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2019

Zhang, Z., Ding, Y., & Qian, S. (2019). Influence of bacterial incorporation on mechanical properties of engineered cementitious composites (ECC). *Construction and Building Materials*, 196195-203. doi:10.1016/j.conbuildmat.2018.11.089

<https://hdl.handle.net/10356/81427>

<https://doi.org/10.1016/j.conbuildmat.2018.11.089>

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Influence of bacterial incorporation on mechanical properties of engineered cementitious composites (ECC)

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Abstract: Incorporation of bacterial technology in concrete has attracted the attention of many researchers in the past decades. While much of the attention was focused on crack self-healing in concrete, it was also observed that such incorporation sometimes alter the mechanical properties of concrete significantly. There are very few studies related to the material performance of fiber reinforced concrete containing bacteria. In this paper, the bacteria were incorporated into engineered cementitious composites (ECC), and its mechanical properties were investigated systematically. At composite performance level, it was found that both compressive and tensile strength increased in bacteria-ECC, meanwhile the ECC with bacteria of higher activity presented more pronounced effect. Furthermore, crack pattern of ECC was also improved due to the addition of bacteria as smaller crack width was observed. In contrast, tensile strain capacity of bacteria-ECC reduced as compared with normal ECC, but still retained at high level. At microscale level, fracture toughness of matrix containing bacteria was higher than that of control mix. Additionally, matrix/fiber interface properties were altered in bacteria-ECC with lower chemical bond and higher frictional bond strength. The findings at microscale well explain the change in composite performance of ECCs based on micromechanics theory.

Keywords: ECC; bacteria; strength; ductility; interface alteration.

Introduction

Concrete is the most consumed construction material worldwide and contributes greatly to the modern civil infrastructures in the past century. Nevertheless, due to its inherent brittleness and low tensile strength, cracking in concrete is inevitable during the service lifetime of concrete infrastructures. Normally, steel rebars are provided to reinforce the concrete in structures, therefore, the crack usually will not cause the collapse of structure directly. Nevertheless, it will accelerate the degradation of concrete by providing preferable aisle for aggressive chemicals to enter inside and corrode the steel rebar, which will endanger safety of concrete structures. Hence, maintenance and repair works are needed to seal cracks in concrete to prolong the service life of civil infrastructures. However, current repair techniques are often expensive and ineffective which needs cycles of repair. To address this issue of unsustainable cycles of repair, concrete enabled with self-healing capacity stands out as a promising approach for sustainable infrastructure development which potentially requires much less repair and maintenance work.

To realize the self-healing capacity in concrete, as an alternative strategy to continuous hydration based self-healing[1-3], high pH tolerant bacteria were incorporated into concrete mixture by use of its capacity of calcium carbonate precipitation induction in the past decade [4, 5]. When cracks are initiated in concrete, the bacteria attached to the crack surface are likely to be activated because of their contact with oxygen and moisture, and precipitate CaCO_3 to heal the cracks [5]. It has attracted many researchers to conduct related studies since the effective self-healing phenomenon by alkaline tolerant bacteria was observed.

Considering the harsh environment inside concrete, a protective carrier is preferable to encapsulate or immobilize bacteria to improve its viability in concrete. It has been proved that crack with millimeter size can be healed this way. Wang et al used the diatomaceous earth to immobilize bacteria, and found that cracks with width of 0.17 mm could be healed completely [6]. Besides that, they also found that the maximum crack width healable is about 0.5 mm and 0.97 mm, respectively, when using hydrogel and poly-condensation reaction based microencapsulation process to serve as the carrier [7, 8]. Khaliq et al reported that the light-weight aggregate could be the bacteria-immobilized carrier to help the concrete heal the crack with width of 0.61 mm [9]. Moreover, immobilized bacteria with expanded perlite, zeolite and graphite nanoplatelets (GNP) et al also exhibit very efficient self-healing phenomenon in concrete [9-11].

In contrast to its benefits on self-healing, incorporation of bacterial carrier into concrete is likely to decrease the compressive and flexural strength of concrete in most instances, which is unacceptable in the practical application [9, 12, 13]. Some researchers investigated the mechanical properties and self-healing behavior of concrete after adding bacteria directly in the mixing. Bundur et al incorporated vegetative bacteria cells into cement paste directly, and demonstrated that calcium carbonate content had a substantial increase by thermogravimetric analysis (TGA). This suggested the encapsulation of bacteria in the cement paste might not be necessary to achieve the goal of self-healing [14]. Khaliq and Keishnapriya et al found that with no carrier the maximum healable crack width reduced as compared to the one with carrier, but could still heal the cracks with 0.3 mm width [9, 15]. On the other hand, an improvement on compressive strength of mortar was observed when bacterial cells were suspended in water during mortar mixing [14, 15]. Some researchers used nutrition culture with inclusion of vegetative bacterial cells to replace the mixing water in mortar and concrete; it reported that the compressive strength increased as well when compared with control case where only water was used for mixing [15-23].

Unlike normal concrete where crack width could be very wide and difficult to control reliably even with steel reinforcements, engineered cementitious composites (ECC) is a kind of high performance fiber reinforced cementitious composites (HPFRCC), with unique characteristics of high tensile ductility and self-controlled tight crack width [24]. This makes it particularly suitable for the development of bacteria based ductile concrete without relying on sometimes expensive and detrimental carriers. As discussed before, when compared to the encapsulated one,

bacteria without carrier may heal less wide crack of 0.3mm width, which is still far beyond typical crack width range of ECC materials.

ECC was initially developed by Li, Leung and coworkers at 1990s based on micro-mechanics theory with feature of high strain capacity at range of 3~5% [25]. The unique high ductility in ECC is a result of careful tailoring of matrix, fiber, and matrix/fiber interface [26-33]. With given fiber, the balance between matrix and matrix/fiber interface properties plays a decisive role on the production of ECC. Dissimilar to typical localized fracture in normal concrete, ECC presents multiple cracking behaviors under tension, meanwhile, average crack width could be controlled at around 60~80 μm [34-38].

More interestingly, with such tiny crack width, micro-crack in ECC has the capacity to heal itself autogenously through continuous hydration of unreacted cementitious materials and precipitation of CaCO_3 within crack space [2, 39, 40]. Nevertheless, such self-healing products could only fully fill very tight cracks when crack width is below 50 μm , beyond which they are mostly incompletely healed [1, 39]. It would be very desirable if the wider cracks in ECC could be self-healed more completely. Incorporation of bacteria into ECC may provide an alternative and effective approach to address this issue. On the other hand, it may also impact the mechanical properties of ECC as adoption of small amount of bacteria may alter the matrix and fibre/matrix interfacial properties, which becomes the focus of this study.

As discussed before, this study is focused on the effect of bacterial incorporation on the mechanical properties of ECC. The effect of bacteria on self-healing behaviour of ECC is not included in this paper, and it will be reported in the future. In the following sections, a brief introduction on ECC material design theory is presented first. This would be helpful for readers to understand the discussion in the later sections. The composite performance of ECCs including compressive strength, tensile behavior, and crack pattern are then reported. Finally, alteration of bacteria on the matrix toughness and fiber/matrix interface are also discussed at the microscale level.

2. ECC design consideration

The cornerstone of high ductile ECC lays in two criteria which are necessary to be satisfied for attaining strain-hardening behaviour [25, 41]. The two criteria, that is energy criteria and strength criteria, are listed in the following equations (1) and (2).

$$\text{Energy based criterion: } J_{tip} \leq \sigma_0 \delta_0 - \int_0^{\delta_0} \sigma(\delta) d\delta \equiv J'_b \quad (1)$$

$$\text{Strength based criterion: } \sigma_0 > \sigma_{cs} \quad (2)$$

Where σ_0 is the maximum bridging stress corresponding to the crack opening δ_0 ; σ_{cs} is the strength of initiating crack in matrix under tension; J_{tip} is the energy needed for the propagation of crack in matrix; J'_b is the complementary energy.

Equation (1) expresses the crack tip toughness J_{tip} needs to be less than the complementary energy J'_b calculated from the fiber bridging stress versus crack opening (σ - δ) curve. This is the concept of energy balance during crack extension, that is, it should have adequate energy left for a crack to propagate (forming new surfaces

of the same crack) in steady state fashion after subtracting the energy consumed by opening initial crack from zero to δ_0 from the energy input provided by external loads. The satisfaction in energy-based criterion ensures the occurrence of steady state cracking which is necessary for multiple cracking behaviour of ECC. Equation (2) states that the cracking strength of matrix (σ_{cs}) must not exceed the maximum fiber bridging stress (σ_0). This criterion ensures subsequent cracks can be triggered before reaching peak fiber bridging stress, hence resulting in a multiple cracking pattern. Failure to satisfy either of the above two criteria will lead to tension-softening behaviour commonly observed in normal FRC, which is characterized by one localized fracture crack.

In ECC design theory, larger margins between J'_b and J_{tip} as well as σ_0 and σ_{cs} are preferred. An abundant energy left for crack propagation indicates better chance for cracks to experience steady state propagation instead of Griffith type crack. Normally, the pseudo strain hardening (PSH) index ($=J'_b/J_{tip}$) was used to quantitatively characterize the margin between J'_b and J_{tip} . It is suggested that an increase in J'_b or lower J_{tip} is desirable to obtain higher PSH index, thus gaining highly ductile ECC. As is known, the J_{tip} is associated with matrix toughness K_m , while J'_b has a very close relation with the matrix/fiber interface properties. For similar discussion on σ_0 and σ_{cs} readers are referred to Wang et al [42] and Kanda et al [43]. In this paper, the influence of bacterial addition on the matrix toughness and matrix/fiber interface are investigated to clarify the underlying mechanism for changes in ECC composite performance.

3. Experimental programs

3.1 Bacterial strains and cultures preparation

There are two bacterial strains: *Bacillus halodurans* DSM 497 (wild type from DSMZ, Germany) and the mutant one based on *Bacillus halodurans* DSM 497, which is obtained by transposon mutagenesis method as described in Ding et al's previous work [44]. The mutant is expected to have higher bacterial activity when comparing to the wild type strain. The bacterial activity is examined by CaCO_3 productivity. Three replicates were tested for each bacterial strain. After 3 days incubation, it was observed that the amount of CaCO_3 produced by mutant (4.4g) equals to 1.4 times that of the wild type (3.1g). This demonstrated higher activity of mutant bacterial strain compared with wild type one. The test details were as follows:

- 100 ml overnight cultures (the wild type and the mutant) were mixed with 100 ml 0.5 M CaCl_2 for incubation and CaCO_3 precipitation;
- Precipitated CaCO_3 was filtered by filter paper;
- Obtained CaCO_3 were dried in 60°C oven for 3 hours;
- Dried CaCO_3 powder was weighted.

Luria-Bertani (LB) was used in this study as typical medium for bacterial growth. For 1 L of LB broth medium, 25 g Luria-Bertani powder was added into 1000 g of distilled water (Approximate Formula for LB medium Per Liter: 10.0 g of Tryptone; 5.0 g of Yeast Extract; 10.0 g of Sodium Chloride). Then pH value of the medium was adjusted to 9.7 by addition of saturated Na_2CO_3 solution.

After LB medium was prepared, the bacteria were grown in it aerobically at 37 °C (1:100 inoculation). Compared with the wild type, the mutant strain showed a relatively high growth rate, which is reflected by very steep slope of optical density at 600 nm versus time curve (see Figure 1a). Under the same condition of overnight growth (37 degree, 200 rpm), the mutant culture seemed quite cloudy, as opposed to transparent look of the wild type group which appeared quite similar to nutrition only (see Figure 1b). The steady state phase bacterial cultures (OD600 of 0.01~0.1 equivalent to around 10^7 ~ 10^8 cells/ml) were used in preparation of ECC mixtures.

3.2 Materials and mix proportions

The ingredients in ECC include cement with strength grade of CEM 42.5, fly ash, fly ash cenosphere (FAC), mixing liquid (water and bacterial cultures), superplasticizer (SP), and Kuraray PVA fiber. To achieve high ductility in ECC, FAC is used to replace silica sand usually adopted in ECCs by equal volume. This is because the FAC in ECC has been proved to be beneficial to ductility by lowering matrix toughness and improving fiber/matrix interface properties [29, 45]. There are three mixtures as listed in Table 1. All mixture proportions are the same except for the type of liquid. For the bacteria-ECCs, bacterial culture is mixed with the solid ingredients by replacing water. In W-ECC and M-ECC, considering some nutrient substances in the liquid, the weight of liquid is slightly higher than water in control-ECC to keep water content constant for the three mixtures.

All three mixtures in this study were mixed using a shear-type Hobart mixer. All dry solid ingredients were mixed for 3 minutes at low speed. Then mixing liquid together with superplasticizer was added into the dry mixtures and mixed for another 3 minutes. Afterwards, the PVA fiber were added into the mortar and mixed for 5 minutes. After mixing, the fresh ECC material was cast into the moulds, and covered with plastic sheet before demolding. Due to influence of nutrient substances on hydration kinetics of cement, hardening time of paste was prolonged [14]. It took 3 days curing before bacteria-ECC can be demolded, while 1 day is enough for the demolding of control-ECC. Then all of the specimens were exposed to air curing for 28 days before test.

3.3 Experimental procedure

This paper focuses on the mechanical performance of ECC with incorporation of bacteria. The compressive strength and tensile properties, including tensile strength, tensile strain capacity and crack pattern, of ECCs are investigated at composite level. At microscale, effects of bacteria on the matrix toughness and matrix/fiber interface are also studied via three-point bending test and single fiber pull-out test, respectively.

3.3.1 Composite properties measurement

Uniaxial compressive test was employed in accordance with ASTM C109 to measure compressive strength of ECCs with specimen dimension of 50.8 x 50.8 x 50.8 mm [46]. This test was performed at 7 and 28 curing days for all ECC mixtures in this paper. Compressive strength of each mixture is obtained by averaging three samples.

Tensile performance of all ECC mixtures was characterized via uniaxial tensile test. The test set-up was illustrated in Figure 2. Dog-bone shaped specimen was

adopted and mechanically interlocked with fixtures instead of coupon specimen being gripped by hydraulic wedge clamps. This could avoid premature fracture in specimen because of stress concentration caused by clamping force. The dimensions of specimen in the gauge length zone are 120 mm (length) x 35 mm (width) x 15 mm (thickness). The quasi-static loading rate is 0.5 mm/min. Two external Linear Variable Differential Transformers (LVDTs) were attached to the tested specimen, thereby allowing deformation of the specimen to be recorded for the calculation of tensile strain.

3.3.2 Micro-scale properties measurement

ECC matrix toughness was measured on a notched beam specimen by three-point bending test according to ASTM E399 [47]. Detailed test set-up can be found in reference [29]. Three specimens with dimensions of 305 x 38 x 76 mm were tested for each mixture. Full span length between two bottom supporting points is 254 mm and the ratio of notch depth to beam height is 0.4.

Sample preparation for single fiber pull-out test is schematically illustrated in Figure 3. Long fibers were placed across rectangular prism mold and then fresh ECC matrix paste (without fibers) was cast into the mold. The prism sample with multiple long fibers was then cut into small pieces with thickness around 1 mm using a precision saw before testing at 28 curing days. Adoption of very thin sample in the test is to ensure successful capture of debonding process during pull-out process before fiber breakage. The detailed test set-up and procedures could be found in references [26]. By nature the data from single fiber test exhibit large scatter. Therefore, at least 8 successful results were averaged to obtain the mean value of chemical bond (G_d), friction force (τ_0), and slip hardening coefficient (β).

4. Experimental results and discussion

4.1 Composite performance

Figure 4 presents compressive strength of ECC mixtures at 7 and 28 curing days. It could be seen that bacteria-ECCs, including W-ECC and M-ECC exhibited increased compressive strength at both curing ages, although their hardening process was delayed at early age by bacterial culture, as reflected by longer duration needed for demolding. Compressive strength of control-ECC, W-ECC, and M-ECC reached 34.4 MPa, 41.1MPa and 43.3 MPa respectively at 28 curing days. Incorporation of wild type and mutant bacteria led to 19% and 26% increment in compressive strength, respectively. Additionally, M-ECC with higher activity of bacteria shows the highest compressive strength among the three ECC mixtures.

Figure 5 displays scanning electron microscope (SEM) observed morphology on the fracture cross-section of M-ECC after tensile test. It shows that massive calcite-like pieces distributed inside ECC, that's most likely the resulting products of biochemical reactions by bacteria. The chemical constitutions of the small pieces detected by Energy dispersive spectroscopy system (EDS) are listed in Table 2. It could be concluded that the small pieces in Figure 5 is largely calcite by observing the atom ratio of Ca:C:O. It has been reported that the formation of CaCO_3 have positive impact on the compressive strength of concrete [48-50]. Additionally, the calcite

might deposit in the pores as filler material, thereby modify the microstructure and decrease the porosity of ECC [13, 18]. Prior studies also proposed that the bacteria in concrete were capable of accelerating carbonation of Ca(OH)_2 and CaCO_3 mineralization, which in turn, provides nucleation sites for C-S-H formation and subsequently accelerate further C-S-H formation [18, 48, 51]. The above discussions may shed lights on the enhancement of compressive strength in ECC with bacteria.

Figure 6 shows tensile stress-strain curves of ECC mixtures. The first cracking strength associated with matrix property, tensile strength and tensile strain capacity of ECC mixtures are derived from these curves. They are defined as the tensile stress at the end of initial elastic stage, ultimate tensile stress and the corresponding tensile strain, respectively. All these properties are summarized as bar graph in Figure 7.

It could be seen from the tensile test results that all ECC mixtures demonstrate pronounced tensile strain-hardening behavior, as reflected by their high tensile strain capacity. This denotes that the unique characteristic of ECC, high ductility, is retained for ECC after incorporation of bacteria. Figure 7 shows that, similar to the trend on compressive strength, addition of bacterial culture also enhances the first cracking strength and tensile strength of both ECCs with bacteria, between which the effect on ECC with mutant bacteria is more pronounced. Tensile strength of W-ECC and M-ECC is 4.97 MPa and 5.45 MPa, which is increased by 9.9% and 20.6%, respectively, when compared with 4.52 MPa of Control-ECC. On the other hand, due to the addition of bacterial culture, tensile strain capacity shows a slight decrease as compared with Control-ECC, especially for M-ECC. Nevertheless, its strain capacity is still more than 3.8% (around 380 times of normal concrete) which could satisfy the requirement of almost all practical applications.

The crack width in ECC is also considered a very important material property as it governs many transport properties of concrete under cracking status, therefore impacts on durability directly. Figure 8 shows crack width distribution in ECCs. With representative ECC specimen of each mixture, the crack width is read after unloading using light microscope with the accuracy of 10 μm . As shown in Figure 8, the maximum crack width in bacteria-ECC decreases while the number of narrow cracks increases, when compared with Control-ECC. This observation is plausible to suggest that a lower water permeability and aggressive ion penetration coefficient may be derived from cracked ECC with bacteria, thereby resulting in better durability.

Average crack width and total number of cracks in ECC are listed in Table 3. It can be seen that more cracks are initiated in bacteria-ECCs, whereas the average crack width is reduced. As mentioned previously, crack width is a key factor for the occurrence of self-healing phenomena in concrete. Due to the addition of bacterial culture into ECC, more cracks within 50 μm appear in W-ECC and M-ECC as illustrated in Figure 8. This indicates that more cracks could be healed autogenously by taking advantage of continuous reaction of cementitious materials. The rest cracks that are wider than 50 μm are expected to be sealed/healed via bacterially induced calcium carbonate precipitation.

To sum up the above discussions, incorporation of bacterial culture in ECC leads to improvement in most mechanical properties and crack pattern which are favorable

for the strength and durability of structural members. Although the tensile strain capacity reduces in bacteria ECCs in comparison with that of Control-ECC, it is still retained at high level. Overall, it can be concluded that incorporation of bacteria in ECC contributes positively to the overall mechanical performance provided adequate tensile strain capacity can be maintained.

4.2 Microscale study

Based on ECC design theory, bacteria induced composite properties alteration can be further explained from the micro-mechanics described in section 2. Matrix fracture toughness of ECC mixtures is shown in Figure 9. As expected, the matrix fracture toughness (K_m) increases with the addition of bacterial culture, among which the mixture with mutant bacteria presents the highest value presumably due to its higher activity. This trend explains the enhancement of the first cracking strength in W-ECC and M-ECC. The crack tip toughness J_{tip} ($=K_m^2/E_m$) calculated based on K_m and stiffness (E_m) of matrix also shows very similar trend with that of matrix fracture toughness. The stiffness of matrix is from the slope of initial linear elastic stage in tensile stress-strain curves as shown in Figure 6. Albeit rather gentle, the increase of J_{tip} is undesirable for achieving higher PSH ($=J'_b/J_{tip}$) index and ductility of ECC.

Besides the crack tip toughness (J_{tip}), the interface parameters which have decisive impact on complementary energy (J'_b) are also critical to the PSH index. The matrix/fiber interface parameters including chemical bond (G_d), frictional bond strength (τ_0), and slip-hardening coefficient (β) are displayed in Figure 10. Very interestingly, the chemical bond (G_d) and slip-hardening coefficient (β) drop with the addition of bacterial culture under the same mixture proportion. The average G_d values for W-ECC and M-ECC are 0.44 J/m² and 0.16 J/m², respectively, and are considered rather low for PVA fiber [26]. Lower chemical bond denotes easier fiber debonding from its surrounding matrix without being ruptured. Hence, it allows more fibers to enter pull-out stage, which is critical to maintain the fiber bridging effect across crack, and therefore favor the increase of J'_b .

The reduction of chemical bond is probably caused by some of the bacterial metabolic products that are attached to the surface of PVA fiber. To validate this hypothesis, the surface of PVA fiber in ECC was observed by fluorescence microscopy. To facilitate for this observation, PVA fibers were obtained from the fractured cross-section of ECC specimen after tensile test, and then stained by 4'6-diamidino-2-phenylindole (DAPI) for 15 minutes under dark condition. After that, the stained fibers were transferred into Zeiss Axio Observer Z1-Inverted epifluorescence laser system (Carl Zeiss AG, Germany) for observation using 40 x lenses with wavelength of 405 nm. As shown in Figure 11(b), the biofilm formation and bacterial aggregation (green colour) were attached to the surface of fiber from M-ECC specimen, which was not the case for fiber from control ECC specimen (Figure 11(a)). It seemed plausible that in addition to the oil-coating, biofilm formation on the PVA fiber further reduced the Al^{3+} and Ca^{2+} concentration at the matrix/fiber interface. As these two ions are critical for the development of strong interfacial thin layer between PVA bulk polymers and surrounding hydration products, their reduced concentration will lower the chemical bond (G_d) [52]. In comparison to

wild type bacteria, mutant bacteria in ECC are expected to generate more metabolic products on the fiber surface because of higher activity, therefore resulting in greater reduction in G_d .

The frictional bond strength (τ_0) shows a reverse trend with G_d and β . It indicates that the bio-coating on the fiber surface doesn't play the lubrication role as that induced by oil-coating and concentrated carbon particle from bottom ash [26, 42]. On the contrary, bio-coating reduce the lubrication effects of oil-coating on fiber surface. A higher τ_0 means stronger frictional force at interface to resist fiber sliding. As a result, crack width is reduced, which is clearly observed in ECC specimens with bacteria in Figure 8 and Table 2. As the frictional bond is closely related to the stiffness and packing density of the interfacial transition zone (ITZ), the higher τ_0 may be contributed by higher stiffness/compactness of ITZ caused by bacterial induced calcite.

As shown in Figure 12, theoretical fiber bridging stress-crack opening displacement relationship is derived based on the interface parameters using micro-mechanics theory [53]. Theoretical complementary energy (J'_b) could be obtained from this kind of curves. The diminishment of chemical bond (G_d) as observed in bacteria-ECC decreases the intersection value between σ - δ curve and Y-axle as shown in Figure 12 (zoom in), and should shift the curve towards lower right, therefore increase the J'_b value [26]. Conversely, the higher frictional bond strength (τ_0) bends the curve to upper left, hence increases the slope of raising branch of the curve. Overall, the combination of these two competing effects reduces the J'_b value. As aforementioned in Figure 9, incorporation of bacterial culture increased crack tip toughness J_{tip} . Considering the trends of J'_b and J_{tip} due to incorporation of bacteria, the PSH index (J'_b/J_{tip}) will surely decrease which is not conducive to high ductility of ECC.

Figure 13 compares the trend of PSH index and tensile strain capacity of ECCs. It shows that the strain capacity of ECC mixtures decreases along with PSH index when the mixture varies from Control-ECC to W-ECC and M-ECC. This observation again suggests that the PSH index can be a robust indicator for tensile strain capacity. On the other hand, the up left shift of the σ - δ curves denotes the growth of maximum fiber bridging stress, which explains the increase of tensile strength in bacteria-ECC specimens.

Overall, friction bond strength increasing prevails over chemical bond decreasing on their effect to J'_b , resulting in the decrease of PSH index. However, it should be pointed out that the reduction of G_d value due to simple bacterial treatment has very significant impact as it provide an alternative approach for fiber surface treatment and tailoring for potential high performance ductile cementitious composites. After all, the G_d value was reduced through relatively costly oil coating process during the manufacturing in the development history of PVA-ECC.

5. Conclusions

In this paper, the impact of directly adding vegetative *Bacillus halodurans* and its mutant cells into ECC material was investigated. The mechanical performance of

ECC including compressive strength and tensile properties were highly influenced after incorporation of bacteria. At macroscale level, the compressive strength and tensile strength of bacteria-ECC increased as compared with Control-ECC due to bacterial metabolism in ECC. On the other hand, the tensile strain capacity shows a reverse trend in bacteria-ECCs, but is still maintained at high level. At microscale level, similar to the strength enhancement, the matrix fracture toughness was also increased in bacteria-ECCs. For the matrix/fiber interface properties associated with fiber bridging performance, lower chemical bond (G_d) and slip-hardening coefficient (β) were observed in bacteria-ECCs, yet the increased frictional bond strength (τ_0) prevailed over decreased chemical bond which in turn leads to the reduction of complementary energy (J'_b). It is interestingly noted that a kind of biofilm and bacterial aggregation was attached to the fiber surface, thereby changing the interface properties. Last but not least, ECC with mutant bacteria of higher activity exhibits more pronounced effect on alteration of material properties.

Acknowledgements

The authors would like to acknowledge the financial support from MOE Tier1 (RG87/15) and School of CEE Research Staff Funding Support for Assistant Professors. The first author would like to graciously thank 111 Project of China (Grant No. B18062), and the National Natural Science Foundation of China (Grant No. 51708061) for partial financial support of this work. We also would like to acknowledge Prof. Stefan Wuertz at SCELSE for supporting bacterial studies in his laboratory.

References

- [1]. Yang YZ, Lepech MD, Yang EH, Li VC. Autogenous healing of engineered cementitious composites under wet-dry cycles, *Cement and Concrete Research*, 39, 2009: 382-390.
- [2]. Zhang ZG, Zhang Q. Self-healing ability of Engineered Cementitious Composites (ECC) under different exposure environments. *Construction and Building Materials*, 2017. 156: 142-151.
- [3]. Sahmaran M, Yildirim G, Erdem TK. Self-healing capability of cementitious composites incorporating different supplementary cementitious materials. *Cement & Concrete Composites*, 2013. 35(1): 89-101.
- [4]. Jonkers HM, Thijssen A, Muyzer G, Copuroglu O, Schlangen E. Application of bacteria as self-healing agent for the development of sustainable concrete. *Ecological Engineering*, 2010. 36(2SI): 230-235.
- [5]. Van Tittelboom K, De Belie N, De Muynck W, Verstraete W. Use of bacteria to repair cracks in concrete. *Cement and Concrete Research*, 2010. 40(1): 157-166.
- [6]. Wang, J.Y., De Belie N. and W. Verstraete, Diatomaceous earth as a protective vehicle for bacteria applied for self-healing concrete. *Journal of Industrial Microbiology & Biotechnology*, 2012. 39(4): 567-577.
- [7]. Wang J, Van Tittelboom K, De Belie N, Verstraete W. Use of silica gel or polyurethane immobilized bacteria for self-healing concrete. *Construction and Building Materials*, 2012, 26(1): 532-540.
- [8]. Wang J, Ersan YC, Boon N, De Belie N. Application of microorganisms in concrete: a promising

sustainable strategy to improve concrete durability. *Applied microbiology and biotechnology*, 2016. 100(7): 2993-3007.

[9]. Khaliq W, M.B. Ehsan, Crack healing in concrete using various bio influenced self-healing techniques. *Construction and Building Materials*, 2016. 102(1): 349-357.

[10]. Bhaskar S, Hossain KMA, Lachemi M, et al. Effect of self-healing on strength and durability of zeolite-immobilized bacterial cementitious mortar composites. *Cement & Concrete Composites*, 2017. 82: 23-33.

[11]. Alazhari M, Sharma T, Heath A, Cooper R., Paine K. Application of expanded perlite encapsulated bacteria and growth media for self-healing concrete. *Construction and Building Materials*, 2018, 160: 610-619.

[12]. Wang JY, Soens H, Verstraete W, De Belie N. Self-healing concrete by use of microencapsulated bacterial spores. *Cement and Concrete Research*, 2014. 56: p. 139-152.

[13]. Luo M, Qian C. Influences of bacteria-based self-healing agents on cementitious materials hydration kinetics and compressive strength. *Construction and Building Materials*, 2016. 121: p. 659-663.

[14]. Bundur ZB, Kirisits M.J, Ferron RD. Biomineralized cement-based materials: Impact of inoculating vegetative bacterial cells on hydration and strength. *Cement and Concrete Research*, 2015. 67: 237-245.

[15]. Krishnapriy S, Babu DLV, Arulraj PG. Isolation and identification of bacteria to improve the strength of concrete. *Microbiological Research*, 2015. 174: 48-55.

[16]. Balam NH, Mostofinejad D, Eftekhari M. Effects of bacterial remediation on compressive strength, water absorption, and chloride permeability of lightweight aggregate concrete. *Construction and Building Materials*, 2017. 145: p. 107-116.

[17]. Mondal S, Ghosh AD. Investigation into the optimal bacterial concentration for compressive strength enhancement of microbial concrete. *Construction and Building Materials*, 2018. 183: 202-214.

[18]. Pei R, Liu J, Wang S, Yang M. Use of bacterial cell walls to improve the mechanical performance of concrete. *Cement & Concrete Composites*, 2013. 39: 122-130.

[19]. Nonakaran SH, Pazhouhandeh M, Keyvani A, et al. Isolation and identification of *Pseudomonas* azotoformans for induced calcite precipitation. *World Journal of Microbiology & Biotechnology*, 2015. 31(12): 1993-2001.

[20]. Achal V, Pan X, Ozyurt N. Improved strength and durability of fly ash-amended concrete by microbial calcite precipitation. *Ecological Engineering*, 2011, 37(4): 554-559.

[21]. Ghosh P, Mandal S, Chattopadhyay BD, Pal S. Use of microorganism to improve the strength of cement mortar. *Cement and Concrete Research*, 2005. 35(10): 1980-1983.

[22]. Ghosh S, Biswas M, Chattopadhyay BD, Mandal S. Microbial activity on the microstructure of bacteria modified mortar. *Cement & Concrete Composites*, 2009. 31(2): 93-98.

[23]. Park S., Park YM, Chun WY, Kim WJ, Ghim SY. Calcite-Forming Bacteria for Compressive Strength Improvement in Mortar. *Journal of Microbiology & Biotechnology*, 2010. 20(4): 782-788.

[24]. Li VC, Wang S, Wu C. Tensile Strain-hardening Behavior of PVA-ECC. *ACI Materials Journal*, 2001; 98(6): 483-492.

[25]. Li VC, Leung CKY. Steady State and Multiple Cracking of Short Random Fiber Composites. *ASCE J. of Engineering Mechanics*, 1992; 118(11): 2246-2264.

[26]. Li VC, Wu C, Wang S, Ogawa A, Saito T. Interface Tailoring for Strain-hardening PVA-ECC. *ACI Materials Journal*, 2002; 99(5): 463-472.

- [27]. Said SH, Razak HA. The effect of synthetic polyethylene fiber on the strain hardening behavior of engineered cementitious composite (ECC). *Materials and design*, 2015; 86: 447-457.
- [28]. Yang EH, Yang YZ, Li VC. Use of High Volumes of Fly Ash to Improve ECC Mechanical Properties and Material Greenness. *ACI Material Journal*, 2007; 104(6): 620-628.
- [29]. Zhang ZG, Zhang Q. Matrix tailoring of Engineered Cementitious Composites (ECC) with non-oil-coated, low tensile strength PVA fiber. *Construction and Building Materials*, 2018. 161: 420-431.
- [30]. Li VC, Mishra DK, Wu HC. Matrix Design for Pseudo Strain-Hardening Fiber Reinforced Cementitious Composites. *RILEM J. Materials and Structures*, 1995; 28(183): 586-595.
- [31]. Yu J, Yao J, Lin X, Li H, et al., Tensile performance of sustainable Strain-Hardening Cementitious Composites with hybrid PVA and recycled PET fibers. *Cement and Concrete Research*, 2018. 107: 110-123.
- [32]. Yu KQ, Wang YC, Yu JT, Xu SL. A strain-hardening cementitious composites with the tensile capacity up to 8%, *Construction and Building Materials*, 2017; 137: 410-419.
- [33]. Yu KQ, Li LZ, Yu JT, et al. Feasibility of using ultra-high ductility cementitious composites for concrete structures without steel rebar. *Engineering Structures*, 2018. 170: 11-20.
- [34]. Zhang ZG, Ma H, Qian SZ. Investigation on properties of ECC incorporating crumb rubber of different sizes. *Journal of Advanced Concrete Technology*, 2015; 31(5): 241-251.
- [35]. Qian S, Li VC. Headed Anchor/Engineered Cementitious Composites (ECC) Pullout Behavior. *Journal of Advanced Concrete Technology*, 2011. 9(3): 339-351.
- [36]. Zhang ZG, Zhang Q, Qian SZ, Li VC. Low E-Modulus Early Strength Engineered Cementitious Composites Material: Development for Ultrathin Whitetopping Overlay. *Transportation Research Record*, 2015; 2481: 41-47.
- [37]. Qian SZ, Li VC. Influence of concrete material ductility on shear response of stud connections. *ACI Materials Journal*, 2006. 103(1): 60-66.
- [38]. Li M, Li V.C. High-Early-Strength Engineered Cementitious Composites for Fast, Durable Concrete Repair-Material Properties. *ACI Materials Journal*, 2011. 108(1): 3-12.
- [39]. Kan L., Shi HS, Sakulich AR, Li VC. Self-Healing Characterization of Engineered Cementitious Composite Materials. *ACI Materials Journal*, 2010. 107(6): 617-624.
- [40]. Zhang Z., Qian S. Ma H. Investigating mechanical properties and self-healing behavior of micro-cracked ECC with different volume of fly ash. *Construction and Building Materials*, 2014. 52: 17-23.
- [41]. Marshall DB, Cox BN. A J-Integral Method for Calculating Steady-State Matrix Cracking Stresses in Composites. *Mechanics of Materials*, 1988; 8: 127-133.
- [42]. Wang SX, Li VC. Engineered Cementitious Composites with High-Volume Fly Ash. *ACI Material Journal*, 2007; 104(3): 233-241.
- [43]. Kanda T, Li VC. A New Micromechanics Design Theory for Pseudo Strain Hardening Cementitious Composite. *Journal of Engineering Mechanics*, 1999. 125(4): 373-381.
- [44]. Ding Y, Peng N, Du Y, Ji L, Cao B. Disruption of Putrescine Biosynthesis in *Shewanella oneidensis* Enhances Biofilm Cohesiveness and Performance in Cr(VI) Immobilization. *Applied and Environmental Microbiology*, 2014. 80(4): 1498-1506.
- [45]. Huang XY, Ranade R, Zhang Q, Ni W, Li VC. Mechanical and thermal properties of green lightweight engineered cementitious composites. *J. Construction and Building Materials*, 2013; 48:954-960.

- [46]. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars, in ASTM C109. 2014.
- [47]. Standard test method for linear-elastic plane-strain fracture toughness K_{Ic} of metallic materials, in ASTM E399-12. 2014.
- [48]. Sato T, Diallo F. Seeding Effect of Nano- CaCO_3 on the Hydration of Tricalcium Silicate. Transportation Research Record, 2010 (2141): 61-67.
- [49]. Aguilera J, Martinez-Ramirez S, Pajares-Colomo I, Blanco-Varela MT. Formation of thaumasite in carbonated mortars. Cement & Concrete Composites, 2003. 25(8): 991-996.
- [50]. Jerga, J. Physico-mechanical properties of carbonated concrete. Construction and Building Materials, 2004. 18(9): 645-652.
- [51]. Lothenbach B, Le Saout G, Gallucci E. Scrivener K. Influence of limestone on the hydration of Portland cements. Cement and Concrete Research, 2008. 38(6): 848-860.
- [52]. Gulgun MA, Kriven WM, Tan LS. McHugh A.J. Evolution of mechano-chemistry and microstructure of a calcium aluminate-polymer composite: Part I. Mixing time effects. Journal of Material Research, 1995. 10(7): 1746-1755.
- [53]. Yang EH, Wang SX, Yang YZ, Li VC. Fiber-bridging Constitutive Law of Engineered Cementitious Composites. Journal of Advanced Concrete Technology, 2008; 6(1): 181-193.

Table 1: Mix proportions of ECC mixtures (g/L).							
Mixtures		Cement	Fly ash	FAC	Mixing Liquid	SP	PVA fiber
Control-ECC		273	956	137	318 (Water)	4	26
Bacteria -ECC	W-ECC	273	956	137	318+9 (Wild bacterial culture)	4	26
	M-ECC	273	956	137	318+9 (Mutant bacterial culture)	4	26

Table 2: EDS element analysis of product on fractured section of M-ECC.

Element	C	O	Al	Si	Ca	Fe
At %	12.55	61.03	5.08	1.71	17.26	1.06

Table 3: Crack information of ECC mixtures.			
Mixture	Control-ECC	W-ECC	M-ECC
Average crack width	77 µm	55 µm	49 µm
Number of cracks	39	43	46

Figure 1 (a) Bacterial growth curve. Optical Density at 600 nm was performed in the 96-well plate reader; (b) Bacterial culture after 16-h growth.

Figure 2 Uniaxial tensile test set-up.

Figure 3 Schematic diagram of sample preparation for single fiber pull-out test.

Figure 4 Compressive strength of ECCs at 7 and 28 curing days.

Figure 5 Morphology image of fractured cross-section of M-ECC.

(c)

Figure 6 Tensile stress-strain relationship of ECC mixtures.

Figure 7 Summary of tensile properties of ECC mixtures.

Figure 8 Crack width distribution in ECCs.

Figure 9 Matrix fracture properties of ECC mixtures.

(a)

(b)

(c)

Figure 10 Matrix/fiber interface parameters for ECC mixtures;
(a) Chemical bond; (b) Frictional bond strength; (c) Slip-hardening coefficient.

(a)

(b)

Figure 11 Fluorescence microscopy observation of PVA fiber from:
(a) control-ECC specimen; (b) M-ECC specimen.

Figure 12 Calculated fiber bridging σ - δ curves.

Figure 13 Correlation between PSH index and strain capacity of ECC mixtures.

High lights

The mechanical properties of ECC with incorporation of bacteria cells were studied.

The incorporation of bacteria enhances the compressive and tensile strength of ECC; while slightly decrease its strain capacity.

Fiber/matrix interface properties were altered in bacteria-ECC with lower chemical bond and higher frictional bond strength.

ECC with mutant bacteria of higher activity exhibits more pronounced effect on alteration of material properties.