

YOU ARE YOUNG ONCE, BUT CAN STAY IMMATURE INDEFINITELY: HOLISTIC VIEW OF SCC DURABILITY

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ABSTRACT

The current view of concrete durability is often fragmented, based on tests that subject specimens to one ageing mechanism at a time. The experimental results are often interpreted using Cartesian true or false logic. Hence, the current life-cycle analysis tools for concrete structures are myopic and do not capture the complexities of real world exposures and multi-damage mechanisms. The ongoing paradigm shift towards performance-based specifications necessitates improving the reliability of current testing standards and introducing rigorous performance-based test methods. Likewise, emerging computational artificial intelligence-based methods such as fuzzy inference systems are promising tools for modeling the durability of concrete structures under realistic environmental exposure and combined degradation mechanisms. This article reports on key findings from the experimental part of a five-year sustained effort at Western University to demystify multiple damage mechanisms on self-consolidating concrete, with a particular focus on sulfate attack.

Keywords: SCC; sulfate attack; multiple damage; holistic approach

INTRODUCTION

Self-consolidating concrete (SCC) is sensitive to chemical attack, for example by sulfate solutions, due to its unique mixture comprising a higher volume of paste with large dosages of supplementary cementitious materials (SCMs) and/or fillers [1]. In particular, SCC has been progressively used in sewage systems, substructures, industrial floors, etc., which are susceptible to external sulfate attack; a complex durability issue associated with controversy and inadequacy of standard tests that correlate to field conditions [2, 3]. In real field exposure, the damage of concrete structures often occurs due to a multitude of mechanisms (chemical, physical and structural) acting in a synergistic manner. There is need to develop performance tests that involve multiple damage mechanisms to improve the understanding of their combined effects on normal and emerging types of concrete, and to allow a better modelling of the performance of concrete structures. Hence, novel research on investigating the resistance of SCC to sulfate attack should be based on an integrated/'holistic' approach that includes other in-service parameters such as environmental conditions and mechanical loading. Such an approach was implemented in a five-year research program, and the main findings of the experimental part of this work are summarized in the current paper. Full details of this program can be found in Ref. [4]. The main objectives of this work were to: i) develop an integrated testing approach on SCC that considers concomitant damaging mechanisms with sulfate attack to simulate field conditions and capture the difference in performance and failure mechanisms, if any, from classical immersion tests, and ii) build predictive models for the performance of SCC capable of accommodating the interplay of other damaging mechanisms with sulfate attack, errors in experimental measurements, uncertainty in exposure conditions and engineering judgment. To achieve these objectives, the scope of this research included a wide range of SCC mixture designs, single, dual and multiple damage-factor experiments, and artificial intelligence modelling. The latter is beyond the scope of the current paper.

METHODOLOGY

Twenty one SCC mixtures with a w/cm of 0.38 and total binder content of 470 kg/m³ were prepared using single, binary, ternary and quaternary binders. All the mixtures were designed to maintain a slump flow of 650 ± 30 mm and L-box (3Ø10 mm bars with 50 mm gaps) ratio (H2/H1) not less than 0.70. The mixtures were divided into three groups: Group A (non-air-entrained SCC with a sand-to-total aggregates mass ratio [S/A] of 50%); Group B (air-entrained SCC mixtures with S/A of 40 and 60%); and Group C (air-entrained SCC with fibre reinforcement and sand-to-total aggregates plus fibres mass ratio of 50%). The binders used included CSA Type 10 (ASTM Type I) portland cement (PC), CSA Type 50 (ASTM Type V) sulfate resistant portland cement

(SRPC), silica fume (SF), Class F fly ash (FA), slag (S), and limestone filler (LF). Details of the mixtures tested are given in Tables 1 and 2. The holistic testing approach comprised five exposure regimes:

Table 1. Proportions of binders per cubic meter of concrete

Binder Description	Binder Code	Cement (kg)	Silica Fume (kg)	Slag (kg)	Fly Ash (kg)	Limestone (kg)
100% SRPC	SRPC	470	--	--	--	--
100% PC	A1, B1, or C1	470	--	--	--	--
92% PC, 8% SF	A2, B2, or C2	430	40	--	--	--
50% PC, 5% SF, 45% S	A3, B3, or C3	235	25	210	--	--
50% PC, 15% LF, 20% S, 15% FA	A4, B4, or C4	235	--	95	70	70
50% PC, 5% SF, 25% S, 20% FA	A5, B5, or C5	235	25	120	90	--

Table 2. Proportions of groups A, B and C mixtures per cubic meter of concrete

Binder Code	Mix. ID	Steel Fibres (kg)	Poly-propylene Fibres (kg)	Fine Aggregate (Kg)	Coarse Aggregate (kg)	Air-Entraining Agent (ml /100 kg of binder)
SRPC	SRPC	--	--	870	870	--
A1	A1-N-50	--	--	870	870	--
A2	A2-N-50	--	--	860	860	--
A3	A3-N-50	--	--	855	855	--
A4	A4-N-50	--	--	845	845	--
A5	A5-N-50	--	--	840	840	--
B1	B1-A-40	--	--	655	1015	45
	B1-A-60	--	--	1015	655	35
B2	B2-A-40	--	--	640	990	70
	B2-A-60	--	--	990	640	50
B3	B3-A-40	--	--	640	985	70
	B3-A-60	--	--	985	640	60
B4	B4-A-40	--	--	625	970	110
	B4-A-60	--	--	970	625	95
B5	B5-A-40	--	--	625	965	120
	B5-A-60	--	--	965	625	100
C1	C1-A-H	30	1	830	805	40
C2	C2-A-H	30	1	825	795	60
C3	C3-A-H	30	1	820	790	65
C4	C4-A-H	30	1	805	780	100
C5	C5-A-H	30	1	800	775	105

Exposure I: A reference exposure similar to that for ASTM C 1012 in which prismatic (75×75×285 mm) SCC specimens were fully immersed in a 5% sodium sulfate solution

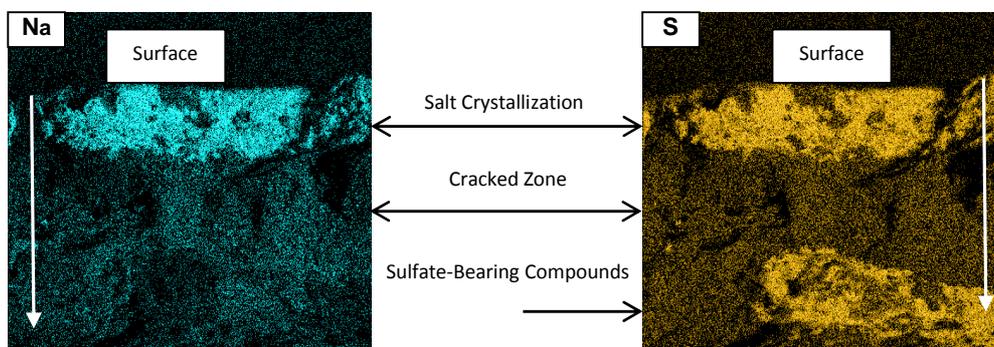
for up to 24 months. The pH was controlled at a range of 6.0-8.0 by titration with diluted sulfuric acid solutions. **Exposure II:** A wetting-drying exposure in which prismatic concrete specimens were subjected to a sulfate solution and drying in hot environment for 24 months (104 cycles). A wetting-drying cycle consisted of four days of full immersion in a 5% sodium sulfate solution (pH 6.0-8.0) and three days of drying at 45°C and 35% RH in an environmental chamber. **Exposure III:** A wetting-drying exposure in which cylindrical (75×150 mm) concrete specimens were subjected to partial immersion in a sulfate solution and drying in a hot environment for 24 months (104 cycles). One cycle consisted of partial immersion (to a depth of 50 mm) in a 5% sodium sulfate solution (pH 6.0-8.0) for four days during which the top two-thirds (100 mm) of each specimen was exposed to drying under $22 \pm 2^\circ\text{C}$ and $55 \pm 5\%$ RH. Then, the entire cylindrical specimens were submitted to drying at 45°C and 35% RH for three days. **Exposure IV:** A freezing-thawing exposure which involved concomitant chemical and physical attack by sodium sulfate and freezing-thawing cycles. Prismatic SCC specimens were fully immersed for 2 days in a 5% sodium sulfate solution followed by 2 days of freezing in air at -18°C . After 365 days (approximately 90 freezing-thawing cycles), the procedure was accelerated. Specimens were subjected to successive freezing-thawing cycles interrupted by wetting and drying periods. A full exposure cycle consisted of 5 days of immersion in 5% sodium sulfate solution at 20°C , 5 days (26 freezing-thawing cycles) in an automated freezing-thawing cabinet adjusted to the ASTM C 666 procedure A except that a 5% sodium sulfate solution was used instead of water, and 2 days of drying at 20°C and 50% RH. Subsequent to the initial 90 freezing-thawing cycles, the number of accelerated cycles for specimens from groups A, B and C were selected to be 10, 15 and 20 cycles, respectively. This is equivalent to 350, 480, and 610 freezing-thawing cycles, respectively. The pH control of solutions was done similar to the previously described exposure regimes. **Exposure V:** In this exposure, SCC specimens from the same mixtures were subjected to multiple damages of sodium sulfate, cyclic environmental conditions and sustained flexural loading. Prismatic SCC specimens were subjected to stress ratios of 25 and 50% of their ultimate flexural strength. Flexural stress was mechanically applied to the specimens in four-point bending and sustained using steel frames with dual springs. These stress levels were maintained till the end of exposure. Comparatively, companion specimens were exposed to sulfate attack and cyclic environmental conditions without flexural stress. Specimens with and without sustained flexural stress were initially immersed for 5 days in a 5% sodium sulfate solution (pH 6.0-8.0) at a temperature of $20 \pm 2^\circ\text{C}$ before being exposed to the cyclic environmental conditions that simulated successive winter and summer seasons. A winter season was represented by 30 successive freezing-thawing cycles: freezing in air at $-18 \pm 1^\circ\text{C}$ for 12 hours followed by thawing in a 5% sodium sulfate solution (pH 6.0-8.0) at $5 \pm 1^\circ\text{C}$ for 6 hours, and 4 hours to ramp to the minimum freezing temperature and 2 hours to ramp to the maximum thawing temperature. A summer season comprised 8 alternating wetting-drying cycles. Each cycle consisted of 2 days of immersion in a 5% sodium sulfate solution (pH 6.0-8.0) at a temperature of $22 \pm 2^\circ\text{C}$ followed by 2 days of drying at 40°C and 40% RH. The exposure lasted for one year, simulating 6 winters alternating with 6 summers under sustained flexural loading and sulfate attack.

During all exposures, the changes in length, mass, strength and dynamic modulus of elasticity of SCC specimens versus time of exposure were determined. The characteristics of the pore structure were analysed by mercury intrusion porosimetry (MIP) and sulfate reaction products were detected by differential scanning calorimetry (DSC) and X-ray diffraction (XRD, Cu-K α). The deterioration of the microstructure was assessed by optical and scanning electron microscopy (SEM) with energy dispersive X-ray analysis (EDX) on thin sections and fracture surfaces.

KEY FINDINGS

The results of continuous immersion tests (Exposure I) showed that all the SCC mixtures tested in this study had high resistance to 5% sodium sulfate solutions. This behaviour was mainly attributed to the physical resistance (low penetrability) of this type of high performance concrete: low w/cm, high powder content and homogenous microstructure. According to those pure diffusion tests, the physical resistance of SCC was more important than the chemical resistance (type of binder). The second level of the holistic testing approach involved the effect of concomitant environmental conditions and sulfate attack. In comparison to Exposure I, the SCC specimens in the wetting-drying exposure (Exposure II) were subjected to the synergistic action of wetting-drying, salt crystallization and sulfate attack. In the partial immersion exposure, the drying portions of specimens underwent progressive crystallization of thenardite, while the immersed portions had similar damage mechanisms to that of the wetting-drying exposure. In both cases, direct penetrability of the sodium sulfate solution into the cementitious matrix was observed by micro-analytical studies (Fig. 1).

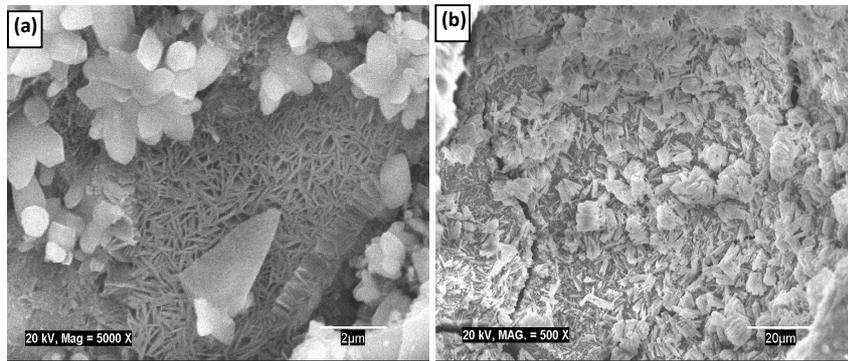
Figure 1. Typical elemental spatial distribution in a thin section from A4-N-50 specimen after Exposure II showing sodium sulfate crystallization near the exposed surface and formation of sulfate-bearing compounds in deep regions.



Results from Exposures II and III showed that non-air-entrained SCC specimens made from quaternary binders (with or without limestone filler) had a very fine pore structure, which made them more vulnerable to severe damage and/or fracture under

conditions that promote salt crystallization. This warrants some caution when such cementitious systems are to be used under similar field conditions. In addition, incipient thaumasite sulfate attack (TSA) was consistently detected in SCC specimens incorporating 15% limestone filler with SCMs under the wetting-drying and partial immersion exposures (Fig. 2), which simulated temperate-hot climates. Thus, as documented by the laboratory tests in this research, the general notion that TSA occurs only at low temperatures below 15°C should be reconsidered.

Figure 2. Formation of very fine thaumasite crystals in the cementitious matrix of C4-A-H specimens after: (a) exposure II, and (b) exposure III (immersed portion).

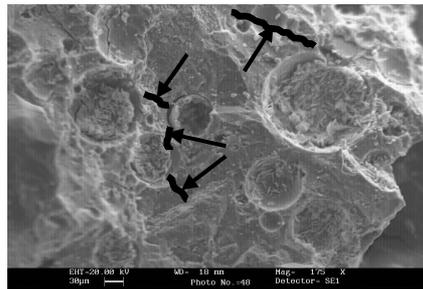


The occurrence of TSA, secondary ettringite, gypsum, and salt crystallization made those specimens more vulnerable to damage relative to the other specimens not incorporating limestone filler. In the wetting-drying and partial immersion exposures, air-entraining bubbles could relieve osmotic pressures generated in the cementitious matrix and provided host locations for the growth of salt and sulfate-bearing crystals, thus discounting the rate of damage and extending the life of SCC specimens. The incorporation of hybrid micro- and macro-fibres improved the resistance of SCC specimens to the wetting-drying and partial immersion exposures owing to their effect on controlling internal cracking and maintaining the integrity of the cementitious matrix.

The effects of combined sulfate attack and frost action on the performance of the SCC mixtures were investigated in Exposure IV (simulating cold climates). This exposure showed potential durability problems of different binders, such as excessive surface scaling of specimens made with 100% PC binders, vulnerability of cementitious matrices having very fine pore structure to intensive micro-cracking from salt crystallization pressures, and incipient TSA of binders incorporating limestone powder. Micro-analytical studies showed direct penetrability of the sodium sulfate solution through micro-cracks induced by freezing-thawing cycles, thus accelerating the damage of specimens. These observations were in harmony with that of Exposures II and III. Air-entrainment initially enhanced the resistance of SCC to the combined chemical-physical attack (sodium sulfate and frost action). The degradation, however, was only delayed and the cementitious matrices were not completely immune to

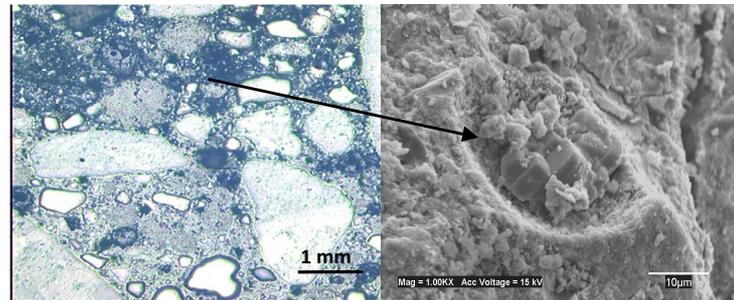
degradation, irrespective of the binder type. With time, accumulation of sulfate attack reaction products together with salt crystallization in air voids (Fig.3) had detrimental effects under prolonged exposure with the risk of a sudden failure, especially for specimens prepared with blended binders that did not tend to scale off. Similar to the conclusions drawn from Exposures II and III, the incorporation of hybrid fibres achieved an overall improvement of the durability of group C specimens due to an effective control of cracking.

Figure 3. SEM micrograph for a fracture surfaces showing filling of air voids with associated micro-cracks [indicated by the arrows] in specimens from a binary binder (B2-A-40).



Cyclic environmental conditions, sulphate attack and flexural loading (Exposure V) caused stress corrosion of the cementitious matrix and led to direct ingress of the solution. Results from this exposure indicated that the conventional approach of incorporating different proportions of SCMs in the cementitious matrix to mitigate sulfate attack may not be fully effective under real in-service conditions since other factors seemed to affect the damage process. For instance, the quaternary binder with SCMs and 15% limestone filler showed constantly inferior performance mainly due to the synergistic effect of sodium sulfate and variable (cold-temperate-hot) temperatures that led to incipient TSA. This trend was confirmatory to observations from the dual damage tests. While the incorporation of hybrid fibre reinforcement controlled the expansion of the SCC specimens, the existence of corroded steel fibres on the surface provoked the first-cracking at relatively low stress levels, which can pose serviceability problems under similar combined exposures. Micro-analytical studies showed very complex deterioration mechanisms in Exposure V. The accumulation of voluminous sulfate reaction products with salt crystallization created expanding zones at exposed surfaces (Fig. 4), which with flexural loading increased the net tensile stresses, and thus initiated the breakage of specimens. Overall, Exposure V had synergistic effects on SCC specimens and caused the coexistence of complex degradation mechanisms (sulfate attack, TSA, stress-corrosion, salt crystallization, surface scaling and corrosion of surface steel fibres) depending on the mixtures design variables. This is fundamentally different from studying a single damage mechanism by immersion tests, which did not reveal any performance risks associated with the SCC mixture designs tested.

Figure 4. Deteriorated zone in B3-A-60 specimen under plain light and SEM showing accumulation of salt crystallites with sulfate reaction products in an air void.



CLOSURE

A new series of sulphate attack tests involving combined damage mechanisms were developed to evaluate the performance of a wide scope of SCC mixture designs. Such a holistic approach revealed complex degradation mechanisms and different failure modes of SCC that can occur under field conditions, depending on key mixture design parameters. This was fundamentally different from the observations recorded under the classical immersion tests customarily used for prequalification of concrete. The combined tests are better able to capture synergistic actions of chemical, physical and structural mechanisms on concrete, which can occur under real field exposures. The holistic approach should contribute to the improvement of performance-based standards and specifications for concrete and producing more reliable knowledge on the durability of normal and emerging types of concrete with inevitable advancements in the durability-based design methods and life-cycle modelling of concrete.

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