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Self-healing properties of ECC according to types of binders

* Huy Hoàng Nguyễn[1)], Jeong-Il Choi[2)], and Bang Yeon Lee[3)]

[1), 2), 3)] School of Architecture, Chonnam National University, Gwangju 61186, Republic of Korea
[1)] hoanghuyjnu92@gmail.com
[2)] himancji@naver.com
[3)] bylee@jnu.ac.kr

ABSTRACT

The paper presents an experimental investigation on the self-healing properties of engineered cementitious composites (ECC) using different calcium-based binding materials, i.e., Portland cement, calcium-based expansive agent (CEA), and ground granulated blast-furnace slag (GGBS). Three mixtures, according to types of binders, were designed and prepared. Polyethylene (PE) fiber with a high tensile strength was used to attain a good fiber bridging capacity for all composite mixtures. The test results showed that all mixtures achieved self-healing efficiency. Especially, the mixture using a high amount of cement had a remarkable self-healing ability, demonstrated by excellent crack width reduction after 36 healing days, compared to two other mixtures.

1. INTRODUCTION

Self-healing phenomena is a natural property that allows the wound to be healed automatically, occurred in both humans and animals. In this light, concrete has been developed to be capable of restoring its original quality after experiencing a cracking event. Generally, the self-healing on concrete was designed based on autogenous healing and autonomic healing, reported by RILEM Committee (2013). Autogenous healing is a terminology related to the automatic generation of new healing materials filling the cracks, whereas autonomic healing involves the healing supports from man-made actions or artificial assistance. Interestingly, engineered cementitious composites (ECC), which were first invented by Li (1990), are the unique construction materials achieving superb mechanical properties and even autogenous healing efficiency and also called strain hardening cementitious composites (SHCC). Based on the micromechanical concept design, ECC show a good tensile performance with a controlled crack width. According to Yang (2009), the crack width on ECC below 60 μm

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[1)] Graduate Student
[2)] Postdoctoral Research Fellow
[3)] Professor

can be perfectly healed after several wet-dry cycles. Although the self-healing behavior of ECC has been demonstrated in the previous literatures from Zhang (2017), Liu (2017), Zhang (2018), and Deng (2018), it is difficult to find the information available in developing self-healing ECC using a different kind of binding materials. Therefore, the purpose of this study is to investigate the self-healing capacity of ECC pre-cracked at a certain tensile strain according to the types of binders. Through crack width analysis, the self-healing of ECC was completely clarified.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials and mix design

Portland cement (PC), calcium-based expansive agent (CEA), and ground granulated blast-furnace slag (GGBS) were the principal binding materials used in the current study. In detail, Table 1 shows the mix proportions of each composite mixture.

Table 1. Mix proportions

Mix ID	Binder			Sand	Water	SP	VMA	DF	Fiber (vol %)
	PC	CEA	GGBS						
S-C	0.75	-	0.25	0.5	0.35	0.01	0.001	0.001	1.75
S-E	0.70	0.10	0.20	0.5	0.35	0.01	0.001	0.001	1.75
S-S	0.20	-	0.80	0.5	0.30	0.01	0.001	0.001	1.75

Polyethylene fiber (PE) with a high aspect ratio was applied to reinforce ECC. As reported by Zhang (2020), PE fiber is appropriate to develop ECC that have good potential for mechanical behavior, specifically on strength and tensile ductility. Table 2 shows the physical properties of the PE fiber used.

Table 2. Mechanical properties of PE fiber

Diameter (μm)	Length (mm)	Aspect ratio	Tensile strength (MPa)	Elastic modulus (GPa)
16	12	750	3 030	112

2.2 Mixing procedure

The dry ingredients were first mixed in a Hobart mixer within three minutes. Then, water was slowly poured into the mixture and mixed for another two minutes. Once the mixture obtained a homogenous condition, PE fiber was carefully inserted into the mixture and mixed around three additional minutes. To guarantee that the fiber was well distributed in the paste, superplasticizer (SP) and viscosity modifying admixture (VMA) were simultaneously added into the fresh mixture. Furthermore, a defoamer (DF) was also charged into the mixture to prevent the generation of air bubbles inside and outside the composites. The last mixing process after adding the chemical admixtures was about two minutes to ensure that all ingredients were well mixed.

Afterward, the fresh mixture was cast into the dumbbell-shape molds (tensile mold) to prepare for the self-healing test. The minimize the moisture evaporation, a plastic sheet was used to cover on the surface of the specimens. The specimens were removed from the molds after two days and put under a water tank (saturated moisture condition) regarding a room temperature at 23 ± 3 ºC until 28 days of age.

2.3 Compressive strength and tension tests

A compressive strength testing machine with a capacity of 300 kN was used for the compressive strength tests, performed according to ASTM C109/C109M. An electrical tension test machine with a capacity of 20 kN was used for tension tests, performed according to the recommendations of the Japan Society of Civil Engineers.

2.4 Self-healing evaluation

At 28 days of age, the tensile specimens were pre-cracked by applying a static load through a universal tensile testing machine followed by the recommendation of the Japan Society of Civil Engineers (2008). The test setup can be referred on the previous literature of Nguyễn (2018). The tensile machine with a capacity of 20 kN was operated at a strain rate of 2.08×10^{-5} 1/s. The tensile load was released once the pre-tensile strain was equal to 2% for the S-C and S-E mixtures and 1% for the S-S mixture. The reason that the pre-strain level of the S-S mixture was lower than two other mixtures because its crack width was quite large, which was determined through a preliminary test, inducing a failure on the specimens. After un-loading, the tensile specimen was taken out from the tensile machine and the crack width on the specimen surface was also observed immediately using an optical microscope at a reasonable magnification of ×84. Overall, there were 24 positions were randomly selected along the gauge length of the tensile specimens. Once the crack width measurement was done, the specimens were submerged again under the water tank throughout 36 healing days. In other words, water was the major condition to trigger the self-healing ability on ECC in this study. The observation process was employed every 7 days throughout the healing timeline. At the final healing day, the self-healing capacity of each mixture was analyzed and compared based on the magnitude of crack width before and after the healing process.

3. RESULTS AND DISCUSSION

3.1 Compressive strength and tensile behavior

The compressive strength values of each mixture are listed in Table 3. All mixtures showed high values of compressive strength, over 94 MPa. Specifically, the S-C mixture had the highest value of compressive strength, higher than those of the S-E and S-S mixtures, respectively, by 10.1% and 8.5%. The compressive strength values of S-E and S-S mixtures were not significantly different.

Table 3. Compressive strength

Mixture	Compressive strength (MPa)
S-C	103.6 (±4.3)
S-E	94.1 (±1.3)
S-S	95.5 (±3.4)

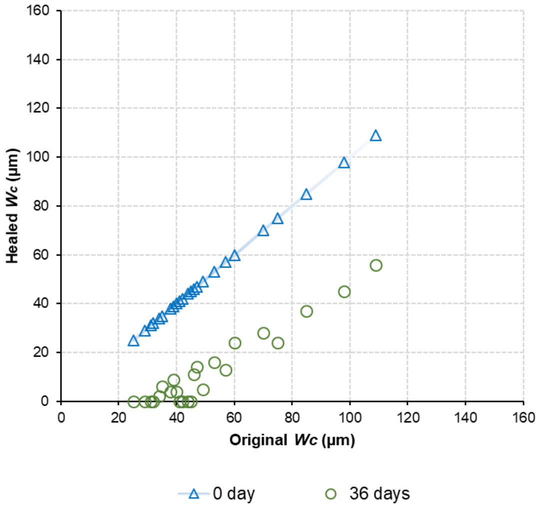
Table 4 provides quantitative information about the tensile performance, i.e. first cracking strength (f_{cr}), tensile strength (f_{ts}), and tensile strain capacity (ε_t). Generally, all mixtures achieved a high tensile strength identical to or greater than 8 MPa and high tensile strain capacity over 4.6%.

Table 4. Tensile properties

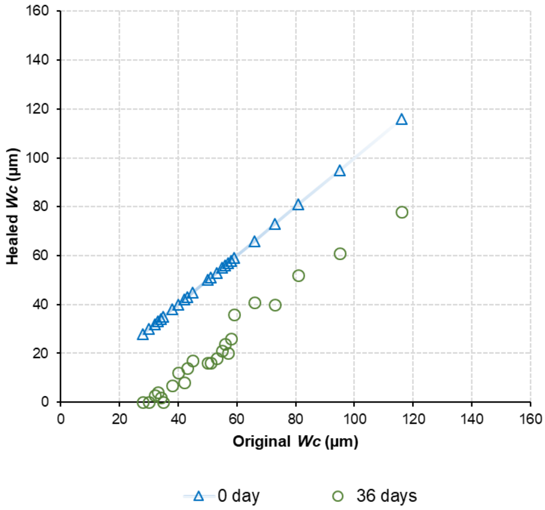
Mixture	f_{cr} (MPa)	f_{ts} (MPa)	ε_t (%)
S-C	3.65 (±0.31)	8.00 (±0.51)	5.25 (±0.76)
S-E	5.21 (±0.66)	8.07 (±0.81)	4.75 (±1.24)
S-S	3.53 (±0.60)	8.24 (±0.61)	4.68 (±0.81)

3.2 Self-healing properties

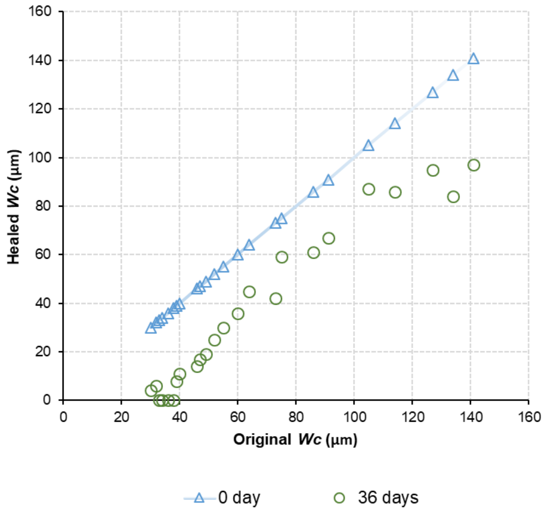
Crack width (W_c) observation is one of the preliminary methods to access the autogenous healing efficiency on the surface of ECC through crack width reduction with time, as expressed by Qiu (2016). To accurately evaluate the healing potential regarding W_c reduction, all W_c selected on each mixture is specifically presented in Fig. 1. The figure includes x and y-axis, corresponding to the original W_c and healed W_c, respectively. There was a 45-degree gradient blue line drawn to highlight the W_c with no healing. Based on the distance between the final green dots and the horizontal axis, the autogenous healing performance could be quickly assessed. In other words, if the green dots are on the x-axis, it indicates the complete healing. Otherwise, if the dots are suspended below the 45-degree line, it demonstrates the partial healing.



(a)



(b)



(c)

Fig. 1 Crack width reduction observed on the specimens' surface of: (a) S-C, (b) S-E, and (c) S-S mixtures

As described, W_c was in the range from 20 μm to 120 μm for the S-C and S-E mixtures, whereas W_c was in the range from 20 μm to 140 μm in the case of the S-S mixture. It should be noted that although the S-S mixture was applied by 1% of tensile strain at the pre-loading event, it had the larger W_c compared to the other mixtures applied by 2% of tensile strain. As seen, W_c on all mixtures was decreased over time, revealing the autogenous healing potential of ECC. Besides, the smaller W_c had more self-healing potential compared to the larger W_c. Overall, the S-C mixture showed good healing performance than two other mixtures because it had more W_c to be returned zero or better partial healing regarding narrower W_c at the final healing stage. The healing ability of the S-E and S-S mixtures was quite similar although it might be recognized that the S-E mixture had a slight healing advantage compared to the S-S mixture due to better partial healing performance. According to the statistical data, the average crack width for fully healing on the S-C, S-E, and S-S mixtures was 36.1 µm, 31 µm, and 35.3 µm, respectively. Those values are quite consistent with the previous study on self-healing ECC of Yang (2009) when ECC has the complete healing threshold with regard to W_c below 50 µm. Fig. 2 shows the representative self-healing phenomena on the best mixture named S-C.

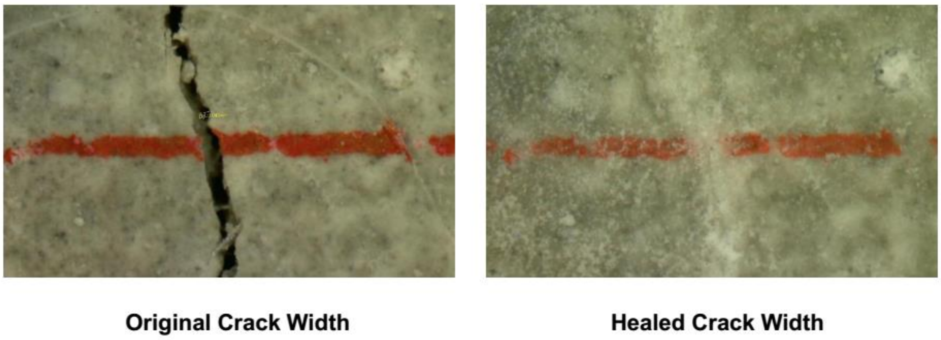


Fig. 2 Self-healing phenomena on the S-C mixture

Through W_c reduction, the autogenous healing performance of each mixture has been assessed generally; however, a direct approach derived from W_c statistics was needed to achieve the most accurate healing outcomes. Following that, the healing rate (ε_h) is an appropriate technique utilized. Based on the original W_c and W_c at the final healing stage (W_{fh}), ε_h can be defined in Eq. (1).

$$\varepsilon_h = 100 - \frac{W_{fh}}{W_c} \ (\%), \tag{1}$$

Theoretically, higher ε_h, higher autogenous healing ability. In detail, Fig. 3 represents ε_h for all mixtures at the final healing period accompanying standard deviation.

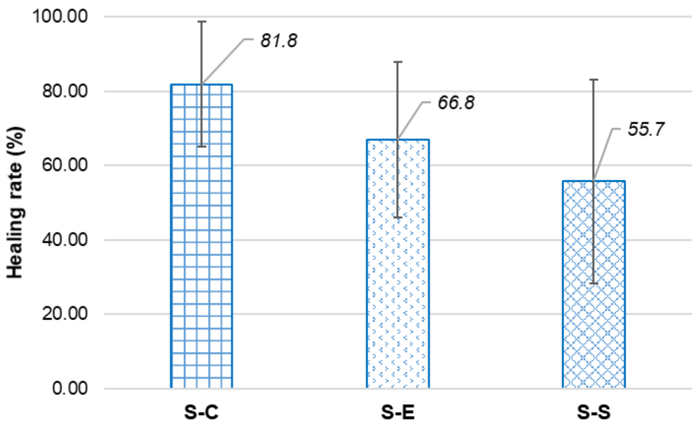


Fig. 3 Healing rate on each composite mixture

As realized, ε_h of all mixtures was positive, which is over 50%, indicating the potential of autogenous healing. Furthermore, ε_h of the S-C mixture was higher than that of the S-E and S-S mixtures by 15.0% and 26.1%, respectively. On the other hand, it can be seen that the standard deviation of the S-C mixture was relatively smaller than those of other mixtures. This means that the crack healing on the S-C was more uniform compared to two other mixtures. Overall, the autogenous healing performance of ECC based on W_c and ε_h can be arranged in the order of S-C > S-E > S-S.

4. CONCLUSIONS

Self-healing properties of ECC using different types of binders have been investigated in the paper. All mixtures showed the self-healing efficiency; however, the self-healing ability of each mixture was completely different. The mixture including a high amount of cement (S-C) achieved the best healing performance regarding the greatest crack width reduction and healing rate over 80%.

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REFERENCES

Committee, J.C. (2008), “Recommendations for design and construction of high performance fiber reinforced cement composites with multiple fine cracks", *Japan Society of Civil Engineers, Tokyo, Japan*.

De Rooij, M., Van Tittelboom, K., De Belie, N., & Schlangen, E. (2013), “Self-healing phenomena in cement-Based materials: state-of-the-art report of RILEM technical committee 221-SHC: self-Healing phenomena in cement-Based materials” *(Vol. 11): Springer*.

Deng, H., & Liao, G. (2018), “Assessment of influence of self-healing behavior on water permeability and mechanical performance of ECC incorporating superabsorbent polymer (SAP) particles”, *Constr. Build. Mater.*, **170**, 455-465.

Li, V.C., Wang, Y., & Backer, S. (1990), “Effect of inclining angle, bundling, and surface treatment on synthetic fiber pull-out from a cement matrix”.

Liu, H., Zhang, Q., Gu, C., Su, H., & Li, V. (2017), “Self-healing of microcracks in Engineered Cementitious Composites under sulfate and chloride environment”, *Constr. Build. Mater.*, **153**, 948-956.

Nguyễn, H.H., Choi, J.-I., Song, K.-I., Song, J.-K., Huh, J., & Lee, B.Y. (2018), “Self-healing properties of cement-based and alkali-activated slag-based fiber-reinforced composites”, *Constr. Build. Mater.*, **165**, 801-811.

Qiu, J., Tan, H.S., & Yang, E.-H. (2016), “Coupled effects of crack width, slag content, and conditioning alkalinity on autogenous healing of engineered cementitious composites”, *Cem. Concr. Compos.*, **73**, 203-212.

Yang, Y., Lepech, M.D., Yang, E.-H., & Li, V.C. (2009), "Autogenous healing of engineered cementitious composites under wet–dry cycles", *Cem. Concr. Res.*, **39** (5), 382-390.

Zhang, D., Yu, J., Wu, H., Jaworska, B., Ellis, B.R., & Li, V.C. (2020), "Discontinuous micro-fibers as intrinsic reinforcement for ductile Engineered Cementitious Composites (ECC)", *Compos. B Eng.*, **184**, 107741.

Zhang, P., Dai, Y., Ding, X., Zhou, C., Xue, X., & Zhao, T. (2018), "Self-healing behaviour of multiple microcracks of strain hardening cementitious composites (SHCC)", *Constr. Build. Mater.*, **169** 705-715.

Zhang, Z., & Zhang, Q. (2017), "Self-healing ability of Engineered Cementitious Composites (ECC) under different exposure environments", *Constr. Build. Mater.*, **156** 142-151.