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Mechanical performance of strain-hardening cementitious composites (SHCC) with bacterial addition

Zhigang Zhang^{1,2}, Dawei Liu¹, Yuanzhao Ding² and Shuping Wang^{3*}

Abstract

Incorporation of bacteria can realize self-healing and enhance strength of concrete, which has been drawn extensive attention in past decades. The studies focused on the properties of fiber reinforced concrete with bacterial addition are still very limited. In this paper, mechanical performance of strain hardening cementitious composites (SHCC) with directly adding vegetative bacterial cells was investigated. The experimental results revealed that the compressive, first cracking, and tensile strength of SHCCs was increased due to the addition of bacteria, while the tensile strain capacity tended to decline. At micro-scale level, the matrix containing bacteria has relative higher fracture toughness to that of reference mix. Interestingly, the bacteria notably lowered chemical bond between PVA fiber and its surrounding hydrates; on the other hand, the frictional bond was enhanced. The findings in this study can provide a reference for modifying the surface of hydrophilic fibers.

Keywords: SHCC, Mechanical performance, Bacteria; micro-scale

Introduction

Concrete is the second most consumed substance in the world only after water, due to its high strength, low cost, and easy availability worldwide et al. It contributes greatly to the infrastructures, and is the foundation of modern development, providing a solid and safe structure for the daily life of people. However, with the development of modern society, the requirements to concrete are always raising in different aspects. In the past decades, researchers have been devoting to improve the performance of concrete, such as high strength, ductility, flowability, durability, and some specific functionality et al.

To improve the fracture toughness, adding fibers into concrete can increase its value by an order of magnitude, meanwhile, it can also effectively mitigate the early cracking phenomenon upon shrinkage. On the other hand, the

tensile ductility of concrete still remain little altered, to convert the quasibrittle feature of concrete, strain hardening cementitious composites (SHCC) or engineered cementitious composites (ECC) was developed by Li and his coworkers in the 1990s. The SHCC exhibits high tensile strain capacity of 3~10% at moderate fiber volume [1–4], which transform the brittle failure of concrete into ductile damage mode. Under tension, it develops multiple micro-cracks on SHCC specimens instead of one single localized fracture crack that in conventional concrete [5, 6]. Typically, the crack width of SHCC can be controlled below 100 μm [1], interestingly; this kind of tight cracks on SHCC can heal itself autogenously as the continue reaction of binder materials under moisture circumstance [7, 8]. However, only very tight cracks that below 50 μm can be filled by healing products fully upon the autogenously self-healing, while the complete self-healing in SHCC was rarely observed when crack width exceeds 100 μm [9].

In addition, bacteria technique is also one of the strategies to improve concrete properties. Normally,

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incorporating bacteria into concrete can realize self-healing by virtue of microbiologically induced calcite precipitation (MICP). It has been widely reported that the millimeter-sized cracks in concrete can be healed by adding bacteria. To ensure the viability of bacteria in the high alkaline environment, a protective carrier is applicable to immobilize or encapsulate bacterial cells. Khaliq et al. immobilized bacterial in light weight aggregate, and found the crack with 0.61 mm wide can be healed [10]. Moreover, the diatomaceous earth, zeolite, and expanded perlite can also be a good carrier to ensure the occurrence of efficient self-healing in concrete [11–13]. Wang et al. synthesized microcapsules based on hydrogel and poly-condensation reaction as the carrier, and found that the maximally healable crack can reach 0.97 mm in width [14].

Compared with the advantage of self-healing, the incorporation of carriers is likely to reduce the strength performance of concrete. Some researchers added the bacterial cells directly into concrete during mixing. It was found that the crack with 0.3 mm in width can still be healed by the adding bacteria directly, although the maximum healable crack width was reduced [15], on the other hand, the calcium carbonate content in concrete had an evident increase, as a result, the compressive strength of concrete was enhanced [16]. Furthermore, Ghosh et al. [17] incorporated the nutrition culture with inclusion of bacterial cells into concrete or mortar by replacing mixing water, and found that the compressive strength raised in comparison with concrete mixed with water.

In previous studies, some research outcomes related to the fiber reinforced concrete (FRC) with addition of bacteria were gained as well. In those investigations, the original intention of adding fibers into bacterial concrete is for a better self-healing due to the restraint of crack width [18, 19]. The results showed that the addition of bacteria could reduce the concrete penetrability because of the calcite sediments [20], moreover, the interfacial bond between fiber and cement matrix can be enhanced [21], and subsequently improved the flexural and split tensile strength of FRC [19, 22]. However, the findings about effect of bacterial adding on the deformation

capacity of FRC are still very limited, especially for the SHCC. The authors found that the bacterial incorporation promoted the multiple cracking phenomena in SHCC with high-volume fly ash, and showed a comparable strain capacity to that of control SHCC mixture [23]. Nevertheless, it is well known that the fly ash content can significantly affect the balance among the fiber, matrix, and fiber/matrix interfacial properties; therefore the mechanical performance of SHCC with different fly ash contents may vary a lot [24, 25]. It is desirable to further explore the influence of bacterial addition on the performance of SHCC with moderate fly ash content.

In this study, incorporating bacterial technique into SHCC is a promising approach to enhance its self-healing capacity, especially for the wide crack that exceeds 100 μm . To avoid the negative impact on strength, the bacterial culture was adopted to substitute water during mix process of SHCC. The direct incorporation of bacteria may also cause the changes in aspects of matrix and matrix/fiber interfacial properties at micro-scale, which in turn to affect mechanical performance of SHCC. This paper emphasized on investigating the effect of bacterial addition on mechanical performance of SHCC at multiple-scales. In the following sections, the compressive strength and tensile properties of SHCCs will be investigated. In the final, the variations of bacteria on fracture toughness of matrix and fiber/matrix interface was discussed at micro-scale level.

Experimental programs

Materials and mix proportions

In this paper, the ingredients in preparation of SHCC include Portland cement with strength grade of CEM-42.5, fly ash, fly ash cenosphere (FAC), water or bacterial cultures, superplasticizer (SP), and PVA fibers. Table 1 lists the mix proportion of the three SHCC mixtures. The FAC was adopted to substitute the silica sand which was the classic ingredient in preparation of SHCC by equal volume. The FAC has a hollow spherical microstructure which is expected to act as small flaws in SHCC that has been approved to facilitate the initiation of cracks, and thus ductility [24, 26]. The FAC has a bulk density

Table 1 Mix proportion of SHCC mixtures (g/L)

Mixtures	Cement	Fly ash	FAC	Mixing Liquid	SP	PVA fiber
Ref-SHCC	388	854	130	318 (Water)	4	26
W-SHCC	388	854	130	327 (Wild bacterial culture)	4	26
M-SHCC	388	854	130	327 (Mutant bacterial culture)	4	26

of 800 kg/m^3 and all the particles can pass through #80 sieves. The three SHCC mixtures that used in this study have the same mix a proportion, the only difference is that the mixing liquids. The water was used in the Ref.-SHCC, while the bacterial culture that contains nutrition substances was mixed into W-SHCC and M-SHCC. The weight of liquid in W-SHCC and M-SHCC is relative higher to that of Ref.-SHCC to remain constant water content in liquids.

In this study, there are two kind of bacterial strains, which are *Bacillus halodurans* DSM 497 (wild type from DSMZ, Germany) and the mutant one from wild type strain based on transposon mutagenesis method as clarified in reference [27, 28]. As expected, the mutant one has a higher bacterial activity than that of wild type strain, which is likely produce more metabolite [28]. The estimated concentration of vegetative cells of wild type and mutant one is $3 \times 10^8/\text{ml}$ and $12 \times 10^8/\text{ml}$, respectively. The cell concentration was determined by optical density at 600 nm (OD600) which normally has a positive relationship to the cell concentration [28]. [Notes: $\text{OD600} = 1.0$ means 10^8 cells/ml of cell concentration.]

During mixing process, all the solid materials were pre-mixed for 1 min using a shear-type Hobart mixer with capacity of 20 L. The liquid with superplasticizer together was added into the dry mixtures afterwards and mixed for 3 min to reach a homogeneous status. In the above procedures, the mixing speed is around 60 r/min. Finally, the PVA fibers were added into the paste slowly and mixed of another 3 min at 198 r/min. After mixing, the SHCC paste was cast into the molds and covered by plastic sheets before demolding. Then all the specimens were cured in air until 28 days.

Experimental procedures

Compressive test was performed on the cubic samples complying with ASTM C109 to measure the compressive strength of SHCCs [29]. The cubic samples have a dimension of $50.8 \text{ mm} \times 50.8 \text{ mm} \times 50.8 \text{ mm}$. The compressive strength of SHCC was obtained by averaging three samples for each mixture.

Uniaxial tensile test was employed to characterize the tensile performance of SHCCs. Figure 1 shows the tensile test set-up. The dogbone shaped specimen was adopted for the tensile test. The dimension of the section within gauge length is $80 \text{ mm} \times 30 \text{ mm} \times 15 \text{ mm}$. The relative smaller cross-section is likely to lure the occurrence of cracking within gauge length. To gain the accurate deformation for strain calculation, two external LVDTs were attached to tested specimens. The loading rate is 0.5 mm/min .

Three-point bending test was conducted to measure the fracture toughness of SHCC matrix (without fibers)

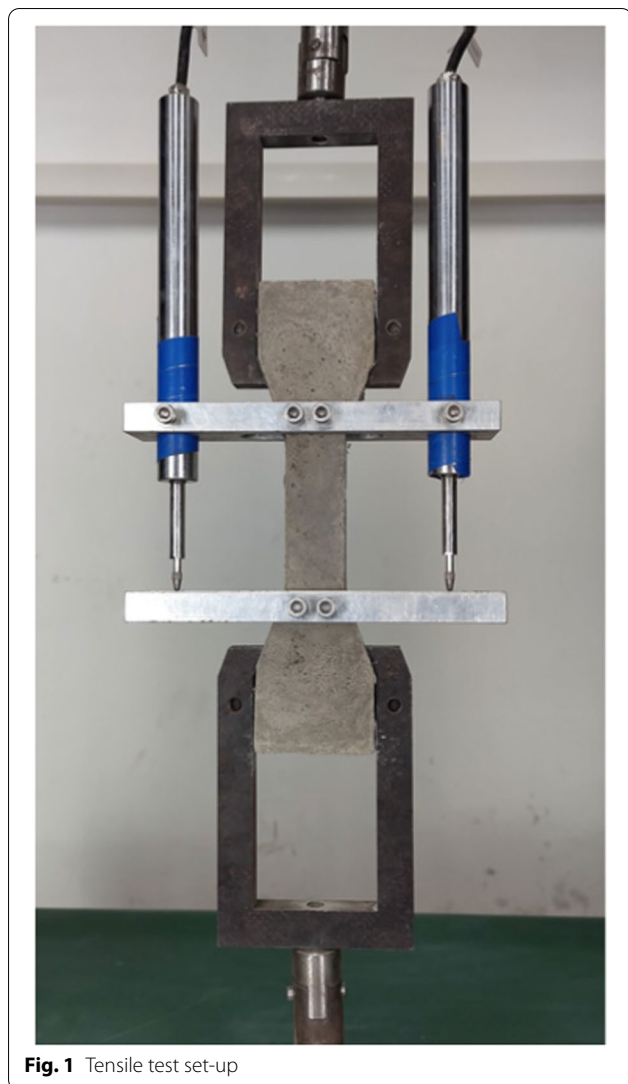


Fig. 1 Tensile test set-up

in accordance with ASTM E399 [30]. The dimension of prism specimen is 305 mm (length) $\times 38 \text{ mm}$ (width) $\times 76 \text{ mm}$ (height). The test set-up can be found in reference [31]. Prior to test, the notch with depth to beam height of 0.4 was produced using saw. During test, the full span length is 254 mm , and the loading point is located above the notch.

Single fiber pull-out test was conducted to gain the matrix/fiber interfacial properties. From this test, the parameters including chemical bond (G_a), frictional force (τ_0), and slip-hardening coefficient (β) between matrix and PVA fiber can be obtained. During preparation of samples, long fibers were embedded in SHCC matrix, and then the samples were cut into slices with thickness around 1 mm by using a precision saw before test at 28 days. For each mixture, at least 8 slice samples

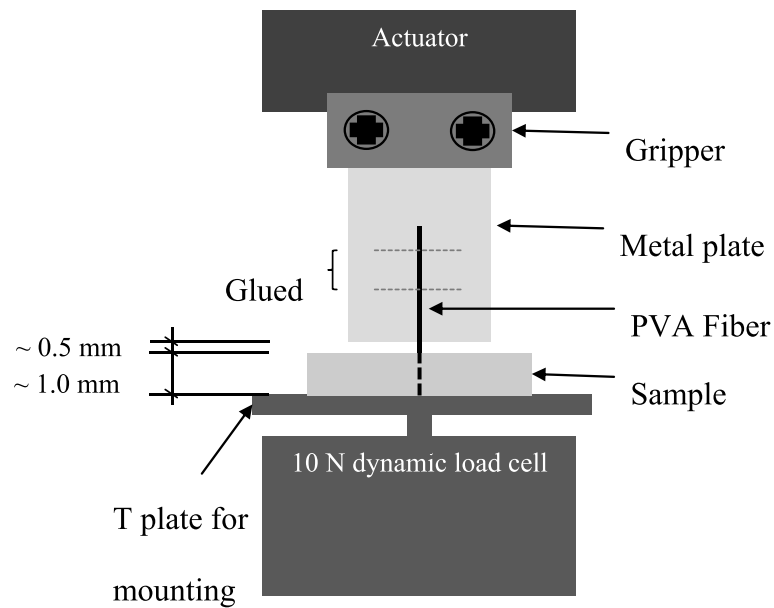


Fig. 2 Illustration of the test set-up

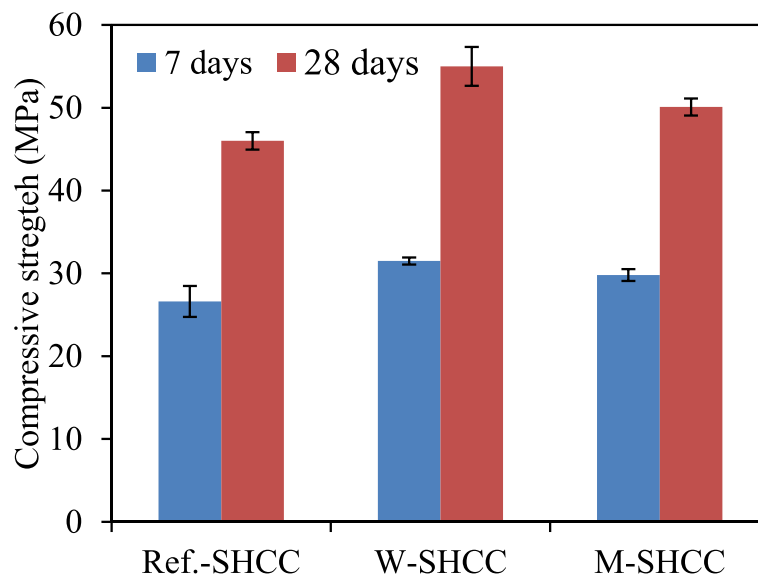


Fig. 3 Compressive strength of SHCCs

were prepared for subsequent calculation of mean value of interfacial parameters. The illustration of this test set-up is displayed in Fig. 2.

Results and discussions

Compressive strength of SHCCs

Figure 3 shows the compressive strength of SHCC mixtures at 7 and 28 curing days. It can be found that

the addition of bacteria resulted in the increment of compressive strength of SHCCs at both 7 and 28 curing days, among which the SHCC with addition of wild type bacteria strain exhibited highest. It is noted that the harden time of W-SHCC and M-SHCC was delayed significantly due to the nutrient substances in bacterial culture, which was reflected that the specimens of W-SHCC and M-SHCC can't be demolded

until 3 curing days while that of Ref.-SHCC was demolded at 1 curing day. However, at 7 days, the compressive strength of SHCCs with bacterial addition is higher than that of Ref.-SHCC, which implies that the microbiological motility facilitate the development of strength between 3 to 7 days. At 28 days, the compressive strength of Ref.-SHCC, W-SHCC, and M-SHCC is 46.08 MPa, 54.97 MPa, and 50.13 MPa, respectively, of which the bacterial addition caused 19.29% and 8.79% increase, respectively. The relative reduction in compressive strength of M-SHCC as compared to that of W-SHCC may attribute to the varied composition of cultures since the mutant bacteria has more cells and higher activity that consume more nutrition and produce more metabolite [28].

Figure 4 (a) presents the microstructural image on the fractured cross-section of W-SHCC specimen after underwent tensile test. It can be observed that there are extensive calcite-like pieces which are likely the products of biochemical reaction as the Ca^{2+} can be drawn by the negative charged bacterial cell wall, and thus resulted in the calcite precipitation. Figure 4 (b) illustrated the elemental mapping, which demonstrated the abundant presence of C, O, and Ca. Based on the element analysis to the products that listed in Table 2, it can be concluded that the small pieces in Fig. 4 (a) is largely calcite. In previous studies, it has

been proved that formation of CaCO_3 is beneficial to the compressive strength of concrete [32], moreover, the calcite may act filler to refine microstructures of SHCCs [16], which elucidate the enhancement of compressive strength of SHCCs with bacterial addition.

Tensile performance of SHCCs

Figure 5 displays the relationship between tensile stress and strain of SHCCs. The tensile properties of SHCC include first cracking strength, tensile strength, and strain capacity can be derived from the curves, which are defined as the maximum tensile stress at the initial linear stage, the ultimate stress and its corresponded strain, respectively. The above properties are illustrated in Fig. 6.

From the curves in Fig. 5, it can be seen that all three SHCC mixtures exhibit the strain-hardening phenomenon under tension which is the unique feature of SHCC materials. The strain capacity of the three SHCC mixtures varies from 0.83% to 1.40%, among which the Ref.-SHCC shows the highest value while the W-SHCC exhibits the lowest. That is, as compared with 1.40% of Ref.-SHCC, the addition of wild type bacterial culture leads to the 40% reduction of strain capacity of SHCC to 0.83%, likewise, the strain capacity of M-SHCC is 1.16% which is decreased by 17%, but is 40% higher than that of W-SHCC.

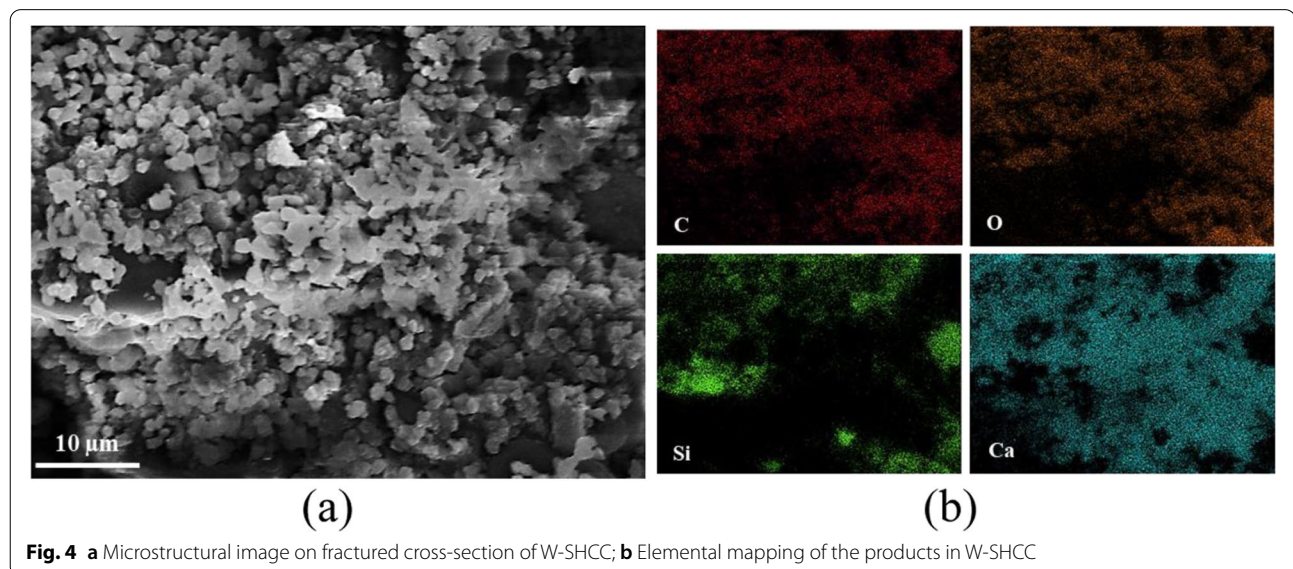


Table 2 EDS element analysis of products in Fig. 4

Element	C	O	Na	Al	Si	Ca
At %	22.51	60.04	1.05	2.10	4.60	9.17

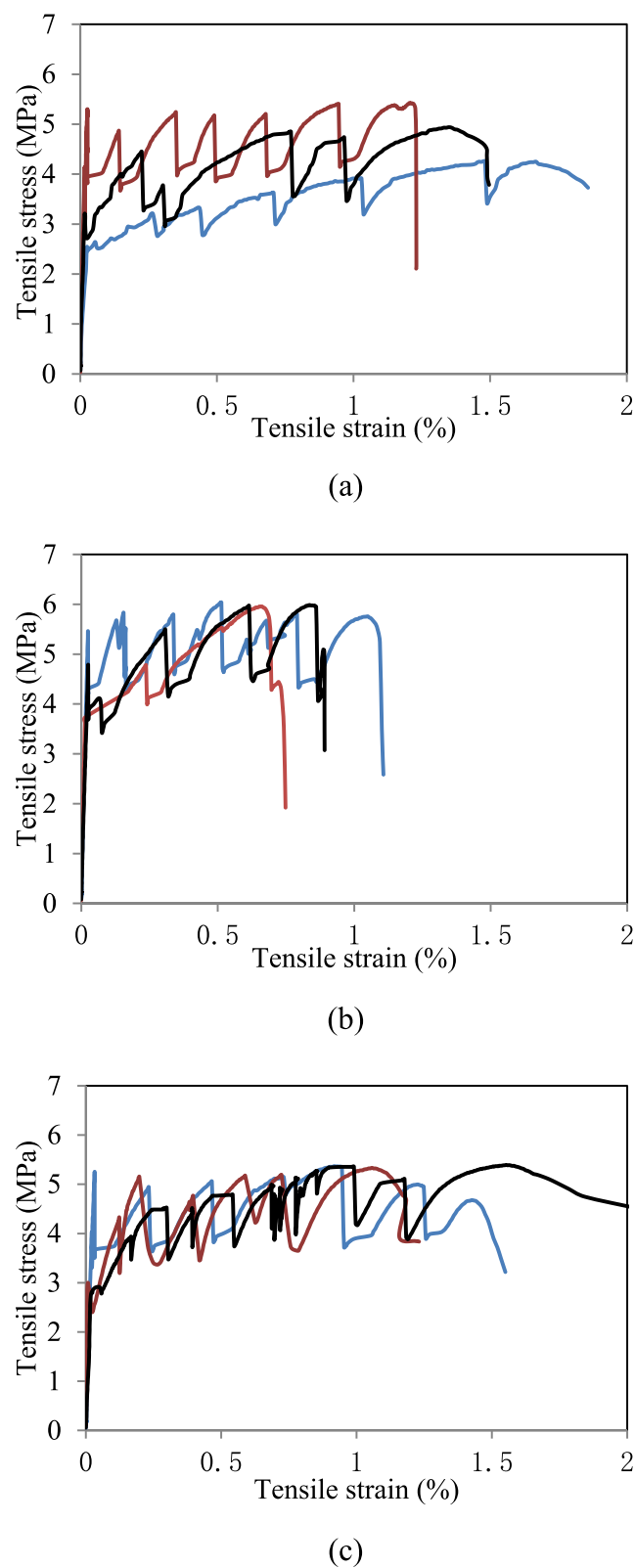


Fig. 5 Tensile stress–strain relationship of SHCCs: **a** Ref.-SHCC; **b** W-SHCC; **c** M-SHCC

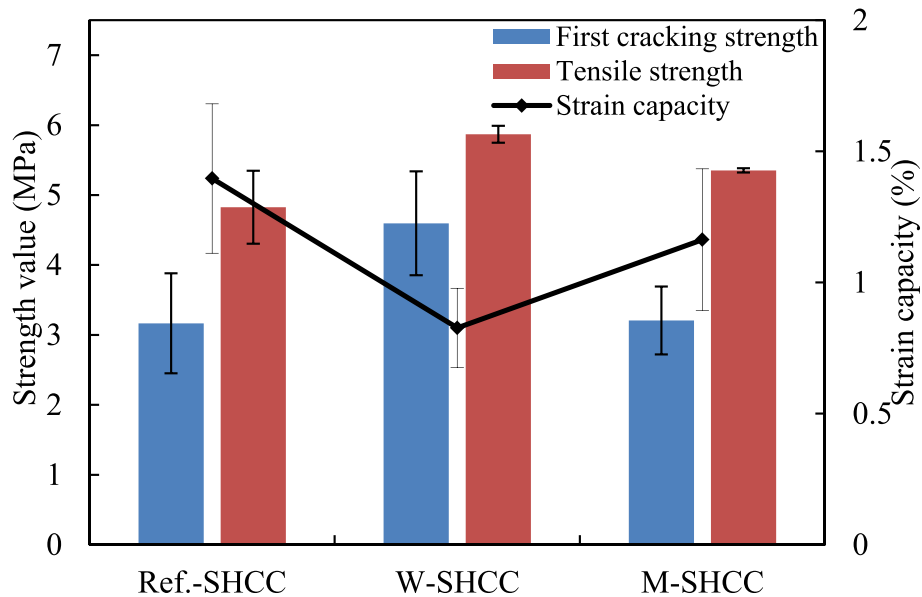


Fig. 6 Tensile properties of SHCCs

As illustrated in Fig. 6, due to the incorporation of bacterial culture, the first cracking and tensile strength of SHCCs shows the similar tendency to that of compressive strength: using bacterial culture to replace water increases strength value of SHCCs, whereas the M-SHCC presents relative lower value to that of W-SHCC. This is because that the compressive and first cracking strength of SHCC is closely associated to matrix performance, and normally, the stress value that can trigger cracks on concrete is proportional relation to compressive strength. In term of tensile strength,

it is dominated by the fiber bridging capacity across one crack which is a result of synergistic actions of plentiful single fiber against surrounding hydrates during pull-out process. The alteration in tensile strength implies that the bacterial addition changes the matrix/fiber interfacial properties, which will be discussed in the following section.

Discussions at micro-scale level

Based on SHCC design theory, to attain high ductility of SHCC, two ways was normally adopted, which are

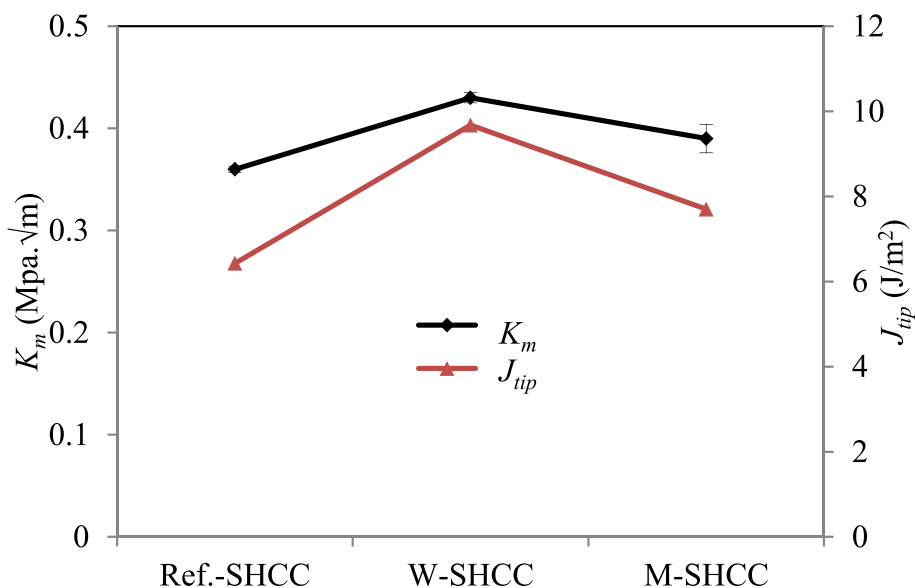


Fig. 7 Matrix fracture properties of SHCC mixtures

limiting matrix toughness (J_{tip}) or increasing the complementary energy (J_b'). The low J_{tip} value requires relative less energy to trigger a crack on SHCC, subsequently is profitable for the development of multiple cracks. The high J_b' value means it can have sufficient residue energy left other than energy consumed by fiber-bridging effect to trigger another crack at a new site on SHCC. With the former, it is easy to reach, such as incorporating defects into SHCCs or diminish cement usage [26, 33], nevertheless, the latter is considerably difficult with a given specific fiber type and dosage. The J_b' value is closely relevant to fiber/matrix interfacial properties. In this section, how the bacterial addition does affect SHCC matrix toughness and interactions between PVA fiber and its surrounding hydrates will be discussed.

Figure 7 presents the fracture properties of SHCC matrix. As can be seen, the addition of bacterial culture increased matrix toughness (K_m) especially for W-SHCC, which explains the change trend of first cracking strength in SHCCs under tension. The crack tip toughness ($J_{tip} = K_m^2/E_m$) also shows the same tendency. The stiffness (E_m) is defined as the slope of initial linear stage in tensile stress–strain curves of SHCC. Compared with Ref.-SHCC, the J_{tip} of W-SHCC and M-SHCC was increased by 50% and 20%, respectively. Such the growth of J_{tip} value means it needs more energy to advance crack tip propagate, which is undesirable for reaching saturated multiple-cracking phenomenon, and thus high ductility of SHCC.

Generally, pseudo strain hardening ($PSH = J_b'/J_{tip}$) index is employed to quantitate the margin between J_b' and J_{tip} , the higher PSH value denotes a better chance to initiate more cracks on SHCC, subsequently higher tensile strain capacity. In addition to J_{tip} , the J_b' that deduced from fiber/matrix interfacial parameters is the other decisive factor to PSH value. Figure 8 (a)~(c) display the fiber/matrix interfacial parameters of SHCC mixtures. It can be found from Fig. 8 (a) that the chemical bond (G_d) between PVA fiber and matrix dropped significantly upon bacterial addition. The mean G_d value of Ref.-SHCC, W-SHCC, and M-SHCC is 4.55 J/m^2 , 1.61 J/m^2 , and 0.37 J/m^2 , respectively. Compared with Ref.-SHCC, the G_d value of W-SHCC and M-SHCC was reduced by 65% and 92%, respectively. Such low G_d value is expected to avail the PVA fiber to debond from its surround blocks without rupture, thereby enhances the fiber-bridging effect, and furthermore conduce the buildup of J_b' . The decrement of G_d value in SHCCs is probably due to the attached bacterial cells and their metabolic products on surface of PVA fiber that as shown in Fig. 9. Aside from the oil-coating on PVA fiber, the attached substances may alleviate the reaction between Ca^{2+} , Al^{3+} in SHCC paste and hydroxyl in PVA bulk polymers, thus prevent

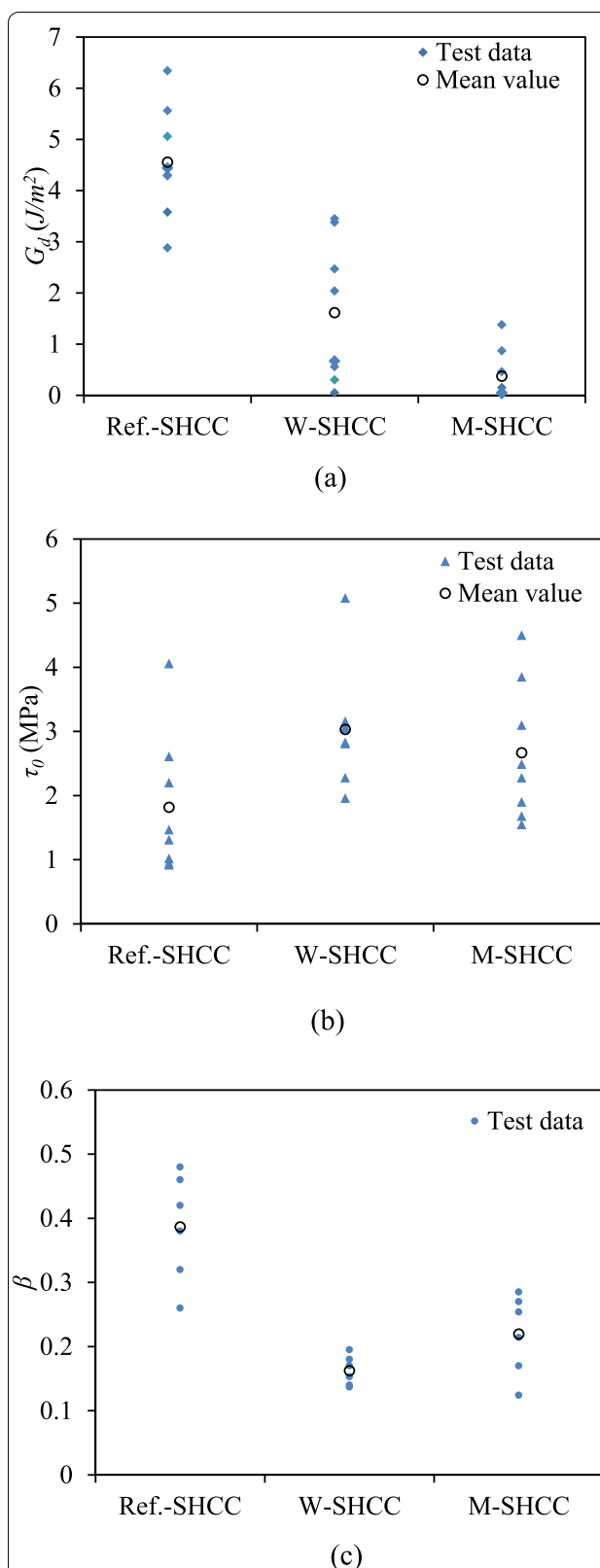


Fig. 8 Fiber/matrix parameters of SHCC mixtures: **a** chemical bond; **b** frictional bond; **c** slip-hardening coefficient

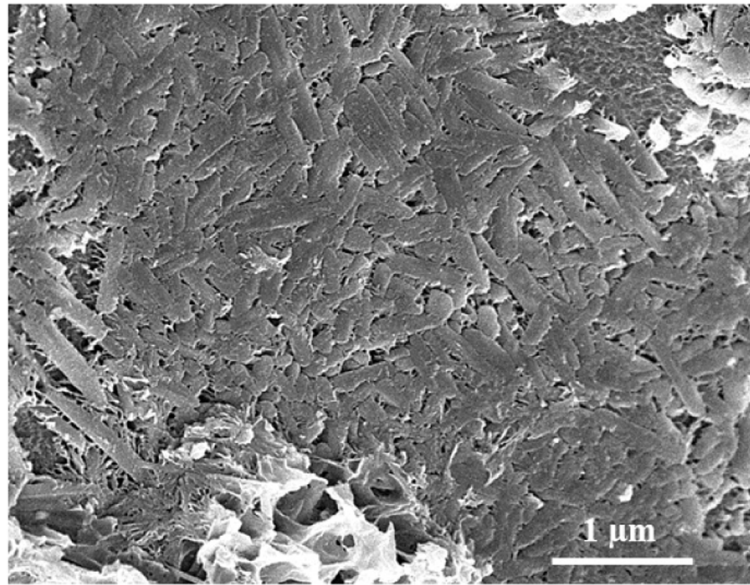


Fig. 9 Image of fiber surface for W-SHCC

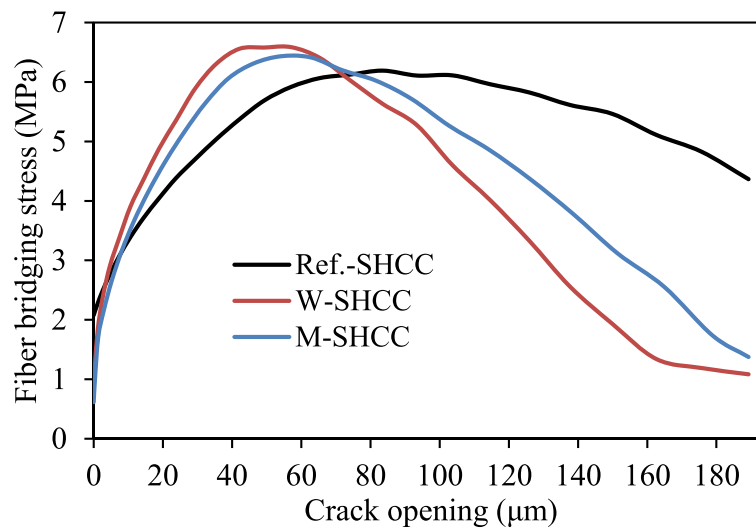


Fig. 10 Theoretical relationships between fiber bridging stress and crack opening

formation of strong chemical bond [34]. It's worthwhile to note that the substantial reduction of G_d upon simply adding bacteria is of great significance for the modification of PVA fiber surface, after all, researchers have paid tremendous efforts to reduce G_d during the historical SHCC development [35].

As shown in Fig. 8 (b), the frictional bond (τ_0) reveals the opposite tendency with G_d . Compared with that of 1.82 MPa in Ref.-SHCC, the τ_0 value increased to 3.03 MPa in W-SHCC and 2.67 MPa in M-SHCC, which increased by 66% and 47%, respectively. The frictional

bond (τ_0) between fiber and matrix is highly dominated by the denseness and hardness of interfacial transition zone (ITZ). In the preceded sections, it reported that the bacterial inclusion enhanced the fracture toughness and strength of matrix that implies a more compacted/tough matrix, of which the fiber is more difficult to slide against its surrounding matrix, and consequently resulted in a higher τ_0 . In another aspect, the slip-hardening coefficient (β) was diminished due to the addition of bacteria, indicating that the fiber can slip-out with less damage or rupture, which is favorable to fiber-bridging properties.

Table 3 The calculated J_b' value and PSH index

Mixtures	Ref.-SHCC	W-SHCC	M-SHCC
J_b'	100.39	78.44	85.06
$PSH (= J_b'/J_{tip})$	15.61	8.12	11.01

Based on the above measured interfacial parameters, the theoretical development of fiber bridging stress versus cracking opening can be derived using micromechanics theory [36]. Figure 10 presents the theoretical fiber bridging stress-crack opening (σ - δ) curves of SHCC mixtures. From Fig. 10, it can be observed that the bacterial addition render the curves shift towards upper-left that caused the increase of maximal fiber bridging stress. This phenomenon well explains the enhancement of tensile strength of SHCCs.

From the σ - δ curves, the complementary energy (J_b') can be obtained. Table 3 lists the computed J_b' value and PSH index of SHCC mixtures. It is found that the inclusion of bacterial culture lower J_b' value. The diminution of G_d value is likely to decline the intersection value between σ - δ curves and Y-axis as displayed in Fig. 9, which assists the increment of J_b' value. On the contrary, the improved τ_0 caused the σ - δ curves to move towards left in Fig. 10, which is detrimental to the gaining of J_b' value. Conclusively, combining the above two competitive efforts resulted in the decrement of J_b' value. More than that, as previously mentioned, the J_{tip} was boost due to the bacterial addition. Considering the tendency of J_b' and J_{tip} value, the PSH index will assuredly decrease as a consequence of bacterial addition. Notwithstanding, as summarized in Table 3, the J_b' and PSH value in M-SHCC is comparatively higher to that of W-SHCC. The PSH index keeps the same change trend as that of strain capacity of SHCCs, which again demonstrated the proportional relation between them.

Conclusions

In this paper, the mechanical performance of SHCC with directly adding bacteria was investigated experimentally. The bacterial addition highly affected the mechanical performance of SHCCs. At composite level, the bacterial metabolism in SHCCs boosted the gaining of strength including compressive, first cracking, and tensile strength. On the contrary, the tensile strain capacity of SHCC containing bacterial cells exhibited lower value to that of reference SHCC mix. Between the *Bacillus halodurans* and its mutant strain, the SHCC with addition of mutant bacterial cells showed a relatively higher tensile strain capacity. At micro-scale level, on a par with the enhanced strength properties, the fracture toughness

of matrix was also improved in bacteria-SHCCs. In term of fiber/matrix interfacial properties, it is noticeable that the bacterial addition effectively alleviated the formation of intense chemical bond between PVA fiber and its surrounding cementitious matrix as well as the slip-hardening coefficient, in another aspect, the interface frictional bond was increased which prevailed the positive effect from the decreased chemical bond, as a result, caused the decrease of complimentary energy (J_b') that is critical to ductility of SHCCs.

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Authors' contributions

Zhigang Zhang: Conceptualization, Methodology, Validation, Data curation, Writing – original draft. Dawei Liu: Data curation. Yuanzhao Ding: Validation, Data curation. Shuping Wang: Methodology, Validation, Writing – review & editing. The author(s) read and approved the final manuscript.

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Availability of data and materials

All data have been presented in the Paper.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no conflicts of interest.

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