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Effect of environmental exposure on autogenous self-healing of cracked cement-based materials

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ABSTRACT

Despite abundant literature on self-healing of cement-based materials, there is dearth of information on how environmental exposure affects self-healing. In this study, self-healing of cracks in cement mortar under different environmental exposure was investigated. Pre-cracked mortar specimens were submerged in water, while identical specimens were exposed to cyclic temperature and relative humidity. Change in crack width was examined using optical microscopy. SEM coupled with energy dispersive X-ray analysis was used to identify healing compounds. Mercury Intrusion Porosimetry, water absorption and permeability were employed to assess porosity. X-ray computed tomography was deployed to explore healing of internal cracks. No significant self-healing occurred in specimens exposed to cyclic T and RH. Although crack self-healing was identified in submerged specimens, X-ray μCT demonstrated that it was limited to exposed surface of specimens. This warrants further research to bridge the gap between laboratory findings on self-healing and actual field performance of ageing civil infrastructure.

1. Introduction

Concrete structures are susceptible to cracking due to mechanical loading and environmental exposure. Hostile species such as chloride and sulfate ions can ingress into the cementitious matrix, leading to costly damage [1–3]. For instance, Fig. 1 shows the percentage of Canadian civil infrastructure currently with an average physical condition of fair to very poor, as captured by the most recent Canadian Infrastructure Report Card [4]. About one-third of Canadian civil infrastructure is either in fair, poor or very poor condition. In the USA alone, the infrastructure deficit was estimated to reach $US 3.6 trillion by year 2020. Indeed, this is a colossal worldwide problem and a global crisis with enormous economic and environmental implications.

Recently, the self-healing behavior of cement-based materials has received increasing attention as a promising tool to mitigating damage inflicted by concrete civil infrastructure (e.g. [5–18]). Several studies have reported that surface cracks in concrete can self-heal autogenously. For instance, Gagné and Argouges [19] indicated that pre-cracked cement mortars made with ordinary portland cement and stored in a fog room exhibited self-healing. It was found that complete self-healing occurred primarily for cracks with small width, while larger width cracks exhibited less self-healing.

Other studies also showed that self-healing of cracks in concrete can be improved using agents capable to promote further hydration or carbonation (e.g. [7,9,11,13,17,20–25]). For instance, Rahmani and Bazrgar [26] found that using coarse cement particles in pre-cracked concrete specimens can recover up to 37% of their initial tensile strength when submerged in water for 90-d. Sisomphon et al. [20] studied the influence of both expansive and crystalline additives on the self-healing of cracks in cement-based mortars. In their study, mortar specimens were pre-cracked and subsequently immersed in water. Results showed that surface cracks with width of around 400 μm exhibited complete healing in cement mortars incorporating expansive and crystalline additives, whereas in the case of control specimens, the maximum crack width that fully self-healed was 150 μm. It was concluded that calcium carbonate ($CaCO_3$) was the main healing product filling surface cracks. Similar results were obtained by Jiang et al. [25] who evaluated the surface crack healing of cement mortar specimens incorporating different mineral additives, including silica-based, chemical expansive, swelling, and crystalline additives. It was also found that $CaCO_3$ was the main healing product formed within cracks.

Incorporating supplementary cementitious materials further enhanced the autogenous self-healing of concrete (e.g. [9,16,23,27–29]). For instance, Huang et al. [9] investigated the effect of activated blast furnace slag on the self-healing of microcracks in cementitious materials. Their results showed that cement paste containing a high percentage of slag had a higher potential of self-healing than that of portland cement paste. Van Tittelboom et al. [29] investigated using

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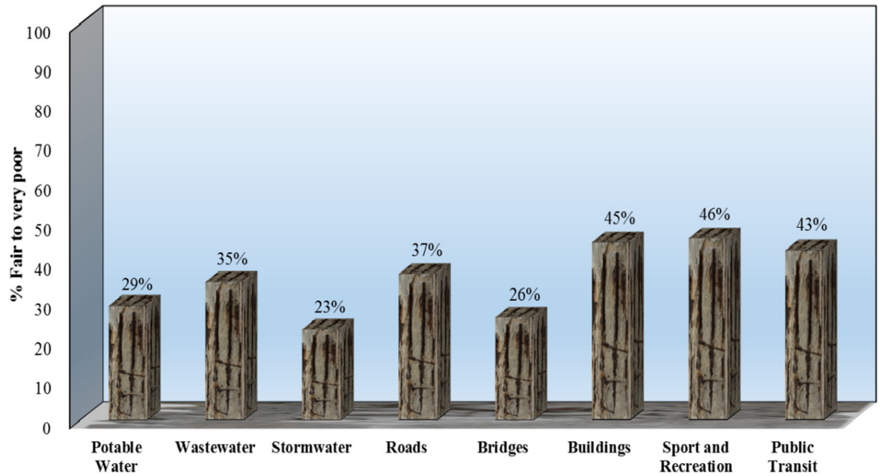

Fig. 1. Average physical condition (fair to very poor) of Canadian civil infrastructure.

both blast furnace slag and fly ash and found that they can enhance the autogenous healing of cracked mortar and cement paste submerged in water. Similarly, Özbay et al. [28] reported improved healing of cracked engineered cementitious composites incorporating high volume fly ash. Termkhajornkit et al. [23] investigated the effect of incorporating different percentages of fly ash on the self-healing efficiency of cement paste. Although no cracks were generated in their experiments, the self-healing was interpreted through changes of mechanical strength, porosity, effective chloride diffusion coefficient, and hydrated products upon increasing the fly ash content.

In the above studies, self-healing was essentially explored though surface crack and mostly under submerged conditions. The self-healing of internal cracks, the effects of varying the curing conditions or exposure to realistic field environmental conditions on the effectiveness of self-healing, and the depth of the self-healing effect remains largely unexplored. Therefore, in the present study, the self-healing of both surface and interior cracks and the effects of different curing conditions on the self-healing of cracks were duly explored.

2. Research significance

To reap real benefits from the emerging studies on self-healing of cement-based materials, there is need to accurately quantify the healing of both surface and internal cracks, along with delineating the effects of variable curing conditions and environmental exposure on the effectiveness of self-healing. Through deploying advanced X-ray computed tomography, the present study demonstrates that self-healing results that are often reported under submerged conditions may not be reproducible under variable curing conditions, and that crack self-healing may be limited to the exposed surface. The findings should stimulate concerted research efforts to bridge the gap between ideal laboratory conditions and realistic field exposure in future self-healing research endeavors.

3. Experimental program

3.1. Materials and specimen preparation

Mortar specimens were made with ordinary Portland cement compliant with CSA A3001 and ASTM C150 standards, along with 20% CSA A3000 Type CI fly ash (ASTM C618 Class C) to promote autogenous self-healing. Water-to-cementitious materials ratio (w/cm) of 0.35 and sand-to-cementitious materials mass ratio (s/c) of 2 were used. The physical and chemical properties of the cement, fly ash and sand are summarized in Tables 1 and 2. The specimens were cast in 10 cm diameter and 5 cm height plastic containers reinforced with a galvanized steel mesh (6 mm × 6 mm with Ø = 1 mm), which was embedded at the centre of the tested (100 diameter and 50 mm height) mortar specimens. After demolding at 1-d, specimens were cured for 28-d in a moist room at RH ≥ 95% and $T = 21 \pm 1$ °C. The curing was carried out according to ASTM C511 (Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes). At the age of 28-d, specimens were removed from the moist room and cracked, as displayed in Fig. 2. All 100 × 50 mm cylindrical specimens were pre-cracked (longitudinal crack) at the age of 28 days by means of a splitting test at a constant loading rate of 0.01 mm/s. The crack width was controlled during the splitting test via a calibration ruler as per the method described by [30]. For each environmental condition, three groups of

Table 1
Physical and chemical properties of cement and fly ash.

Components/property	Cement type (10)	Fly ash CI
Silicon oxide (SiO_2) (%)	19.6	42.4
Aluminum oxide (Al_2O_3) (%)	4.8	21.2
Ferric oxide (Fe_2O_3) (%)	3.3	7.1
Calcium oxide (CaO) (%)	61.50	16
Magnesium oxide (MgO) (%)	3.0	–
Sulfur trioxide (SO_3) (%)	3.50	2.40
Loss on ignition (%)	1.90	1.60
Insoluble residue (%)	0.44	–
Equivalent alkalis (%)	0.7	–
Tricalcium silicate (C_3S) (%)	55	–
Dicalcium silicate (C_2S) (%)	15	–
Tricalcium aluminate (C_3A) (%)	7	–
Tetracalcium aluminoferrite (C_4AF) (%)	10	–
Blaine fineness (m^2/kg)	371	–
Autoclave expansion (%)	0.09	–
Compressive strength 28 days (MPa)	40.9	–
Specific gravity	3.15	2.60
Time of setting (min) Vicat Initial	104	–
Pozzolanic activity index (%)	–	100

Table 2
Physical and chemical properties of sand.

Property	Value
Absorption (%)	1.09
Micro-deval (A) (%)	17.00
Specific gravity (apparent) (%)	2.72
Specific gravity (dry) (%)	2.65
Specific gravity (SSD) (%)	2.68
Unit weight (kg/m^3)	1512
Materials finer than 75-μm (sieve # 200) (%)	2.10