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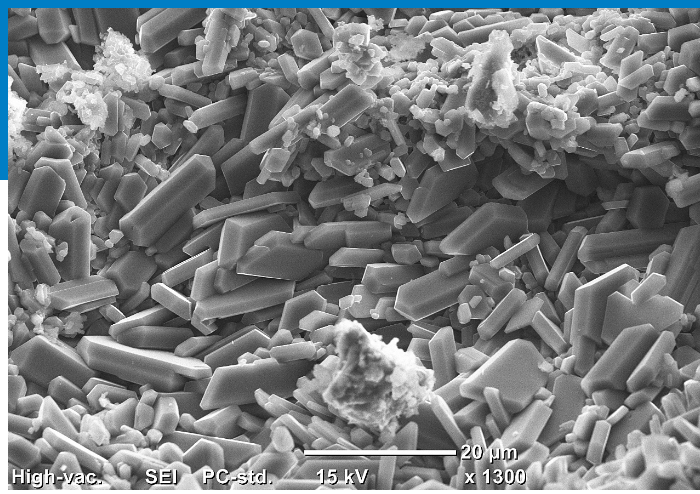

Sulfate Attack on Concrete: A Holistic Perspective

Editors:
Mohamed T. Bassuoni, R. Doug Hooton and Thanos Drimalas

SP-317

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Preface

The papers presented in this volume were included in a three-part session sponsored by ACI Committee 201, Durability of Concrete, about sulfate attack on concrete at the ACI Convention in Philadelphia, PA, on October 23-24, 2016. In line with the practice and requirements of the American Concrete Institute, peer review, followed by appropriate response and revision by authors, has been used.

Deterioration of concrete due to sulfate attack is a complex process characterized by multiple damage manifestations including volumetric expansion, cracking, spalling, softening, and in some cases mushiness. Sulfate attack can generally be classified as internal or external to the cementitious matrix, and the underlying damage modes can be chemical or physical. The scope of papers involves a multitude of theoretical and experimental aspects of different forms of sulfate attack. Readers are urged to critically evaluate the work presented herein, in the light of the large body of knowledge and scientific literature on this durability topic.

We dedicate this volume of papers to the memory of Prof. Robert L. Day, past chairman of Canadian Standards Association (CSA) Committee A23.1/A23.2 (Concrete Materials and Construction), for his invaluable contributions to the field of durability of concrete.

The editors sincerely thank all the presenters in this session and authors of the articles included in this SP, as well as the reviewers for their objective assessment of the papers. Their technical contributions provided a holistic perspective of sulfate attack on concrete.

Mohamed T. Bassuoni, Chairman and Editor
R. Doug Hooton, Co-chairman and Co-editor
Thano Drimalas, Co-chairman and Co-editor

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Criteria for Concrete Mixtures Resistant to Chemical Sulfate Attack

Karthik H. Obla and Colin L. Lobo

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.