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Estimating the self-healing capability of cementitious composites through non-destructive electrical-based monitoring

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ABSTRACT

Self-healing evaluation of cementitious composites was made by non-destructive test (NDT) methods (electrical impedance [EI], rapid chloride permeability test [RCPT] and resonant frequency [RF]). Correlations among results obtained from different NDT methods were reported. Conclusions revealed that EI testing is easy to perform, takes very limited time and looks promising for self-healing assessment although the method itself seems to be remarkably influenced by anything modifying the ionic state of specimens. A solid exponential relationship exists between EI and RCPT measurements, but results from RF tests do not correlate with EI and RCPT results due to different parameters affecting individual tests.

1. Introduction

Historically, concrete materials used in different infrastructure types have been designed to possess specific properties and to meet a pre-determined lifetime. In accordance with European standards, that service life is at least 75 years for concrete used in large-scale public works [1], although the public has expectations of "last-forever" structures to accommodate ever-growing urban populations. However, when we consider deterioration after only 20 to 30 years due to the combined influence of mechanical and environmental loads [2], many structures built in the second half of the last century are already approaching the end of their service life.

Cracks are an unwelcome trigger that speed up the deterioration. They are inherently present in concrete; their existence does not necessarily pose safety problems, although there are a number of reasons why they are generally considered undesirable. Cracks, regardless of origin, can impact the overall durability of concrete structures. In structures designed for their retaining capability, cracking can significantly jeopardize tightness. In conditions where absolute tightness is required (e.g. radioactive shielding), cracking poses a problem. Corrosion, freeze–thaw susceptibility, alkali-aggregate reactivity and other common durability problems may also be aggravated given the fact that moisture and aggressive substances accelerating the mechanisms would more easily be transported into the concrete material itself with the formation of cracks. In addition to durability-related concerns, cracks also pose esthetic issues. Nevertheless, for the sake of increased structural serviceability in the presence of cracks, an effort can be made on the basis of newly emerging self-healing materials.

Self-healing is a current topic of interest among researchers worldwide, with many focusing on the development of cementitious self-healing materials that mimic the features of living systems. Despite significantly varying techniques and methodologies used with different material classes, all self-healing materials have one common feature: they reduce repair and/or maintenance applications and continuously renew structural performance that would otherwise be reduced as a result of cracking. This enhanced structural longevity could be the key to reduce the demand for new construction, resulting in less pollution, energy consumption and greenhouse gas emissions.

As mentioned earlier, the concept of self-healing has drawn the attention of many scientists, who have published a number of papers that offer invaluable information about state-of-the-art

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methodologies used to trigger self-healing in cement-based materials [3–7]. Despite the recent functionalization of self-healing by emerging techniques, most of the early self-healing studies have mainly concentrated on autogenous healing, which occurs intrinsically with no external interference due to the composition of the cementitious matrix. As an emerging material favoring intrinsic autogenous healing due to inherent tight microcracking behavior under excessive loading, Engineered Cementitious Composites (ECCs) were first introduced to the research community by Li et al. in the late nineties [8]. Since then, studies related to the material have kept growing in number. In addition to exploring mechanical and durability properties, many papers have focused on the self-healing performance of ECCs under commonly encountered environments [9–15]. Papers evaluating the self-healing performance of cement-based materials have also been published, based on a variety of test methods [7]. Present paper describes direct electrical impedance measurements conducted for self-healing evaluation. This method was used because it was easy to perform in a very limited timeframe, and resulted in reasonable values based on previous trials. No studies on self-healing evaluation through direct electrical-based methods were encountered during the literature review. Self-healing performance of ECCs incorporating different pozzolanic materials was evaluated with direct electrical impedance measurements, and the efficiency of this method in verifying self-healing performance was compared with previously used non-destructive test (NDT) methods (e.g. rapid chloride permeability and resonant frequency tests). Correlation of the results from different test methods was further detailed.

2. Experimental investigation

2.1. Materials and mixture proportions

The experimental study consisted of series of tests performed on two separate ECC mixtures produced with different pozzolanic materials (PMs); Class-F fly ash (FA-F, F_ECC) and ground granulated blast furnace slag (GGBFS, S_ECC). Along with the different PMs, the mixtures were produced using CEM I 42.5 general-use ordinary Portland cement (PC, similar to ASTM Type I cement), silica sand with maximum aggregate size of 0.4 mm, polyvinyl-alcohol (PVA) fibers with a diameter of 39 μm, length of 8 mm, nominal tensile strength of 1610 MPa and specific gravity of 1.3, water and polycarboxylic-ether based high range water reducing admixture (HRWRA) with a solid content of 40%. Chemical and physical properties of Portland cement and different PMs are shown in Table 1. Both ECC mixtures were produced with a water

Table 1
Chemical and physical properties of portland cement, fly ash and slag.

Chemical composition, %	FA-F	GGBFS	PC
CaO	3.48	35.09	61.43
SiO_2	60.78	37.55	20.77
Al_2O_3	21.68	10.55	5.55
Fe_2O_3	5.48	0.28	3.35
MgO	1.71	7.92	2.49
SO_3	0.34	2.95	2.49
Available alkalies as Na_2O_{eq}	2.02	0.94	0.70
Loss on Ignition	1.57	2.79	2.20
$SiO_2+Al_2O_3+Fe_2O_3$	87.94	48.38	29.37
Physical properties			
Specific gravity (dimensionless)	2.10	2.79	3.06
Blaine fineness (m^2/kg)	269	425	325

Table 2
Proportions for ECC mixtures.

Mix ID.	Ingredients, kg/m^3						PM/PC	W/CM
	PC	PM	Water	PVA	Sand	HRWRA		
F_ECC	566	680	331	26	453	5.1	1.2	0.27
S_ECC	593	712	347	26	474	6.0	1.2	0.27

to cementitious materials (CM = PM + PC) ratio (W/CM) of 0.27, and a pozzolanic material to Portland cement ratio (PM/PC) of 1.2. PVA fibers were used on a volumetric basis by 2% and the amount of HRWRA used in the mixtures was based on the achievement of reasonable fresh properties. The amounts of ingredients used in one cubic meter of each mixture are shown in Table 2. During the production of ECC mixtures, a mortar mixer with 25-liter capacity was used. Solid ingredients (Portland cement, fly ash or slag, and aggregate) excluding PVA fibers were first mixed at 100 rpm for a minute. Water and HRWRA were then added into the dry mixture and mixed at 150 rpm for 1 min and then at 300 rpm for another 2 min. As a final step, PVA fibers were added in the fresh mixture and mixing at 150 rpm for an additional 3 min was continued.

2.2. Specimen preparation and initial pre-loading

As mentioned earlier, this study differs from the previous ones in that the self-healing capability of ECC was investigated primarily with direct electrical measurements (electrical impedance), along with rapid chloride permeability and resonant frequency tests. Multiple Ø100 × 200 mm cylindrical specimens were produced from a single batch of each mixture, prepared by a 25-liter-capacity mortar mixer to be used in different NDT methods for self-healing evaluation. After 24 h in a laboratory climate at 50 ± 5% RH, 23 ± 2 °C, specimens were removed from their molds and cured in isolated plastic bags at 95 ± 5% RH, 23 ± 2 °C until the end of 28 days. At 28 days, Ø100 × 50 mm-cylinders were extracted from the Ø100 × 200 mm-cylinders using a diamond blade saw. The Ø100 × 50 mm-cylinders were used for all NDT methods. Specimen dimensions were reduced given the fact that Ø100 × 50 mm-sized cylinders are used for rapid chloride permeability tests (RCPT) (also explained in Section 2.3) and identical specimens were intended to be used for an easier correlation among different NDT methods utilized for the self-healing assessment. Tests were performed on sound specimens (with no initial pre-loading) and companion specimens pre-loaded under splitting tensile loading. Since there is a high likelihood for ECCs with different PMs to display varying ultimate splitting tensile deformation levels, four 28-day-old Ø100 × 50 mm^2 specimens from each mixture were tested up to failure under splitting tensile loading, and average ultimate deformation capacities of different mixtures were defined before applying pre-loading. To do this, splitting tensile loading was applied to the specimens up to failure using a closed-loop controlled material testing system at a loading rate of 0.005 mm/s. Two linear variable displacement transducers (LVDTs) were fixed on the test set-up to measure the splitting tensile deformation of the specimen. After crushing of specimens, splitting tensile stress – deformation graphs were drawn and deformation levels corresponding to maximum splitting tensile stress levels were specified as ultimate splitting tensile deformation capacity. Average results were 1.7 and 1.5 mm for F_ECC and S_ECC mixtures, respectively with coefficient of variation (COV) less than 15% for both mixtures. In light of these results, a common pre-loading level (70% of ultimate splitting tensile deformation capacity) was set to achieve microcracking damage that was as similar as possible for the different ECC mixtures. With the