtures with portland cement and no SCMs did not perform as well as expected by the ACI 318 provisions.
3. The use of w/cm as the primary provision for concrete mixtures in ACI 318 for sulfate resistance does not evaluate the benefits provided by SCMs in reducing the permeability of concrete. This study suggests that for cementitious material combinations with higher sulfate resistance, as determined by ASTM C1012, it might be appropriate to permit a higher w/cm for Exposure Classes S1 and S2. This will permit more economical concrete mixtures with improved ease of placement for foundations and lower load bearing members submerged in sulfate-bearing soil or water.
4. Concrete mixtures at a w/cm of 0.40 with SCMs indicated very high sulfate resistance with prolonged exposure in the USBR 4908 test. It is proposed that mixtures that contain SCMs and comply with the ASTM C1012 expansion criteria for Exposure Class S2 can be used for exposure class S3 with a w/cm of 0.40.
5. This study could not establish clear criteria to replace the w/cm requirement with an alternative permeability indicator test, such as ASTM C1202.

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Table 1 - ACI 318-14 Requirements for Concrete Exposed to Sulfates

Exposure Class	**Max. w/cm**	**Minimum f'_c, psi (MPa)**	**Cementitious Materials - Types**			**ASTM C1012 expansion**
			ASTM C150	**ASTM C595**	**ASTM C1157**	
S0	N/A	2500 (17)	N/A	N/A	N/A	
S1	0.50	4000 (28)	II	Types IP, IS, or IT with (MS) designation	MS	0.10% at 6 m
S2	0.45	4500 (31)	V	Types IP, IS, or IT with (HS) designation	HS	0.05% at 6 m or 0.10% at 12 m
S3	0.45	4500 (31)	V plus pozzolan or slag cement	Types IP, IS, or IT with (HS) designation plus pozzolan or slag cement	HS plus pozzolan or slag cement	0.10% at 18 m

*Sulfate concentration in soil or water associated with exposure classes is in ACI 318-14

Table 2 - ASTM C1012 Mortar Mixture Proportions and Test Results

Mix ID	I	II	V1	V2	I-25SL	II-35SL	V1-50SL	I-15FA	II-20FA	V1-30FA
Cement Type	I	II	V-1	V-2	I	II	V-1	I	II	V-1
PC C_3A, %	12	8	3	5	12	8	3	12	8	3
Slag cement, %					25	35	50			
Fly ash, %								15	20	30
ASTM C1012 Expansion, %										
6 months	0.45	0.06	0.02	0.03	0.03	0.04	0.02	0.03	0.04	0.02
12 months	NA	0.16	0.05	0.04	0.04	0.04	0.02	0.09	0.04	0.02
18 months	NA	0.51	0.20	0.16	0.05	0.05	0.03	0.34	0.06	0.03
27 months	NA	1.07	0.38	0.33	0.08	0.05	0.03	0.61	0.12	0.04
36 months	NA	1.56	0.49	0.44	0.20	0.07	0.06	0.93	0.24	0.05
ACI 318 Exposure Class	S0	S1	S2	S2	S3	S3	S3	S2	S3	S3

Table 3 - Concrete Mixtures, Results, and Exposure Classes

Mix ID	PC	SCM, %		w/cm	Strength, psi[a]	C1202, coulombs[b]	USBR 4908		Exposure Class		
		SL	FA				Length Change, %	Visual Rating	C1012 (Exp, %)[c]	318	4908
Series 1											
0.5PC-I	I			0.50	5,690	2947	F (12)[d]	0	S0	S0	S0
0.5PC-II	II			0.50	6,440	3610	1.3	0	S1 (0.06)	S1	**S0**
0.4FA15-I	I		15	0.40	8,400	913	0.049	3	S2 (0.09)	**S2**	S3
0.5FA15-I				0.50	5,980	1593	0.071	1		S1	S1
0.6FA15-I				0.60	4,630	2627	F (33)	0		S0	S0
0.4SL25-I		25		0.40	9,540	704	0.034	3	S3 (0.05)	S3	S3
0.5SL25-I				0.50	7,700	1161	0.044	1		S1	S1
0.6SL25-I				0.60	5,710	1947	F (19)	0		S0	S0
Series 2											
0.45PC-V1	V-1			0.45	8,800	2861	0.138	1	S2 (0.05)	S2	**S1**
0.45PC-V2	V-2			0.45	7,720	3184	0.069	1	S2 (0.04)	S2	**S1**
0.4FA20-II	II		20	0.40	7,490	1848	0.036	3	S3 (0.06)	S3	S3
0.5FA20-II				0.50	5,310	2662	0.034	2		**S1**	S2
0.6FA20-II				0.60	3,990	3856	0.039	2		**S0**	S2
0.4SL35-II		35		0.40	10,020	705	0.034	3	S3 (0.05)	S3	S3
0.5SL35-II				0.50	6,740	943	0.035	2		**S1**	S2
0.6SL35-II				0.60	5,730	1790	0.054	1		**S0**	S1
0.4FA30-V1	V-1		30	0.40	7,610	1543	0.037	3	S3 (0.03)	S3	S3
0.5FA30-V1				0.50	4,870	3731	0.036	3		**S1**	S3
0.6FA30-V1				0.60	3,590	4772	0.036	2		**S0**	S2
0.4SL50-V1		50		0.40	7,500	593	0.031	3	S3 (0.03)	S3	S3
0.5SL50-V1				0.50	7,500	887	0.030	2		**S1**	S2
0.6SL50-V1				0.60	6,200	1077	0.035	2		**S0**	S2

[a] Specimens moist cured for 28 days; 1 MPa = 145 psi
[b] Specimens moist cured for 56 days
[c] Expansion reported at the limiting test period – 6 m for S1; 12 m for S2; 18 m for S3
[d] Specimens failed (month terminated)

Table 4 – Summary of Current and Proposed Criteria for Sulfate Resistance

Exposure Class	Min f'_c, psi (MPa)	Max w/cm	Cement Type[a]	ASTM C1012 criteria	ACI 318 criteria
S0	2500 (17)	NA	NA	NA	Current
S1	4000 (28)	0.50	II or MS	0.10% at 6 m	Current[b]
	3500 (21)	0.55	(II or V) + SCM; or HS	0.10% at 12 m	Proposed[c]
S2	4500 (31)	0.45	V or HS	0.10% at 12 m	Current[b]
	4000 (28)	0.50	(II, V or HS) + SCM	0.05% at 12 m	Proposed[c]
S3	4500 (31)	0.45	V or HS + SCM	0.10% at 18 m	Current[b]
	5000 (35)	0.40	(I, II, V or HS) + SCM	0.10% at 12 m	Proposed[c]

[a] ASTM C150 Type I, II or V; ASTM C595 Types IP, IS or IT with MS or HS designation; ASTM C1157 Type MS or HS

[b] Cement Type and ASTM C1012 are alternate criteria

[c] Both Cement Type and ASTM C1012 criteria govern

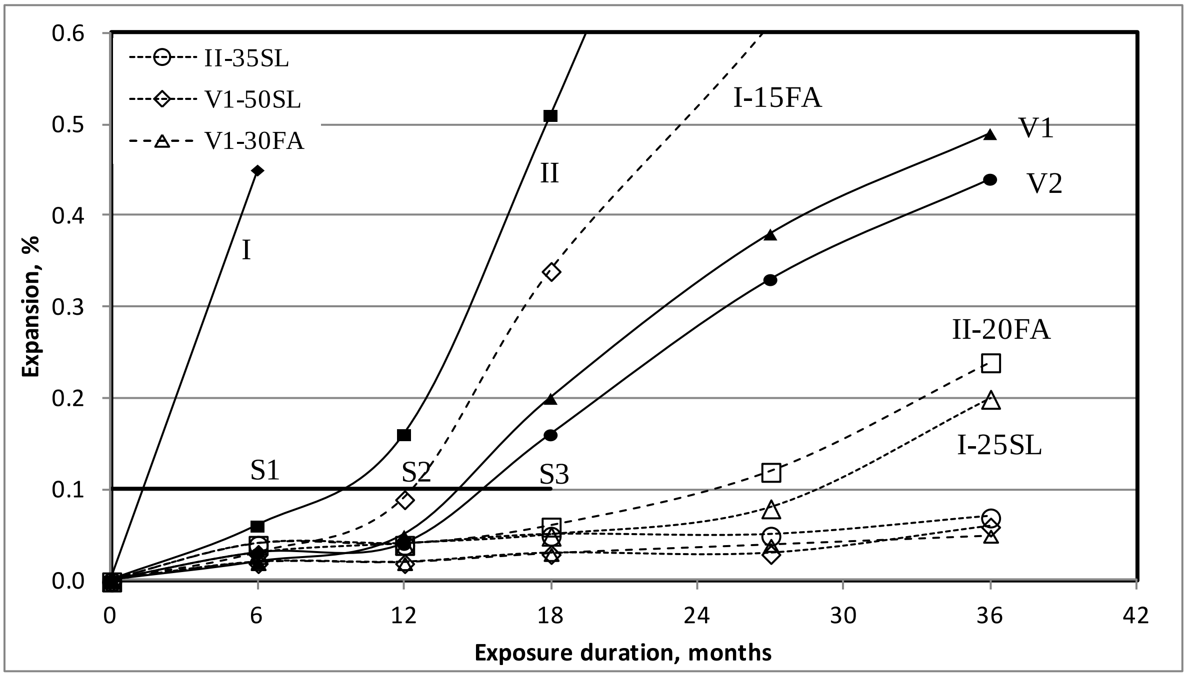

Figure 1 – ASTM C1012 Expansion Results for 10 Mortar Mixtures

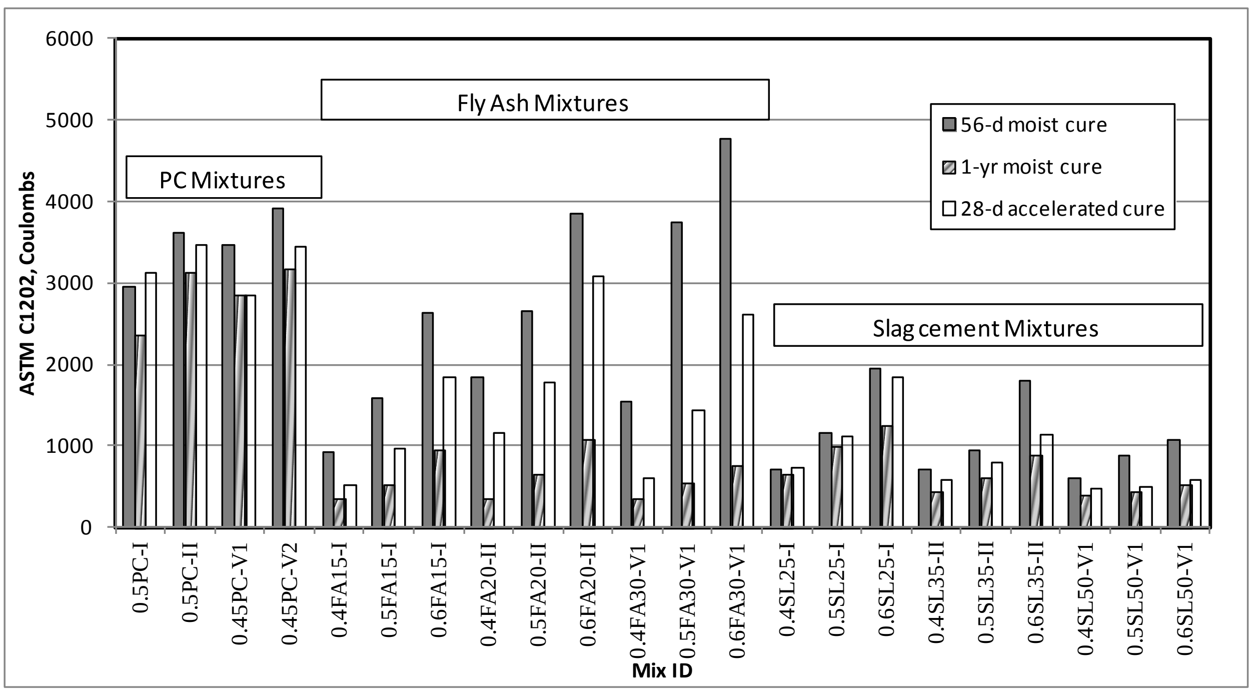

Figure 2 – ASTM C1202 (RCP) Results for Concrete Mixtures

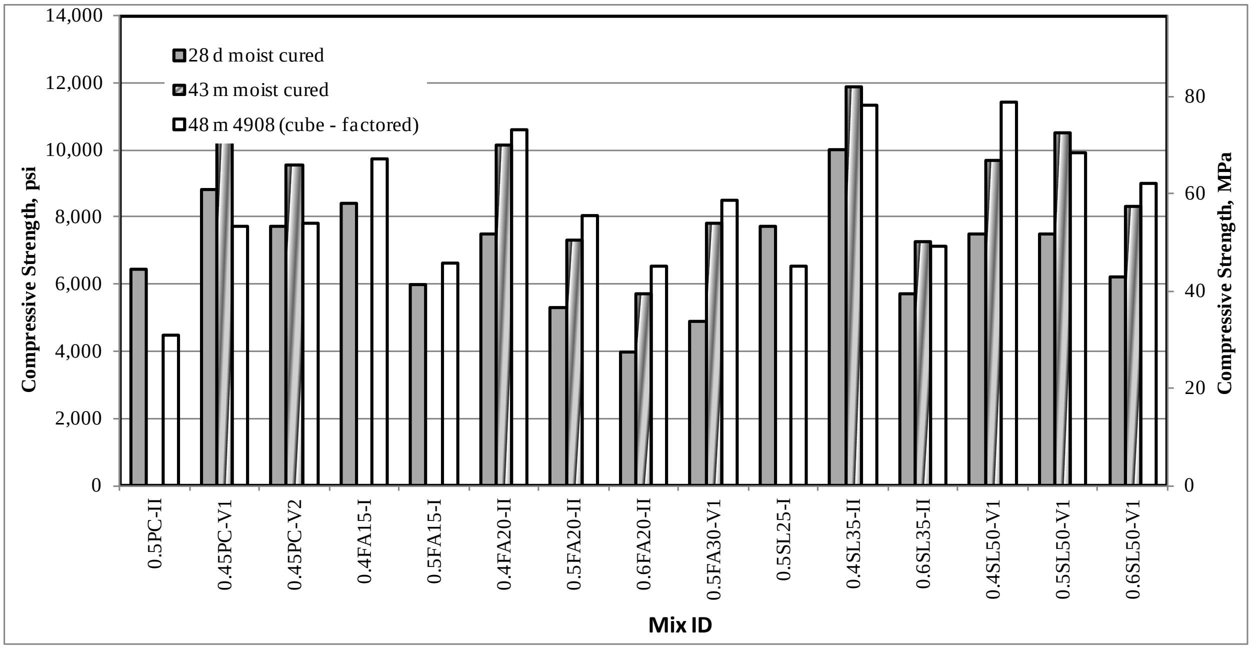

Figure 3 – Comparison of Strength of Concrete Mixtures – Standard-cured and Exposed to Sulfate