Stimulated autogenous-healing capacity of fiber-reinforced mortar incorporating healing agents for recovery against fracture and mechanical properties

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This study aimed to investigate the effect of autogenous healing capacity with the addition of expansive and crystalline agents on mechanical and fracture behaviors of fiber-reinforced (FR) mortar specimens with crack mouth opening displacement (CMOD) controlled test set-up. The experimental results of a self-healing approach of FR mortar were analyzed in terms of first cracking peak load (FCPL) increase, index of fracture toughness recovery (IFTR), and index of fracture energy recovery (IFER). Initially, the specimens were pre-cracked at different crack widths ranging from 30 μm to 200 μm after 28-days of curing. After pre-cracking, the specimens were kept in water for 56- and 120-day healing. A controlled three-point bending test (PBT) was applied on prism specimen having a central notch of 40 mm depth for pre-cracking as well as the post-conditioning stage for determining the FCPL. However, the crack surfaces were monitored by a high-range digital microscope and scanning electron microscope (SEM) to examine the nature of healed products near the damaged area. Test results revealed that a significant recovery of small cracks ($\leq 50 \mu\text{m}$) could be achieved for self-healing specimens by using healing agents (HA), while for large cracks ($\geq 100 \mu\text{m}$) partial recovery could be achieved after the 120-day healing period.

Keywords: *self-healing, crack width, fracture properties, mechanical properties, mortar*

1. Introduction

Cracking in concrete causes severe problems that affect not only the strength-related properties but also the service life of concrete structures. Cracking occurs due to various reasons such as the heat of hydration, environmental changes, and volumetric changes. Various techniques were used to repair concrete but those were expensive and sometimes unreachable, i.e., underwater structures and high-rise buildings. Therefore, cracks must be repaired as soon as possible to restore the strength

as well as the durability of concrete structures by keeping in view the economy of the project. The self-healing technology for crack repairing is one of the growing alternatives, which fills or repairs the damage [1]. Many studies investigated the self-healing capability of concrete and one of which used cementitious materials for recovery against mechanical and durability performance [2]. Crystalline admixtures were also used to achieve robust self-healing [3]. Capsules were also utilized which recover damaged concrete by releasing the liquid into the cracks [4]. Fly ash (FA) can be used as a supplementary cementitious material for generating crystalline product which enhances the strength

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and durability of concrete as well [5]. Geomaterials are also important for the permeability aspect of self-healing [6]. Polyvinyl alcohol (PVA) fibers were used to achieve controlled damage otherwise specimen failed abruptly during the pre-cracking stage [7]. A recent study reported by Ferrara *et al.* [8] showed that various techniques are used to achieve the robust crack healing effect; furthermore, a detailed review of various researches is also shown that future research on the self-healing effect especially in investigating the fracture performance of concrete with and without steel bars is very vital.

Mechanism of autogenous healing of concrete considering mechanical and permeability performance incorporating various mineral admixtures has been studied by many researchers. Ferrara *et al.* [9] investigated the effect of crystalline admixture on the self-healing behavior of concrete by evaluating mechanical performance in terms of index of load recovery (ILR) and index of damage recovery (IDR). Another work was conducted by Buller *et al.* [10] and they investigated the mechanical performance of FRC mortar using special self-healing agents at an early age of healing duration. This study investigated the IDR, index of stress recovery (ISR), and index of dissipation energy gain (IDEG) at 28 days and 56 days of healing duration and found that due to the use of self-healing agents, narrower cracks attained better recovery (50%) in terms of IDEG at 56 days of healing duration. Nishiwaki *et al.* [11] reported that water-tightness and recovery in energy absorption capacity can be effectively restored in cracks where their width is $<100\text{ }\mu\text{m}$. Tittelboom *et al.* [12] investigated the biological repair technique because the synthetic polymer repair technique may be harmful to the environment. They used Ureolytic bacteria, such as *Bacillus sphaericus*, in concrete and obtained self-healing efficiency using a water permeability test. The bacteria were able to precipitate calcium carbonate (CaCO_3) in their micro-environment by converting urea into ammonium and carbonate thus filling the cracks. They concluded that the pure bacteria cultures were not capable to bridge the crack except those protected in silica gel. Jonkers *et al.* [13] also used bacteria as a tool to enhance the sus-

tainability of the concrete materials.

In all of the above-mentioned researches, the main focus was on the mechanical/permeability performance by using the self-healing process, and the fracture behavior of concrete based on the self-healing effect has hardly been studied in the literature [14]. Many authors investigated the fracture behavior of concrete without considering the self-healing concept [15, 16]. Golewski [17] investigated the fracture toughness and compressive strength of concrete using low calcium FA. In other research [18], the authors investigated the fracture behavior of FR mortar using a three-point bending test (PBT) without considering the self-healing concept. Khosravani *et al.* [19] reported the dynamic evaluation of fracture behavior of ultra-high performance concrete (UHPC) using the Brazilian test. Dynamic tensile strength and dynamic elastic modulus of UHPC were investigated. Furthermore, finite element analysis was also performed which was then compared with experimental test results, which showed good correlation and suitable results for UHPC. Khosravani *et al.* [20] also used spalling test to analyze the dynamic performance of UHPC. Dynamic tensile strength, dynamic elastic modulus, and fracture energy were obtained both by experimental and numerical simulation approaches and they concluded that both numerical and experimental simulation shows that obtained parameter is reliable and suitable for predictable simulation.

Considering the available literature, the current study has been undertaken to study the self-healing capability of FR mortar in terms of fracture behavior. It is necessary, as considering fracture behavior not only crack propagation effect in concrete can be reduced but also strength and durability performance could be improved. Also, a technique of finding actual crack healing by considering fracture behavior during the healing process has also been proposed for the utilization of the results from the practical design perspective.

An objective of the current study is to investigate the mechanical and fracture properties of FR mortar specimens by adding crystalline admixtures, expansive agents, and geomaterials. Furthermore, the effects of crack width and healing age on crack healing recovery were also investigated.

A controlled crack mouth opening displacement (CMOD) by three-PBT was conducted on prism specimens to induce the cracks after initial curing of 28 days. Mechanical property in terms of first cracking peak load (FCPL) increase and fracture property in terms of fracture toughness and fracture energy were examined at healing duration of 56 days and 120 days. Scanning electron microscope (SEM) and Energy dispersive X-ray spectroscopy (EDS) analyses were also carried out to determine the nature of healed products near the cracked area.

2. Research significance

The effect of crack self-healing on mechanical, durability, and water permeability properties with controlled damage is well established. However, the effect of crack self-healing on fracture and mechanical properties mainly fracture toughness, fracture energy, and FCPL is relatively less studied. Various investigations are reported on fracture properties of concrete without considering the healing mechanism [21], and the effect of crack healing was hardly touched by any author [5]. Therefore, in the current study, not only mechanical properties in terms of FCPL are determined but also fracture properties in terms of fracture toughness and fracture energy using a controlled three-PBT are also evaluated. In addition, a detailed analysis of load vs. CMOD response through three-PBT is also performed and explained. The data acquired from this study will be used for dual purposes. First, it will be used as a baseline for future study which consists of using steel bars in the concrete specimen for investigating flexural and shear behaviors of the cracked specimen after crack healing. Second, the data will be used practically in structures like dams, underwater structures, and skyscraper designs where the fracture mechanism is a key factor to be considered.

3. Experimental campaign

3.1. Materials and mix proportions

Type I ordinary Portland cement (OPC) and fine aggregates of density 2.60 g-cm^{-3} , fineness modu-

lus 2.43, and absorption rate 1.47% were used. To prepare mortar specimens for mechanical and water permeability testing, three types of mortar mix were used: OPC, HA1, and HA2 as given in Table 1. HA1 comprised sodium carbonate (Na_2CO_3) and calcium stearate (Ca^{2+}) embedded in the zeolite, which is a porous and highly adsorptive material that can accommodate ions. The proportions of Na_2CO_3 , calcium stearate, and zeolite in HA1 were in the ratio of 1:0.5:1.5. To prepare HA1, Na_2CO_3 was dissolved in water, zeolite was added to the mix, and the mixture was dried at 40°C for 24 h and then immediately dried at 100°C for 72 h. Powdered healing agents passed through a 0.06 mm sieve were obtained by sieving and crushing HA1 composed of such a mix and stearate. HA2 comprised HA1 powder, calcium sulfoaluminate (CSA) as an expansion agent, and bentonite as a geomaterial in the proportions of 3:2:1 [10].

3.2. Test methods

To investigate the self-healing capability of FR mortar mix and its effect on the re-gain of fracture and mechanical properties, duplicate prism specimens of $100 \times 100 \times 400 \text{ mm}$ with a central notch of 40 mm depth were cast and tested under three-PBT according to RILEM standards [22] as shown in Figure 1(a). After an initial water curing period of 28 days, all specimens were pre-cracked at various levels of CMOD ranging from $30 \mu\text{m}$ to $200 \mu\text{m}$ using three-PBT, as shown in Figure 1(a). A CMOD-controlled three-PBT set-up followed for pre-cracking as well as for the post-conditioning of the same prism specimen. During the test, CMOD was monitored using a clip gauge as shown in Figure 1(a), and after achieving the targeted CMOD, the loading was stopped and the specimen was unloaded. All the cracked specimens were then subjected to water immersion exposure conditions at a constant temperature of 20°C for healing observation. However, only one exposure condition, i.e., water immersion was selected with the healing period of 56 days and 120 days. The reason why only one exposure condition was selected is that because, in the case of wet/dry, open-air, and humidity chamber exposure conditions, the effect of

Table 1. Mix proportions for the three FR mortar mixtures with ratio.

Mix type	Water	Cement	Fiber (vol%)	Fine aggregate	Healing agent		f_c' (MPa)	Slump flow (mm)
					HA1	HA2		
OPC	0.40	1.00	0.5	2.00	–	–	54.6	170
HA1	0.40	1.00	0.5	1.97	0.03	–	47.3	165
HA2	0.40	1.00	0.5	1.94	–	0.06	49.6	169

FR, fiber-reinforced; OPC, ordinary Portland cement.

healing agents on healing rate was negligible especially in wider crack widths ($>100 \mu\text{m}$), even goes on decreasing as with the increase in healing duration.

Fracture and mechanical properties were investigated at the end of the final test setup in terms of FCPL increase, index fracture toughness K_{IC} recovery (IFTR), and index of fracture energy G_F recovery (IFER).

Fig. 1. Test set-up using (a) three-PBT and (b) for estimating the fracture toughness in three-PBT apparatus by RILEM [22]. PBT, point bending test.

The FCPL increase due to the crack healing effect was calculated by considering the peak load during the pre-cracking stage and peak load attained by the same specimen at initial cracking as illustrated in Figure 2(a) as well as defined in Eq. (1).

$$\text{FCPL increase} = \frac{\text{Load at initial cracking after healing}}{\text{Peak load during pre-cracking stage}} \quad (1)$$

For fracture toughness, the following equation was used depending on the test results obtained through three-PBT and as per the recommendation of RILEM [22]. Fracture toughness for both pre-cracking and post-conditioning stages was determined based on the stress intensity factor (K_{IC}).

$$\text{Stress intensity factor } (K_{IC}) = \frac{4P}{B} \sqrt{\frac{\pi}{W}} \cdot \left[1.6(a_0/W)^{\frac{1}{2}} - 2.6(a_0/W)^{\frac{3}{2}} + 12.3(a_0/W)^{\frac{5}{2}} - 21.2(a_0/W)^{\frac{7}{2}} + 21.8(a_0/W)^{\frac{9}{2}} \right] \quad (2)$$

where K_{IC} is stress intensity factor as reported in RILEM [22], P is the applied load, B is the thickness of the specimen, a_0 is the notch depth, and W is the width of the specimen as shown in Figure 1(b). In a three-PBT, a fatigue crack is created at the tip of the notch by cyclic loading as illustrated in Figure 1(b). A plot of load vs. CMOD as shown in Figure 2(a) is used to determine the load at which the crack starts growing. This load is substituted in Eq. (2) to find the fracture toughness. After calculating the fracture toughness of each virgin and healed specimen, recovery against crack healing was obtained using Eq. (3).

$$\text{Index of fracture toughness recovery (IFTR)} = \left(\frac{K_{IC \text{ healed specimen}}}{K_{IC \text{ virgin specimen}}} \right) \quad (3)$$

where $K_{IC \text{ healed}}$ is referred to the fracture toughness of specimen after the crack healing process,

(a)

(b)

Fig. 2. (a) Load vs. CMOD response during the three-PBT and (b) microscopic analysis for measuring crack width before and after the self-healing process. CMOD, crack mouth opening displacement; PBT, point bending test.

i.e., after 56 days and 120 days of healing duration; and $K_{IC \text{ virgin}}$ is referred to the fracture toughness of reference specimen.

Fracture energy is obtained by estimating the area under the curve (W_o) as shown in Figure 3. For obtaining the area for the healed specimen, the proposed methodology consists of backward shifting of the post-conditioning curve along the x-axis until the peak of the curve (post-conditioning) touches the pre-cracking curve as shown in Figure 3(b).

Initially, the response obtained from a three-PBT was plotted in terms of load vs. CMOD response but based on the standards available for calculation of fracture energy, load values were converted into stress values using the Eq. (4). The same test setup was followed for the evaluation of fracture energy that was adopted for the determination

(a) Area of a reference specimen

(b) Area of healed specimen

Fig. 3. Stress vs. CMOD response for estimation of fracture energy based on the area under the curve considering actual crack healing. CMOD, crack mouth opening displacement.

of fracture toughness and FCPL increase.

$$\sigma = \frac{3P \cdot L}{2b(d-a)^2} \quad (4)$$

where P is the maximum load attained by the specimen, L is the support length during 3-PBT (300 mm), b is the width of the prism (100 mm), d is the prism depth (100 mm), and a is the notch depth (40 mm) [10]. After obtaining the stress values, the area under the curve (W_o) for all mix type specimens was obtained and the required fracture energy was calculated by the following Eq. (5).

$$G_F = \frac{(W_o + m \cdot g \cdot \delta_o)}{B(D-a_o)} \quad (5)$$

where W_o is the area under the load–CMOD curve, m is the weight of prism sample between

span, g is gravitational acceleration, δ_0 is maximum crack opening, B is the width of the prism, D is the height of the prism, and a_0 notch depth. Then, the following Eq. (6) was used for the determination of recovery of fracture energy due to the actual crack healing effect as illustrated in Figure 3(b).

$$\text{Index of fracture energy recovery (IFER)} = \left(1 - \frac{G_{F \text{ healed specimen}}}{G_{F \text{ virgin specimen}}} \right) \quad (6)$$

where $G_{F \text{ healed}}$ is the fracture energy due to healing effect (area $W_{o \text{ healed specimen}}$) and $G_{F \text{ virgin specimen}}$ is the total fracture energy of the reference specimen. That is, the area under the stress (σ) vs. CMOD curve until the stress level reaches 1.0 MPa, which is fixed as a benchmark for ease in calculation, since there was a negligible amount of load carried by the specimen after that stress level as shown in Figure 3.

3.3. Crack characteristics determination

It is important to check the properties of the stimulated healing agent before and after the healing process to investigate the ability of self-healing efficiency and crack characteristics. Microscopic observations were performed on each specimen with a high range digital microscope having a resolution of 160–3,400 $\times$ to measure crack length and width. After pre-cracking, each specimen was marked with three points along crack length at upside and downside, and images were captured as shown in Figure 3(b), and crack width was measured then at each point. Then all the prism specimens were placed in water curing for healing for a period of 56 days or 120 days. After the healing process, photographs were taken again at the same marked points. Both images were compared to ascertain how much the cracks were healed. Furthermore, SEM analysis was also performed on each healed specimen for every mix type to characterize the nature of healed products accumulated around the crack surface after the healing duration ended.

4. Results and discussion

4.1. Effect of healing materials, crack width, and healing duration on load vs. CMOD curve

Load vs. CMOD response of a few selected specimens is plotted in Figure terms of pre-cracking and the post-conditioning response of the same specimen under a three-PBT. Depending on the mix type, after analyzing the changes in the plots of load vs. CMOD, it was found that the FCPL, as defined in Figure 2(a), increased when healing agents were used. At the end of 120 days of the healing period for crack width $<50 \mu\text{m}$, FCPL of HA1-120D-43.3 and HA2-120D-36 showed a better increase than OPC-120D-34.8 with 42% and 48% increase, respectively. Furthermore, for the crack widths $>50 \mu\text{m}$, FCPL values of HA1 and HA2 were 65% and 89% higher than those of OPC specimen after 120 days of healing respectively.

Curve behavior is quite interesting, which suggests elastic as well as ductile behavior for longer loading durations in case of crack widths $<50 \mu\text{m}$ and $100 \mu\text{m}$ when healing agents (HA1, HA2) were used. Figure 4 represents the curve behavior of OPC, HA1, and HA2 specimens for 56 days and 120 days of healing durations.

In the figures mentioned, better steep slopes of curves and better loading resistance against applied load are observed due to better crack bridging effect and strong bond between the crack faces. The reason for the better performance may be the crack would have filled with the healing agent after 120 days which not only resists better loading capacity after the damage but also enhanced the ductility of the mortar specimen since the behavior of the curve is almost linear until the initial cracking appears. Not only load-carrying capacity is increased after crack healing, but it also has a higher value of FCPL during the post-conditioning stage for HA1 and HA2 which shows compact and strong crack healing. It is also worth remarking that higher values of maximum load-carrying capacity have been achieved which clearly shows that the narrow cracks are filled by healed products mainly (calcium carbonate precipitation). It also suggests that healing agents are suitable for narrow cracks (in the

Fig. 4. Load vs. CMOD response of each specimen during the three-PBT at pre-cracking and post-conditioning stages. CMOD, crack mouth opening displacement; PBT, point bending test.

range of 30–80 μm) to restore fracture and mechanical properties.

4.2. Mechanical properties (FCPL increase)

Mechanical properties of the FR mortars with different healing materials were analyzed using increase in FCPL as shown in Figure 5(a). Load at FCPL points was compared with initial peak load during the pre-cracking stage to get a better understanding of ductile and linear curve behavior. Steep values of FCPL for special mixtures are quite better when compared with the OPC specimen as in Figure 5(a). Table 2 depicts the calculated values of the FCPL with respect to peak load value of

the same specimen during the test for few specimens, for all dataset which was tested during this study (see Tables A1–A3 in Appendix). For 50 μm cracked specimens, after 56-day healing, an FCPL increase of 48% and 22% was noticed in HA2-56D-35 and HA1-56D-44, respectively, when compared to those with the OPC-56D-39. However, an FCPL increase of 58% and 41% were found in HA2-120D-36 and HA1-120D-43.4, respectively, when compared with OPC-120D-35.5 specimen at the same crack with width of 50 μm . HA mix includes crystalline admixtures and expansive agents, which generates more calcium carbonate precipitation due to quick and strong chemical reaction in the presence of moisture as confirmed from Figure

4 and fills the crack gap by extra expansion capacity which was also confirmed by Buller *et al.* [10].

imen, thus improving the ductility and elastic behavior of materials.

4.3. Index of fracture toughness (K_{IC}) recovery (IFTR)

The fracture toughness in terms of critical intensity factor was proposed and investigated in this study to restrict the further propagation of crack/damage by using the self-healing process of concrete in recovery damage. Fracture toughness values in terms of critical intensity factor (K_{IC}) are presented in Figure 5(b). Based on Eqs. (2) and (3), few specimen values of K_{IC} and IFTR are summarized in Table 3, for all specimen data see A1–A3 in Appendix. Load vs. CMOD diagram in Figures 4 and 5(b) portrays that the healing agents increase the fracture toughness values in terms of recovery against cracking in both the crack ranges after 120-day healing.

Figure 5(b) depicts that healing agents contribute more effectively as compared to OPC specimens. Maximum values of IFTR were achieved in HA1-120D-32 and HA2-120D-36 specimens, i.e., 0.420 and 0.487 respectively, with an increase of 42% and 65% to that of OPC-120D-34.8 specimen after 120 days of healing. It is attributed to the fact that the full depth crack healing resulted in compact surfaces which allows decreasing the further widening and propagation of the crack.

4.4. Effect of crack healing on fracture energy (G_f) recovery

The fracture energy occurred within the fracture zone; it is the region in front of the crack tip where stress decreases as the crack opens. The calculated area under the curve and related amount of fracture energy as per calculation based on Eqs. (5) and (6) are given in Table 3 as well as can be seen from Figure 5(c). For all specimen data see A1–A3 in Appendix.

The maximum value of IFER was achieved in HA1-120D-43.4 and HA2-120D-37 and is found to be 7% and 19% higher than OPC-120D-34.8 specimen in crack width $<50 \mu\text{m}$, however, the same trend observed in higher crack width. Test results based on increased fracture energy recovery

Fig. 5. Different self-healing indices based on the three-PBT. PBT, point bending test.

It is because higher values of FCPL increase show that crystalline materials and expansive agents tend to penetrate deep inside the cracks due to which specimen showed larger load-bearing capacities in terms of higher peak load during the post-conditioning stage than that of OPC specimen. From Figure 5(a), it can be observed that the values obtained are consistent and not overlapped as can be seen from the values in the case of OPC spec-

Table 2. Tabulated values of FCPL increase for few crack width.

Mix type	W (μm)	FCPL (kN)	P _{loading}	FCPL increase	Mix type	W (μm)	FCPL (kN)	P _{loading}	FCPL increase
OPC-56D	36	1.32	4.29	0.31	OPC-120D	34.8	1.27	4.29	0.3
	65	0.39	3.06	0.13		73	0.54	3.29	0.16
	141	0.25	3.25	0.08		133	0.25	3.26	0.08
	183	0.19	3.18	0.06		165	0.22	3.36	0.07
HA1-56D	44	1.41	3.7	0.38	HA1-120D	43.4	1.8	4.1	0.44
	79	0.52	3.12	0.17		81	1.04	3.39	0.31
	135	0.29	3.25	0.09		147	0.31	2.27	0.14
	169	0.2	3	0.07		166	0.26	2.98	0.09
HA2-56D	35	1.81	3.9	0.46	HA2-120D	36	1.9	3.9	0.49
	61	0.71	3.02	0.24		70.3	1.22	3.36	0.36
	136	0.3	3.1	0.1		143	0.57	3.03	0.19
	187	0.21	2.33	0.09		160	0.39	3.39	0.12

FCPL, first cracking peak load; OPC, ordinary Portland cement.

Table 3. Tabulated values of fracture toughness for each type of mix and IFTR.

Mix type	W (μm)	FCPL (kN)	P _{loading}	K _{IC_Precrack}	K _{IC_Healed}	IFTR	Mix type	W (μm)	FCPL (kN)	P _{loading}	K _{IC_Precrack}	K _{IC_Healed}	IFTR
OPC-56D	34	1.24	4.29	0.034	0.0098	0.29	OPC-120D	36	1.31	4.29	0.034	0.0104	0.31
	65	0.39	3.06	0.0243	0.0031	0.13		73	0.54	3.29	0.0261	0.0043	0.16
	141	0.25	3.25	0.0258	0.002	0.08		133	0.25	3.26	0.0259	0.002	0.08
	168	0.18	2.96	0.0235	0.0014	0.06		184	0.21	3.52	0.0279	0.0017	0.06
HA1-56D	44	1.41	3.7	0.0294	0.0112	0.38	HA1-120D	43	1.8	4.1	0.0325	0.0143	0.44
	72.4	0.6	3.2	0.0254	0.0048	0.19		81	1.04	3.39	0.0269	0.0083	0.31
	142	0.26	3.02	0.024	0.0021	0.09		147	0.31	2.27	0.018	0.0025	0.14
	169	0.2	3	0.0238	0.0016	0.07		166	0.26	2.98	0.0236	0.0021	0.09
HA2-56D	35	1.81	3.9	0.0309	0.0144	0.46	HA2-120D	36	1.9	3.9	0.0309	0.0151	0.49
	61	0.71	3.02	0.024	0.0056	0.24		70	1.22	3.36	0.0267	0.0097	0.36
	130	0.28	2.86	0.0227	0.0022	0.1		139	0.5	2.72	0.0216	0.004	0.18
	187	0.21	2.33	0.0185	0.0017	0.09		160	0.39	3.39	0.0269	0.0031	0.12

FCPL, first cracking peak load; IFTR, index of fracture toughness recovery; OPC, ordinary Portland cement.

ery demonstrate that a higher value of fracture energy resulted due to the greater area under the load vs. CMOD curve as in (load vs. CMOD curves). Note that the use of a healing agent increases both load-carrying capacity and area under curve significantly as compared to OPC in the post-conditioning stage. It suggests that better fracture energy is absorbed by the specimen after the healing period. Based on the results shown in Figure 5(c), it is observed that the proposed indices to calculate the fracture energy is more appropriate than

calculating the ICH as similarly reported by Ferrara et al. [9] by considering the effect of actual crack healing effect, because the healing mechanism can enhance resistance to existing infrastructure against earthquake, impacts, and explosions.

This resistance to external loading like an earthquake is strongly related to the fracture energy at certain loading rates. Thus, enhancing fracture energy using the crack self-healing technique after certain damage is one of the effective approaches to prevent structural collapse or destruction and

Table 4. Tabulated values of fracture energy considering the area under the curve (W_o) based on actual crack healing and IFER.

Mix type	W (μ m)	W_o Pre-crack	W_o healed	$G_{f_{pre\ crack}}$	$G_{f_{healed}}$	IFER	Mix type	W (μ m)	W_o Pre-crack	W_o healed	$G_{f_{pre\ crack}}$	$G_{f_{healed}}$	IFER
OPC-56D	36	4.92	2.11	0.354	0.148	0.58	OPC-120D	34.8	4.92	2.11	0.342	0.108	0.68
	75	0.89	0.31	0.736	0.324	0.56		70.9	1.94	0.62	0.696	0.275	0.61
	141	2.28	0.49	1.384	0.942	0.32		137	2.39	0.59	1.344	0.883	0.34
	183	1.52	0.33	1.795	1.324	0.26		184	1.95	0.41	1.805	1.226	0.32
HA1-56D	37.3	1.9	1.17	0.366	0.108	0.7	HA1-120D	43.4	3.1	1.8	0.426	0.098	0.77
	79	1.01	0.39	0.775	0.314	0.59		78	1.72	0.66	0.765	0.314	0.59
	142	2.56	0.64	1.393	0.893	0.36		147	2.29	0.58	1.442	0.873	0.39
	178	1.92	0.36	1.747	1.197	0.31		173	2.21	0.42	1.697	1.099	0.35
HA2-56D	38.6	2.77	1.89	0.379	0.094	0.75	HA2-120D	37	2.53	1.8	0.363	0.069	0.81
	67	1.49	0.75	0.658	0.324	0.51		77	2.73	1.21	0.756	0.304	0.6
	136	1.58	0.5	1.334	0.795	0.4		144	1.81	0.59	1.413	0.765	0.46
	187	1.48	0.55	1.835	1.148	0.37		160	1.96	0.42	1.57	0.922	0.41

IFER, index of fracture energy recovery; OPC, ordinary Portland cement.

can protect human life furthermore. It is therefore found that this approach suggests a more accurate way to tackle the crack propagation effect after the crack healing process, rather than to consider only crack closure due to healing as suggested by Ferrara et al. [9].

4.5. Microscopic and SEM analysis

The comparison of healed products based on the images of the digital microscope is presented in Figure remarkable sealing of crack was observed in cracked specimens containing self-healing agents in the case of a water immersion exposure condition. This trend is observed because HA mix includes crystalline admixtures and expansive agents, which generates more calcium carbonate precipitation due to quick and strong chemical reaction in the presence of moisture as observed from Figure 4 and fills the crack gap by extra expansion capacity which was also confirmed by Buller et al. [10]. These products accelerate the healing process by supplying water to unhydrated particles of cement and generate crystalline products in the shape of white residue around the crack surface as shown in Figure 6, which is the key factor in the sealing of cracks. Recovery of healing/crack closing is almost complete as compared to original crack width at 120 days of healing duration in almost all three mix

types, which confirms the effectiveness of healing materials in crack closing at early age healing duration.

Also, SEM analysis was carried out and the pictures are shown in Figure 7. Further details and more descriptions about SEM analysis test results can be found in another study reported by Buller et al. [10].

5. Conclusions

Based on the detailed experimental investigations, the following conclusion can be drawn from this study.

An improved load carrying capacity during the reloading stage was obtained when healing agents were used. This shows that the damaged specimens having crack width of 35–80 μ m exhibited ductile behavior. This is because the healing materials generate crystalline products near the damaged area resulting in full-depth crack healing. Thus, compact and strong surfaces were achieved that extended initial cracking during the reloading stage.

A substantial increase in IFER and IFTR (almost 80% recovery) at the healing period of 56 days and 120 days was observed in the crack range of 35–80 μ m. This could be confirmed by the strong

Fig. 6. Captured images of a different specimen during microscopic observation at the end of 120 days healing duration (A) OPC specimen, (B) HA1 specimen, and (C) HA2 specimen. OPC, ordinary Portland cement.

and rapid generation of healed products near the crack as observed in the images of SEM.

The obtained increase in FCPL values shows the compactness and strong bonding resistance between crack surfaces, which sustained much higher loads during the reloading stage. That reflects the role of healing agents in enhancing the load-bearing capacity of the material.

The findings of this study show that the me-

chanical and fracture recovery is based on the bonding capacity of crack faces as well as resistance between interconnecting healed particles, which can be improved by increasing the healing duration further. Therefore, it is of utmost importance to evaluate the mechanical as well as fracture performance of self-healing materials to ensure the sustainability of concrete structures.

Fig. 7. SEM image of crack surfaces at a healing period of 56 days (magnification: 3,000). SEM, scanning electron microscope.

Declarations

Availability of data and material

No supplementary data and material are needed for this research work.

Compliance with ethical standards

None.

Conflicts of interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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Author contributions

Abdul Salam Buller – conceptualization, experiments, data analysis, writing of original draft (first author); Fahad ul Rehman Abro – experiments, data analysis, writing review and editing (co-author); Tariq Ali – writing review and editing, (co-author); Sadam Hussain Jakhrani – writing review and editing (co-author); Abdul Hafeez Buller – data analysis, writing review and editing (co-author); and Zain Ul-Abdin – data analysis, review and editing (co-author and corresponding author)

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Appendix

Table A1. Tabulated values of FCPL increase for few crack width.

Mix type	W (μm)	FCPL (kN)	P _{loading}	FCPL in-crease	Mix type	W (μm)	FCPL (kN)	P _{loading}	FCPL in-crease
OPC-56D	36	1.32	4.29	0.31	OPC-120D	34.8	1.27	4.29	0.3
	39	1.34	4.29	0.31		35.5	1.31	4.29	0.31
	34	1.24	4.29	0.28		40.2	1.21	4.29	0.28
	65	0.39	3.06	0.13		73	0.54	3.29	0.16
	72	0.36	3.24	0.11		70.9	0.42	3.36	0.13
	75	0.31	3.3	0.1		76	0.38	3.31	0.12
	141	0.25	3.25	0.08		137	0.25	3.38	0.07
	138	0.23	3.46	0.07		144	0.26	3.3	0.08
	145	0.21	3.33	0.06		133	0.25	3.26	0.08
	183	0.19	3.18	0.06		165	0.22	3.36	0.07
	172	0.17	2.83	0.06		184	0.21	3.52	0.06
	168	0.18	2.96	0.06		177	0.24	3.59	0.07
HA1-56D	37.3	1.52	4.17	0.36	HA1-120D	32	1.72	4.1	0.42
	44	1.41	3.7	0.38		43.4	1.8	4.1	0.44
	32	1.24	3.58	0.34		44	1.66	4.4	0.4
	72.4	0.6	3.2	0.19		81	1.04	3.39	0.31
	79	0.52	3.12	0.17		78	0.89	3.31	0.27
	68	0.49	3.19	0.15		85	0.91	3.65	0.25
	139	0.28	3.8	0.07		133	0.33	3.13	0.11
	135	0.29	3.25	0.09		140	0.35	3.11	0.11
	142	0.26	3.02	0.09		147	0.31	2.27	0.14
	178	0.22	3.33	0.07		173	0.24	3.49	0.07
	181	0.23	3.39	0.07		175	0.21	2.73	0.08
	169	0.2	3	0.07		166	0.26	2.98	0.09
HA2-56D	35	1.81	3.9	0.46	HA2-120D	36	1.9	3.9	0.49
	38.6	1.77	3.9	0.45		37	1.88	3.9	0.48
	41	1.68	3.9	0.43		39.6	1.73	3.9	0.44
	69.9	0.68	3.16	0.22		83	1.02	3.03	0.34
	61	0.71	3.02	0.24		70.3	1.22	3.36	0.36
	67	0.65	3.1	0.21		85	1.11	3.41	0.32
	136	0.3	3.1	0.10		139	0.5	2.72	0.18
	130	0.28	2.86	0.10		143	0.57	3.03	0.19
	137	0.26	2.77	0.09		144	0.45	3.35	0.13
	175	0.22	1.96	0.11		180	0.38	3.65	0.10
	184	0.24	2.54	0.09		170	0.38	3.2	0.12
	187	0.21	2.33	0.09		160	0.39	3.39	0.12

FCPL, first cracking peak load; OPC, ordinary Portland cement.

Table A2. Tabulated values of fracture toughness for each type of mix and IFTR.

Mix type	W (μm)	FCPL (kN)	P loading	K _{IC_Precrack}	K _{IC_Healed}	IFTR	Mix type	W (μm)	FCPL (kN)	P loading	K _{IC_Precrack}	K _{IC_Healed}	IFTR
OPC-56D	36	1.32	4.29	0.0340	0.0105	0.31	OPC-120D	35	1.27	4.29	0.0340	0.0101	0.30
	39	1.34	4.29	0.0340	0.0106	0.31		36	1.31	4.29	0.0340	0.0104	0.31
	34	1.24	4.29	0.0340	0.0098	0.29		40	1.21	4.29	0.0340	0.0096	0.28
	65	0.39	3.06	0.0243	0.0031	0.13		73	0.54	3.29	0.0261	0.0043	0.16
	72	0.36	3.24	0.0257	0.0029	0.11		71	0.42	3.36	0.0267	0.0033	0.13
	75	0.31	3.3	0.0262	0.0025	0.09		76	0.38	3.31	0.0263	0.0030	0.11
	141	0.25	3.25	0.0258	0.0020	0.08		137	0.25	3.38	0.0268	0.0020	0.07
	138	0.23	3.46	0.0275	0.0018	0.07		144	0.26	3.3	0.0262	0.0021	0.08
	145	0.21	3.33	0.0264	0.0017	0.06		133	0.25	3.26	0.0259	0.0020	0.08
	183	0.19	3.18	0.0252	0.0015	0.06		165	0.22	3.36	0.0267	0.0017	0.07
	172	0.17	2.83	0.0225	0.0013	0.06		184	0.21	3.52	0.0279	0.0017	0.06
HA1-56D	168	0.18	2.96	0.0235	0.0014	0.06	HA1-120D	177	0.24	3.59	0.0285	0.0019	0.07
	37.3	1.52	4.17	0.0331	0.0121	0.36		32	1.72	4.10	0.0325	0.0136	0.42
	44	1.41	3.7	0.0294	0.0112	0.38		43	1.80	4.10	0.0325	0.0143	0.44
	32	1.24	3.58	0.0284	0.0098	0.35		44	1.66	4.40	0.0349	0.0132	0.38
	72.4	0.6	3.2	0.0254	0.0048	0.19		81	1.04	3.39	0.0269	0.0083	0.31
	79	0.52	3.12	0.0248	0.0041	0.17		78	0.89	3.31	0.0263	0.0071	0.27
	68	0.49	3.19	0.0253	0.0039	0.15		85	0.91	3.65	0.0290	0.0072	0.25
	139	0.28	3.8	0.0301	0.0022	0.07		133	0.33	3.13	0.0248	0.0026	0.11
	135	0.29	3.25	0.0258	0.0023	0.09		140	0.35	3.11	0.0247	0.0028	0.11
	142	0.26	3.02	0.0240	0.0021	0.09		147	0.31	2.27	0.0180	0.0025	0.14
	178	0.22	3.33	0.0264	0.0017	0.07		173	0.24	3.49	0.0277	0.0019	0.07
HA2-56D	181	0.23	3.39	0.0269	0.0018	0.07	HA2-120D	175	0.21	2.73	0.0217	0.0017	0.08
	169	0.2	3	0.0238	0.0016	0.07		166	0.26	2.98	0.0236	0.0021	0.09
	35	1.81	3.9	0.0309	0.0144	0.46		36	1.90	3.90	0.0309	0.0151	0.49
	38.6	1.77	3.9	0.0309	0.0140	0.45		37	1.88	3.90	0.0309	0.0149	0.48
	41	1.68	3.9	0.0309	0.0133	0.43		40	1.73	3.90	0.0309	0.0137	0.44
	69.9	0.68	3.16	0.0251	0.0054	0.22		83	1.02	3.03	0.0240	0.0081	0.34
	61	0.71	3.02	0.0240	0.0056	0.24		70	1.22	3.36	0.0267	0.0097	0.36
	67	0.65	3.1	0.0246	0.0052	0.21		85	1.11	3.41	0.0258	0.0088	0.34
	136	0.3	3.1	0.0246	0.0024	0.10		139	0.5	2.72	0.0216	0.0040	0.18
	130	0.28	2.86	0.0227	0.0022	0.10		143	0.57	3.03	0.0240	0.0045	0.19
	137	0.26	2.77	0.0220	0.0021	0.09		144	0.45	3.35	0.0266	0.0036	0.13
	175	0.22	1.96	0.0156	0.0017	0.11		180	0.38	3.65	0.0290	0.0030	0.10
	184	0.24	2.54	0.0202	0.0019	0.09		170	0.38	3.2	0.0254	0.0030	0.12
	187	0.21	2.33	0.0185	0.0017	0.09		160	0.39	3.39	0.0269	0.0031	0.12

FCPL, first cracking peak load; IFTR, index of fracture toughness recovery; OPC, ordinary Portland cement.

Table A3. Tabulated values of fracture energy considering the area under the curve (W_o) based on actual crack healing and IFER.

Mix type	W (μm)	W_o Pre- crack	W_o healed	Gf pre crack	Gf healed	IFER	Mix type	W (μm)	W_o Pre- crack	W_o healed	Gf pre crack	Gf healed	IFER
OPC-56D	36	4.92	2.11	0.354	0.148	0.58	OPC-120D	34.8	4.92	2.11	0.342	0.108	0.68
	39	4.92	2.26	0.383	0.157	0.59		35.5	4.92	2.03	0.349	0.123	0.65
	34	4.92	2.19	0.334	0.177	0.47		40.2	4.92	1.97	0.395	0.147	0.63
	65	1.09	0.35	0.638	0.353	0.45		73	1.97	0.64	0.716	0.255	0.64
	72	0.97	0.29	0.706	0.334	0.53		70.9	1.94	0.62	0.696	0.275	0.61
	75	0.89	0.31	0.736	0.324	0.56		76	1.88	0.59	0.746	0.304	0.59
	141	2.28	0.49	1.384	0.942	0.32		137	2.39	0.59	1.344	0.883	0.34
	138	3.04	0.81	1.354	0.971	0.28		144	3.2	0.82	1.413	0.903	0.36
	145	2.56	0.57	1.423	0.981	0.31		133	2.85	0.57	1.305	0.873	0.33
	183	1.52	0.33	1.795	1.324	0.26		165	1.87	0.37	1.619	1.128	0.30
	172	1.97	0.41	1.688	1.275	0.24		184	1.95	0.41	1.805	1.226	0.32
	168	2.12	0.39	1.648	1.275	0.23		177	2.11	0.29	1.737	1.236	0.29
HA1-56D	37.3	1.9	1.17	0.366	0.108	0.70	HA1-120D	32	3.1	1.75	0.314	0.089	0.72
	44	1.9	1.14	0.432	0.137	0.68		43.4	3.1	1.8	0.426	0.098	0.77
	32	1.9	1.1	0.314	0.147	0.53		44	3.1	1.71	0.432	0.138	0.68
	72.4	1.33	0.48	0.710	0.285	0.60		81	1.77	0.55	0.795	0.334	0.58
	79	1.01	0.39	0.775	0.314	0.59		78	1.72	0.66	0.765	0.314	0.59
	68	1.1	0.42	0.667	0.343	0.49		85	1.66	0.63	0.834	0.363	0.56
	139	2.11	0.36	1.364	0.883	0.35		133	1.6	0.42	1.305	0.824	0.37
	135	2.31	0.43	1.325	0.883	0.33		140	1.88	0.46	1.374	0.854	0.38
	142	2.56	0.64	1.393	0.893	0.36		147	2.29	0.58	1.442	0.873	0.39
	178	1.92	0.36	1.747	1.197	0.31		173	2.21	0.42	1.697	1.099	0.35
	181	2.13	0.42	1.776	1.236	0.30		175	1.88	0.51	1.717	1.148	0.33
	169	2.33	0.48	1.658	1.177	0.29		166	2.03	0.53	1.629	1.128	0.31
HA2-56D	35	2.77	1.82	0.344	0.108	0.69	HA2-120D	36	2.53	1.74	0.354	0.079	0.78
	38.6	2.77	1.89	0.379	0.094	0.75		37	2.53	1.8	0.363	0.069	0.81
	41	2.77	1.78	0.403	0.138	0.66		39.6	2.53	1.69	0.389	0.098	0.75
	69.9	1.53	0.79	0.686	0.265	0.61		83	1.91	0.85	0.815	0.245	0.70
	61	1.7	0.85	0.599	0.363	0.39		70.3	2.7	1.18	0.690	0.285	0.59
	67	1.49	0.75	0.658	0.324	0.51		77	2.73	1.21	0.756	0.304	0.60
	136	1.58	0.5	1.334	0.795	0.40		139	1.66	0.6	1.364	0.775	0.43
	130	1.66	0.57	1.276	0.795	0.38		143	1.73	0.65	1.403	0.765	0.45
	137	1.51	0.47	1.344	0.814	0.39		144	1.81	0.59	1.413	0.765	0.46
	175	1.4	0.5	1.717	1.099	0.36		180	2.22	0.32	1.766	1.010	0.43
	184	1.66	0.62	1.805	1.177	0.35		170	1.81	0.39	1.668	1.020	0.39
	187	1.48	0.55	1.835	1.148	0.37		160	1.96	0.42	1.570	0.922	0.41

IFER, index of fracture energy recovery; OPC, ordinary Portland cement.