Effects of Slag Content on Self-Healing Behavior of Engineered Cementitious Composites

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ABSTRACT

Slag, the by-product from blast furnace, is often used to partially replace the cement in engineered cementitious composites (ECC), a novel type of fiber reinforced concrete with self-healing potential. This study investigated the effects of slag content on self-healing robustness of ECC. Three different cement replacing ratios, i.e 0%, 30%, and 60% (referred as GGBS0, 30, and 60), were involved. For each slag content level, the healing-induced crack width recovery and resonant frequency (RF) recovery were check against a wide range of single-crack width (up to 300 μm). Such methodology eliminated the influence of crack width on self-healing, and focused on the effects of slag content only. The results show that GGBS30 had the most crack width recovery, allowing full RF recovery at crack width of 86 μm. For GGBS0 and GGBS60, the allowable crack width for full RF recovery was only 36 μm and 59 μm, respectively.

1. INTRODUCTION

The robustness of ECC self-healing depends on healing conditions, intrinsic crack width, and matrix chemical composition. While the first two factors are investigated in many studies, the effect of chemical composition is less understood. Current work focuses on the effect of slag, an important group of ingredients replacing Portland cement in ECC, on self-healing behavior of ECC, with attempt to separate the influence of crack width on self-healing.

2. MATERIALS AND METHODS

Type I Portland cement (CEM I 52.5N), ground granulated blast-furnace slag (GGBS), sieved river sands (below 600 μm in particle size), and 12mm PVA fibers (Φ=39 μm, nominal strength=1600 MPa) were used to make ECC specimens. The three mix designs with different GGBS content were shown in Table 1. Dog-bone tensile specimens were made using these mix designs for the tensile precracking-healing-evaluating program.

At the age of 40 days, dog-bone specimens were pre-cracked under uniaxial tension to produce a single crack with pre-determined crack width ranging from 0 to 300 μm for the self-healing study. For each mix design, all pre-cracked specimens together with three uncracked virgin specimens were conditioned for 14 wet-dry cycles to engage self-healing. Specifically, each conditioning cycle consists of one day in water and one day in air (20°C), which was suggested by Yang et al. [1]. Images of specimen surface before and after wet-dry conditioning were taken by Nikon DS-Fi2 high resolution camera equipped with high magnification zoom lenses to monitor changes of crack width and to reveal the morphology of healing products. For each specimen, three to six locations were measured and the average crack width was reported. The fundamental TRF of all specimens was measured before and after wet-dry cycles to evaluate the stiffness recovery of the sample as an indicator of self-healing. The normalized TRF, i.e. the ratio of TRF of pre-cracked specimen to TRF of virgin specimens experiencing the same wet-dry conditioning (average of three), was calculated and reported.

Table 2– Proportions of mix design in current research

Mix No.	Cement (kg/m^3)	GGBS (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	PVA fiber (kg/m^3)	SP (L/m^3)	slag/binder ratio	W/b ratio
GGBS0	1411	0	282	423	26*	3.6	0.00	0.30
GGBS30	976	418	279	418	26*	3.0	0.30	0.30
GGBS60	551	827	276	414	26*	2.4	0.60	0.30
GGBS0a	1411	0	282	423	8.5**	3.6	0.00	0.30
GGBS30a	976	418	279	418	8.5**	3.0	0.30	0.30
GGBS60a	551	827	276	414	8.5**	2.4	0.60	0.30

*The fiber content was fixed at 2% in volume fraction.

** The fiber content was fixed at 0.65% in volume fraction, to eliminate multiple cracking at relatively large crack width

3. RESULTS AND DISCUSSIONS

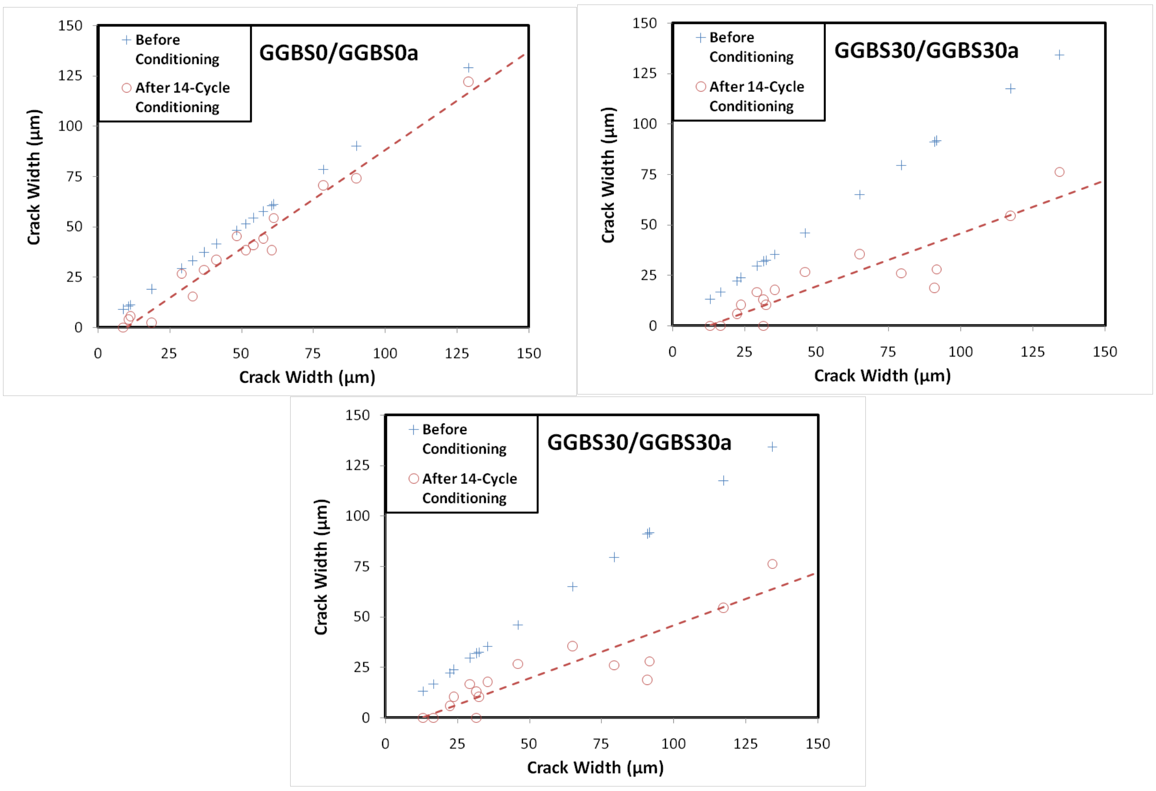

Figure 1: Crack widths before and after the 14-cycle conditioning of GGBS0/0a, GGBS30/30a, and GGBS60/60a

Fig. 1 shows the surface crack width recovery of the three groups as a function of initial crack width, i.e. GGBS0, 30and 60 before and after the 14 wet-dry conditioning cycles. As can be seen, GGBS content greatly affects the reduction of crack width. Of which, GGBS0 shows minimum crack width reduction while GGBS30 exhibits the highest potential to engage $CaCO_3$ precipitation in cracks for healing. The precipitation of CaCO3 highly depends on the amount of free calcium ion leached out from matrix in wetting conditioning. The free Ca^{2+} is provided from dissolving of $Ca(OH)_2$ in pore solution [2] which depends on two important factors: the amount of $Ca(OH)_2$ in matrix and the alkalinity of pore solution. Previous research on hydration of slag-blended cement indicated that slag consumes $Ca(OH)_2$ and lowers the pH of pore solution [3]. While GGBS30 may have less $Ca(OH)_2$ content in matrix as compared to that of GGBS0, lower pH in pore solution of GGBS30 greatly promotes the dissolution of $Ca(OH)_2$ and results in higher overall free Ca2+ in the pore solution of GGBS30 system. At higher GGBS replacement ratio, i.e. GGBS60;however, less $Ca(OH)_2$ is generated from cement and much of the $Ca(OH)_2$ is consumed by slag [4], and therefore less free Ca^{2+} is available in the pore solution as compared to that in the GGBS30 system. As a result, GGBS30 shows the highest potential to engage CaCO3 precipitation in cracks for healing followed by GGBS60 andGGBS0.

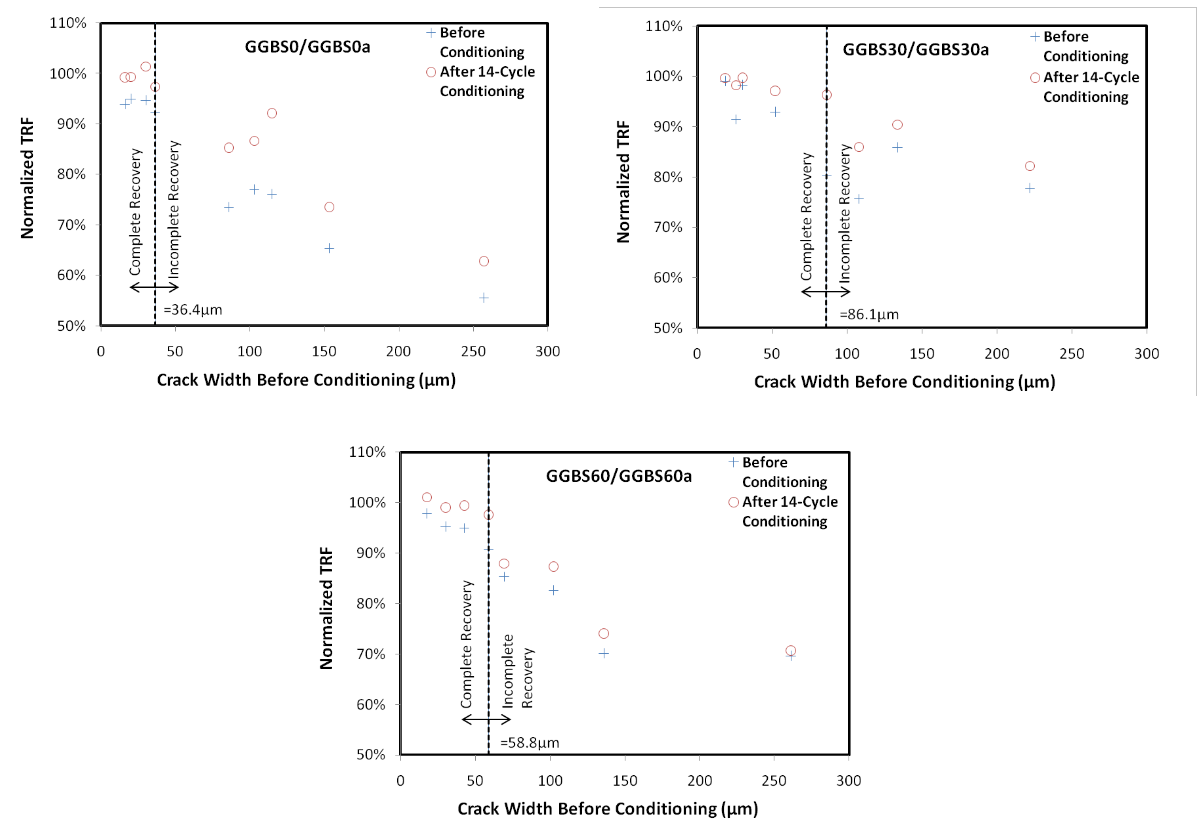

Figure 2: Normalized transverse resonant frequency (TRF) as a function of crack width from GGBS0/0a, GGBS30/30a, and GGBS60/60a

Fig.2 shows the normalized TRF as a function of single crack width for different GGBS content before and after 14 cycles of wet-dry conditioning. Before conditioning, pre-cracked specimens had remarkably lower TRF compared to uncracked specimens. As shown in Fig. 2, GGBS30 allows complete recovery of TRF as long as the crack width is less than 86 μm while the maximum allowable crack width for complete recovery of TRF for GGBS60 and GGBS0 are 59 µm and 36 µm, respectively. It again shows GGBS30 has better potential to engage self-healing and this corresponds well to the observation on crack width reduction in Fig.1.

4. CONCLUSIONS

Current research studies the influence of GGBS content on mechanical properties of ECC and on self-healing. Compressive strength, tensile stress-strain curves, and flexural strength-deflection curves of GGBS-ECC were tested. Crack width reduction as well as recovery of transverse resonant frequency (TRF) on single-cracked specimen after 14 wet-dry conditioning cycles were monitored to reveal the effect of GGBS content on self-healing.

Increase of GGBS content results in higher compressive strength, tensile strength and MOR due to continuous hydration of GGBS in the presence of $Ca(OH)_2$ in pore solution. GGBS content greatly affects self-healing. While the replace of cement by GGBS causes less $Ca(OH)_2$ in matrix, lower pH in pore solution of GGBS-cement system greatly promotes the dissolution of $Ca(OH)_2$ and results in higher overall free Ca^{2+} in the pore solution. As a result, GGBS30 shows the highest potential to engage $CaCO_3$ precipitation in cracks for healing followed by GGBS60 and GGBS0.

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