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Influence of cracking and healing on the gas permeability of cementitious composites

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HIGHLIGHTS

- Influence of cracking and self-healing on the gas permeability of ECC were studied.
- Gas permeability, resonant frequency and crack analysis tests were conducted.
- Self-healing was strongly influenced by the chemical compositions of the mixtures.
- Application of pre-loading led to significant increases in GP and RF results.
- Recovery in GP results could be increased to 96% through proper curing.

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ABSTRACT

The main objective of the study presented in this paper was to investigate the influence of cracking and self-healing on the gas permeability of Engineered Cementitious Composites (ECC). To deliberately introduce microcracks, specimens were pre-loaded to different deformation levels under splitting tensile loading and exposed to different environmental conditionings for the assessment of self-healing. Gas permeability (GP) and resonant frequency (RF) tests, crack characteristics observation and microstructural analysis were conducted to analyze the effect of cracking and healing on the properties of cementitious composites. Test results indicate that the self-healing effect determined through GP and RF tests was strongly influenced by changes in the chemical compositions of the mixtures. Application of pre-loading led to significant increases in GP results, so that even microcracks of less than 50 μm caused a GP coefficient fifty times higher than that of sound specimens. However, the recovery in GP results could be escalated up to 96% after only a month through proper material design and conditioning. It therefore appears that microcracking and subsequent healing is influential on the GP recovery rates of specimens, but not on RF recovery rates.

1. Introduction

The durability of concrete structures is governed by permeability and diffusion properties to a considerable extent [1]. However, in most cases, measurement of these properties is made on specimens that are not load-induced or cracked [2], which leads to underestimation of overall permeability results. It is therefore of great value to have knowledge of permeability and diffusion properties of both sound and damaged (cracked) concrete-like cementitious composites, since many deteriorating mechanisms affecting overall durability are closely connected to the flow of liquid and/or gaseous aggressive agents through porous or cracked media [3]. Once cracking takes place in the concrete material, it is almost impossible to maintain initial durability characteristics since cracks provide preferential access for aggressive agents such as water, chloride ions, oxygen, and carbon dioxide. Therefore, conventional cementitious composite materials have a high tendency to show cracking due to limited ductility, which must be minimized as much as possible to ensure enhanced durability. Within this context, materials that account for the high brittleness of traditional cementitious composites have recently come into prominence.

An ideal construction material lowers the possibility of cracking and keeps crack widths as tight as possible for greater durability. One such material, called Engineered Cementitious Composites

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(ECC), was first introduced by Li and his colleagues over the last few decades [4]. Using micro-mechanics based design theory, ECC was deliberately engineered to achieve controlled tight cracks under excessive loading in tension. Formation of multiple microcracks is an intrinsic property of ECC, and it is not influenced by rebar ratio and structural dimensions. This characteristic occurs due to the delicate balance of fiber, matrix and interface, which suppresses localized brittle failure and improves strain-hardening behavior. Nowadays, ECC with crack widths of less than 100 μm can easily be produced. Given its well-controlled multiple tight cracking behavior, ECC is a unique material that may significantly contribute to self-healing, which is a mechanism highly dependent on the formation of cracks with tight widths [5–7].

Self-healing phenomenon in cementitious materials is an attractive characteristic, and studies related to it are growing in number. The term "self-healing" refers to the ability of a material to seal cracks, and is attributable to the continuous hydration of anhydrous cementitious materials and carbonation, which form stable $CaCO_3$ after the reaction between portlandite and CO_2 or carbonic acid dissolved in water. Although both mechanisms are effective in sealing cracks, self-healing is mainly associated with the carbonation [5,8]. Self-healing that occurs through carbonation is mainly responsible for changes in transport properties, and is therefore important for infrastructures such as underground structures, offshore structures, water tanks, water channels and dams where impermeability is of significance. The influence of self-healing on several permeability properties has been studied extensively. Lepech and Li [9] studied the water permeability of mechanically loaded standard ECC (also called M45) and reinforced mortar specimens. They concluded that regardless of pre-loading deformation level, the water permeability coefficient of ECC specimens stabilized in time as a result of self-healing, and as long as crack widths were kept under the 100 μm threshold, the permeability coefficient remained nearly identical to that of sound material, indicating that cracking is not an issue in terms of water permeability up to a certain limit. Sahmaran et al. [10], however, concluded that unlike water permeability properties, microcracking significantly exacerbated the chloride ion permeability of ECC specimens incorporating different supplementary cementitious materials (SCMs). They determined that in addition to the permeability properties realized through the ingress of water and chloride ions, permeation of gaseous substances into cementitious materials is also of vital significance, considering carbonation, subsequent corrosion initiation and propagation. A large number of research papers focus on the evaluation of gas permeability of concrete mixtures in terms of both mechanical and durability perspectives. However, to the best of the authors' knowledge, there is a lack of study focusing on self-healing of cracks in which the extent is assessed through air-flow measurements, especially in the case of strain-hardening cementitious composites. The study described in this paper addresses that absence.

To study self-healing from this perspective, ECC mixtures incorporating three different SCMs (i.e. Class-F fly ash [F], Class-C fly ash [C] and ground granulated blast furnace slag [S]) were produced. To generate microcracks over the specimens, different levels of splitting tensile deformations were introduced through mechanical pre-loading. Pre-loaded and sound specimens were exposed to two different environmental regimes (continuous air [CA] and continuous water [CW]) to pre-determined testing ages. The study focused primarily on the influence of cracking and subsequent healing on the gas permeability (GP) properties of cementitious composites incorporating different SCMs. In addition to GP, resonant frequency (RF) measurements, X-ray diffraction analysis (XRD) and scanning electron microscopy (SEM) observations were also performed to assess the effects of cracking and self-healing.

2. Experimental program

2.1. Materials, mixture proportions and basic mechanical properties

During ECC mixture production, three different SCMs representing a large spectrum of chemical compositions from highly pozzolanic to almost cementitious (low calcium – Class-F fly ash [F_ECC], high calcium – Class-C fly ash [C_ECC] and ground granulated blast furnace slag [S_ECC]) were used. As shown in Table 1, all mixtures were produced with a water to cementitious material ratio (W/CM) of 0.27 and a mineral admixture (fly ash [FA] or slag [S]) to Portland cement ratio (MA/PC) of 2.2. In addition to the three SCM types mentioned above, ingredients also included CEM I 42.5R type ordinary Portland cement (PC), silica sand with maximum aggregate size of 400 μm, polyvinyl alcohol fibers (PVA) of 8 mm in length and 39 μm in diameter with a nominal tensile strength of 1610 MPa and specific gravity of 1.3, water and high range water reducing admixture (HRWR). Chemical and physical properties of the different SCMs and PC are presented in Table 2. Particle size distributions of solid ingredients are shown in Fig. 1.

Ø150 × 300 mm cylindrical specimens were prepared for use in GP and RF tests. After 24 h inside the molds at 23 ± 2 °C, 50 ± 5% RH, specimens were demolded and subjected to moisture curing in plastic bags at 23 ± 2 °C, 95 ± 5% RH for 7 days. After the initial 7-day curing, further air curing was applied to the specimens under laboratory conditions at 23 ± 2 °C, 50 ± 5% RH until the age of 28 days. Before the commencement of GP and RF tests, basic mechanical properties of ECC mixtures covering compressive strength and flexural parameters (i.e. flexural strength and flexural deformation) were evaluated. Compressive strength tests were performed using 50 mm-cubic specimens. Characterization of flexural parameters was determined under four-point tensile loading of 360 × 75 × 50 mm (length × width × height) beam specimens. All tests related to mechanical properties were performed at the end of 28 days using at least six different specimens. Specimens were kept in plastic bags at 23 ± 2 °C, 95 ± 5% RH for 7 days, followed by additional 21 days under laboratory conditions at 23 ± 2 °C, 50 ± 5% RH. The basic mechanical properties of ECC specimens are tabulated in Table 1, which shows that all of the parameters were markedly affected by the use of different SCMs. For compressive strength results, average 28-day values for F_ECC, C_ECC and S_ECC specimens were 35.1, 46.7 and 72.5 MPa, respectively. The reason for the significant differences between S_ECC and fly-ash-bearing ECCs was found to be the high cementing value and large specific surface area of slag particles. The C_ECC specimens showed a 33% higher average compressive strength than F_ECC specimens, which was found to be in relation to the higher fineness and lime content of Class-C fly ash particles (Table 2). 28-day flexural strength results of ECC specimens fell between the values of 9.6 and 12.0 MPa, depending on SCM type.

Table 1
ECC mixture proportions and basic mechanical properties.

Mixture proportions	F_ECC	C_ECC	S_ECC
Cement	1	1	1
W/CM	0.27	0.27	0.27
Aggregate/binder ratio	0.36	0.36	0.36
FA/PC	2.2	2.2	–
S/PC	–	–	2.2
PVA, by volume (%)	2	2	2
HRWR (kg/m^3)	3.8	4.2	4.5
Basic mechanical properties (28 days)			
Compressive strength (MPa)	35.1	46.7	72.5
Flexural strength (MPa)	9.6	8.7	12.0
Flexural deformation (mm)	5.5	3.6	3.5

Table 2
Chemical and physical properties of Portland cement, fly ashes and slag.

Chemical composition	PC	F	C	S
CaO	61.43	3.48	15.50	35.09
SiO_2	20.77	60.78	46.97	37.55
Al_2O_3	5.55	21.68	11.86	10.55
Fe_2O_3	3.35	5.48	7.98	0.28
MgO	2.49	1.71	6.51	7.92
SO_3	2.49	0.34	3.47	2.95
K_2O	0.77	1.95	3.23	1.07
Na_2O	0.19	0.74	2.33	0.24
Loss on ignition	2.20	1.57	0.45	2.79
$SiO_2 + Al_2O_3 + Fe_2O_3$	29.37	87.94	66.81	48.38
Physical properties				
Specific gravity	3.06	2.10	2.27	2.79
Blaine fineness (m^2/kg)	325	290	306	425