Spotlight on mechanical properties of autogenic self-healing of concrete

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ABSTRACT

Self-healing concrete is defined as the concrete ability to recover its cracks. Cracks in concrete are a common phenomenon that reveals adverse effects on a structure's integrity, durability, and serviceability due to its relatively low tensile strength. Recently, self-healing techniques have been developed to ensure crack recovery and implemented in strategic structures to optimize maintenance costs. This study aims to highlight one self-healing technique type named the "autogenic self-healing technique". Four mixes including the control were designed and established to examine the self-healing mechanism when using mineral admixtures such as fly ash and polyvinyl alcohol fiber (PVA fiber) at various percentiles. All mixes encountered 20% cement volume replacement by fly ash with various PVA fiber percentile additions: 1, 1.5, and 2%. Compressive, flexural, and tensile strengths were examined after cracking and failure. The cube prism and cylinder specimens were cracked and then cured at 28 days for testing to failure. The results showed that the compressive strength recovered in mixes with 1.5 and 2% PVA. This work provides promising insight on cracks healing or recovery to a certain extent.

Introduction

Concrete is the second most consumed material and Its annual global production is about 3.8 billion cubic meters which is roughly 1.5 tons per capita [1]. However, due to the sheer mass of concrete because of its high compressive strength, durability, and cost-effectiveness consumed annually, and its associated resource deployment and environmental impacts [2]. Thus, for greener concrete replacing cement with supplementary cementitious materials (SCM) or lowering maintenance and repair costs would be an alternative. The former can be performed by introducing self-healing techniques, which are principally divided into two types, autogenic and autonomic [3]. Autogenic self-healing in concrete is an intrinsic material-healing property that initiates from the cementitious materials which exhibit a rehydration property of unhydrated cement remaining on the crack surface [3]. In contrast, a self-healing process that involves the incorporation of material components that are not traditionally used in concrete is termed autonomic self-healing [3].

Several factors affect the efficiency of autogenous healing [4] since it is a time-dependent phenomenon. Nevertheless, other than ongoing hydration at an early age, and precipitation of calcium carbonate, various water regimes and crack geometry would affect the healing efficiency presented in the crack closure. The wider the crack (≥200 µm), the faster the initial process since more space is available for the healing products and easier supply of carbon dioxide and water. However, the overall closure of cracks was observed to be higher for smaller cracks (~ 50 µm) as it is easier to fill. Further, a low water-to-binder ratio with unhydrated cement particles leads to a higher self-healing efficiency.

Like the bones in humans, the mechanism of crack healing that is possessed through sustained and long-term loading with the addition of PVA fiber and the existence of fly ash would reduce the cement amount utilization and in turn, increase the life cycle. The mechanism of inclusion PVA for triggering the self-healing would be through the viscosity provided by the fiber surface which attracts the calcium carbonate $CaCO_3$ produced from the water ingress while further curing into the concrete activating unhydrated C_3A and considering the excess $Ca(OH)_2$ that is produced from the initial hydration. Thus, the calcium carbonate would fill the cracks created by the existing load. Not all cracks can be healed; however, the crack closure can be reduced or enhanced based on other factors such as crack width and depth and the crack surface that can handle the precipitation of the calcium carbonate for more crack filling and closure.

Homma et al. [13] utilized three fibers (polyethylene (PE), steel cord, and hybrid composites) to examine the self-healing properties of fiber-reinforced cementitious composites (FRCC) through cracking using tension test and retained at 28 days after water curing. Their results revealed that the PE fiber has provided the most influence based on the volume in bridging the crack and crystallization products attached easily to the larger numbers of PE fibers. Similarly, Mauser et al. [15] stated that the autogenous methods mainly depend on mineral admixtures such as fly ash and fiber addition, such as polyvinyl alcohol (PVA) fibers. Their investigation revealed that these additives have great potential for the self-healing process in concrete and provide good results in real applications under certain curing conditions. These fibers could help in enhancing self-healing through the process of controlling the crack and accelerating $CaCO_3$ precipitation. Recent studies by Liang et al. [16] and Hammad et al. [17] showed that these fibers (PVA) have provided high polarity synthetic composite and act as a bridge through the crack [17].

Although the observation has various challenges and limitations when applying mineral admixture and PVA additives, utilizing the triggers and microcapsules systems. These challenges can be limited by the chemical triggers existing within the solution and along the fibers including, pH values and ion charge on the fiber surfaces. Here in this study, a permeative study on the influence of utilizing Fly ash as a replacement of cement by 20% with the addition of PVA fiber at different volumes of the fraction to stand on the healing of the cracks in concrete specimens and evaluating the compressive, flexural and tensile strength recovery after exposing to wet and drying cycle of curing regime at 7 and 28 days of age

Experimental Program

Materials and Mix Design

An Ordinary Portland Cement with a grade of 42.5, MPa (N/mm²) and fly ash class F was utilized. The physical, chemical, and mechanical properties of the cement and fly ash are described in Table 1.

Table 1. Physical, chemical, and mechanical properties

Chemical composition in (%)		
Component (%)	**OPC**	**FA class F**
SiO_2	47.09	47.09
Al_2O_3	17.41	17.41
Fe_2O_3	8.34	8.34
CaO	13.98	13.98
MgO	1.85	1.85
SO_3	4.65	4.65
Na_2O	2.44	2.44
K_2O	1.8	1.8
Loss ignition	2.2	1.79
Physical properties		
Specific gravity	3.16	2.15
Mechanical properties		
Compressive strength (MPa)		
1 day	25	-
2 days	38	-
28 days	68	-

In addition, combined fine and coarse aggregates with a grain size distribution with a nominal aggregate size of 12.5 mm are provided in Fig. 1 and their physical properties are presented in Table 2 along with the physical and mechanical properties of the Polyvinyl alcohol (PVA) fiber that was utilized in the concrete mixture. The ASTM C33 [18] provided the limits of the total aggregate including fine and coarse aggregate for a nominal aggregate size of 12.5 mm. The curve is within the limits as per the ASTM requirements.

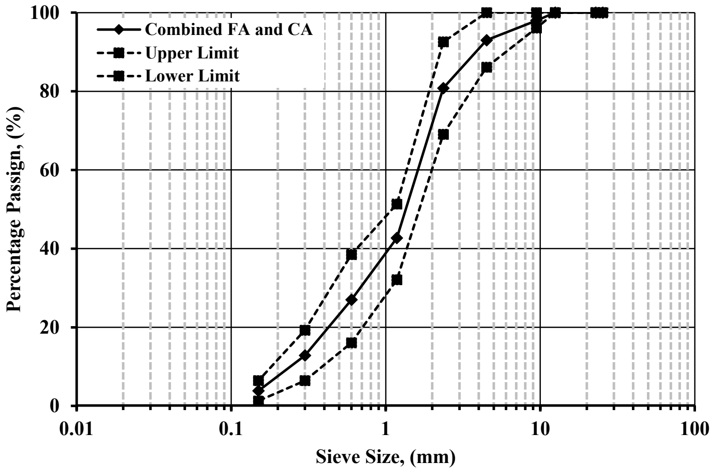


Fig. 1. Sieve analysis of fine and coarse combined aggregate with limit ASTM C33 [18]

Table 2. Physical properties of fine and coarse Aggregate

Property	Physical properties FA	CA	PVA
Specific gravity	2.62	2.65	
Absorption percentile	1.6%	1%	
Fineness modulus	6.62	2.72	
Length	-	-	9 mm
Diameter	-	-	0.04 mm
Specific gravity	-	-	1.12
Elastic modulus	-	-	40 GPa
Tensile strength	-	-	1320 MPa

Concrete mix design

The concrete mixes were designed through the ACI 211.1-91 [19], including three mixes containing PVA fiber added while having a control mix for comparison purposes. Three of the six mixes include PVA fibers at different volume percentiles ranging from 1 to 3%. Table 3 presents the concrete mix design for a one-meter cube, targeting the strength of grade C32 and the water-to-cement ratio of 0.43. The specimens were prepared for cubes of dimensions 150 mm and prisms dimensioned 100 x 100 x 500 mm. The four mixtures include one control mix, and three PVA mixes at different percentiles; 1, 2, and 3%. As shown in Table 3, the control mix was donated by "OC," while those with PVA were denoted by "PVAC". While the "1" indicates the percentile of PVA fiber added. For instance, "1" means 1 percent of PVA volume fraction was added, while "`2" and "3" stands for 2 and 3 percent of PVA volume fraction [20].

Table 3. Details of concrete mix design

ID	Water, liter /m^3	Cement content, kg/m^3	Fly Ash, kg/m^3	Fine Aggregate, kg/m^3	Coarse Aggregate, kg/m^3	PVA Addition (%) by volume
OC	172	400	120	550	1165	---
PVAC1	172	400	120	550	1165	1%
PVAC2	172	400	120	550	1165	2%
PVAC3	172	400	120	550	1165	3%

Mixing Process and Sample Preparation

Zhou et al. [21] adopted certain procedures for the mixing process including adding the dry components; cement and fly ash together while mixing for 2 minutes in the electric concrete mixer. Two-thirds of the total appropriate solids volume was mixed with half of the water for 2 minutes and the sand was added incrementally over 1 minute. After the full sand addition was mixed for an additional 2 minutes. The PVA fibers were slowly added over 1 minute. All the mixing was conquered at a low speed (600 rpm). The mixture was left without mixing for 1 minute and then mixed for 2 minutes at high speed (4000 rpm) to distribute the fibers uniformly. The remaining mixing water was incrementally added over 1 minute at low speed and the mixing continued for 2 minutes to produce a homogenous mixture at high speed. The specimens of cubes and prisms were prepared after pouring the concrete mixes into the molds while being placed on the vibrating table to ensure concrete compaction. After leaving the molds for 24 hrs, the specimens were then de-molded and placed in curing tanks for 7 and 28 days until testing. Each mixture comprises 6 cube specimens and the cracking load was assigned to the control mix as reference. Similarly, 6 prism specimens were encountered for each mix at two different ages, 7 and 8 days. For assessing the gain and recovery of compressive, tensile, and flexural strengths, each mix has three undamaged and pre-damaged specimens that were exposed to the healing process. The pre-damaged specimens are those subjected to loading till cracking at about 60 to 80% of the specimen capacity. Then, the specimens were exposed to the healing process which was wet and dry curing cycles for 28 days of age to both ages; 7 and 28 days.

Test Methods

Several tests were conducted such as slump tests as per ASTM C143 / C143M [22]. The compressive strength test as per BS EN 12390-3 [23] is carried out to determine the loading capacity of hardened concrete. However, the compressive strength was tested into two levels; pre-cracking and then testing the specimens till failure after exposure to the healing process. The specimen was loaded to 60 - 85% of the peak load for specimens of induced cracking then the process of healing was applied. The pre-cracking specimens were then tested till failure 7 and 28 days [24]. The cracked and healed strength obtained after the curing periods and evaluated the concrete mixtures' inherent healing capabilities over time at curing durations, as shown in Fig. 2-a and b.

(a) (b)

Fig.2 Typical cube specimen (a) after pre-damaged by 60 to 85 % of the ultimate capacity after healing process exposure, and (b) testing the pre-damaged specimens till crushing failure.

Similarly, the same loading scheme was followed for prism and cylinder specimens to evaluate the flexural and splitting tensile strengths of the specimen as per ASTM C78/C78M [25] and ASTM C496 [26], whether pre-cracking or failure (after exposure to the healing scheme) [27, 28], as shown in Fig. 3-a,b, and c.

(a) (b) (c)

Fig. 3. Typical prism specimen at (a) pre-cracking by 60% of the ultimate capacity, (b) after healing process exposure as per the age assigned, and c) testing the healed specimens till failure

(a) (b)

Fig. 4. Typical cylinder specimen at (a) pre-cracking by 60% of the ultimate capacity, and (b) after healing process exposure as per the age assigned for testing till failure.

The curing regime in which both cube or prism specimens are cyclic wet and dry. The curing process involves submerging the specimens into the water tank and drying them in the air at room temperature, inside the laboratory. The process was repeated successively at 24-hour intervals, as suggested by Yang et al. [29]. The strength recovery was calculated as the percentage increase in peak load from the post-cracking to the post-healing state.

Experimental Results and Discussion

Slump

The slump was tested to determine the workability of the concrete after adding PVA fiber per the mix design. Fig. 5 represents the slump results for each mix. From Fig. 5, the results showed that the addition of PVA fiber would reduce workability to a high level. The mix OC (control mix) provided a 10 cm slump. For mix PVAC1, the slump was reduced more than that of mix OC by 95% when adding a VF of 1% PVA fiber while mixes PVAC2 and PVAC3 were reduced by 97 and 98% when the VF of the PVA fiber added by 2 and 3%. The slump for mix PVAC1 was 1 cm while for Mix PVAC2 and 3 were 0.5 cm and 0.

From the results, the slump is influenced by the addition of PVA fiber although the replacement of fly ash with cement should enhance the workability. However, fly ash did not counteract the negative impact caused by the PVA fiber interactions between additives that dilute cement paste continuity. The spherical surface of fly ash would be the reason for improving the workability or reducing water which was already considered while designing. Topiča et al. [30] suggested that this was due to the viscosity accompanied by the PVA fibers which cause mixing and pouring problems. Hence, increasing the PVA content would increase this viscosity and reduce the slump.

Similar findings were deduced by Zhang et al. [31] who attributed this behavior to the creation of a network structure by the PVA fibers within the cementitious composite. This action restrained segregation and workability from being possessed. Further, they assumed that some cement particles might be absorbed onto the fiber surfaces and wrapped the fibers around. This behavior would reduce the effective paste to contribute to the mixture's workability. Hence, the findings confirm the need to use superplasticizers when using PVA fiber after exploring the influence of the superplasticizer on the performance of PVA fiber in the healing process of concrete [32].

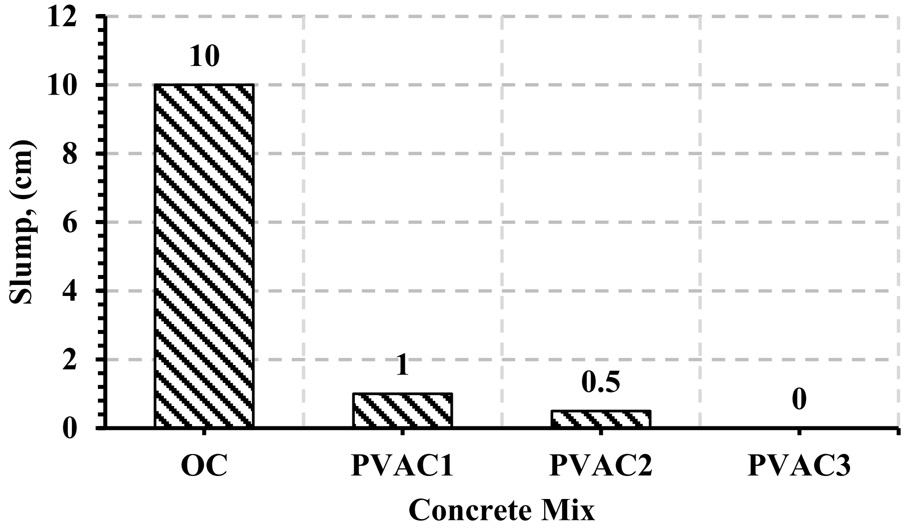


Fig. 5. Slump results for all mixes before hardening state properties.

Compressive strength

Fig, 6 shows the strength gained through the ages 7 and 28 days after initiating cracking through pre-cracking specimens and the recovery gained after applying the healing process of a wet and dry cycle for each mix. The healing process of cycles wet and dry was applied for 28 days only.

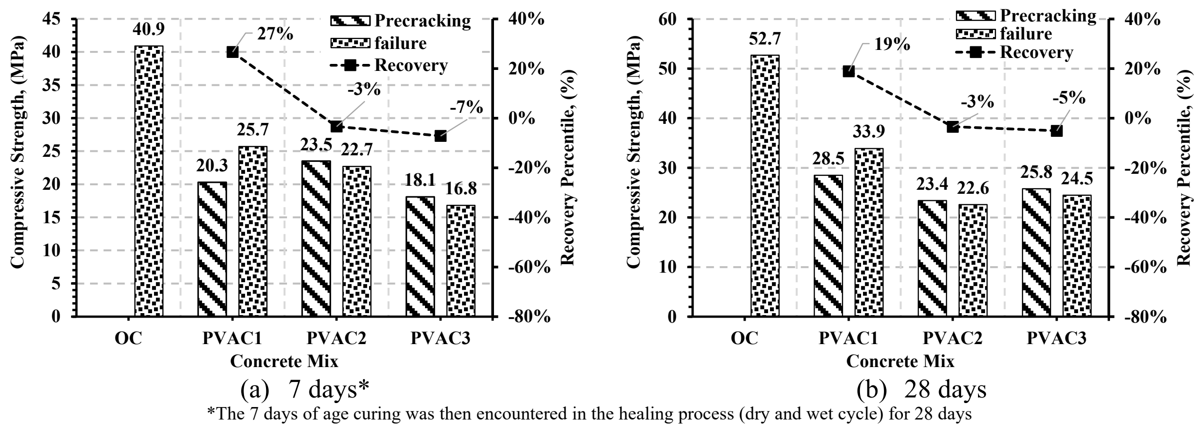


Fig. 6. Compressive strength results for the cube specimens for all mixes after hardening with (pre-damaged) and without (undamaged) applying the healing process at (a) 7 and (b) 28 days of age.

Zhang et al. [31] stated that the concrete itself cannot heal on its own as the hydration reaction of cement particles and the crystallinity of additives is unable to close cracks of this size. The evidence was deduced when leaving the initiated cracked cube specimen after 28 days of curing at room temperature. Self-healing granules, on the other hand, provided closure for the crack as stated by Zhang et al.[31] where their results revealed that at 7 days of curing 0.963 mm would be repaired in just 7 days. However, it should be mentioned that the faster healing process is dependent on the types of healing material used whether it is bacteria or chemical additives. From Fig.6, the compressive strength of cube specimens for added PVA fiber at 1, 2, and 3% and the recovery at 7 days were 27, -3, and -7%, respectively for mix PVAC1, PVAC2, and PVAC3. Thus, the PVAC1 provided the highest compressive strength recovery which is attributed to the low compressive strength of the pre-cracking cube specimens. Also, it should be mentioned that the OC mix might have provided a greater grade at failure stress than other mixes with an addition at 7 days of age.

At 28 days, the recovery revealed a similar trend to that of 7 days. The mix PVAC1, 2, and 3 provided a recovery of 19, -3, and -5%, respectively. In general, lowering the PVA fiber would reduce the porosity and therefore would increase the compressive strength. Thus, increasing the PVA fibers would, in turn, reduce the compressive strength of the concrete mixture regardless of the bridging provided by the PVA fibers and the precipitation of high calcium carbonate that would enhance the concrete performance and fill the voids as explained by Feng et al. [32] and Qiu et al. [33].

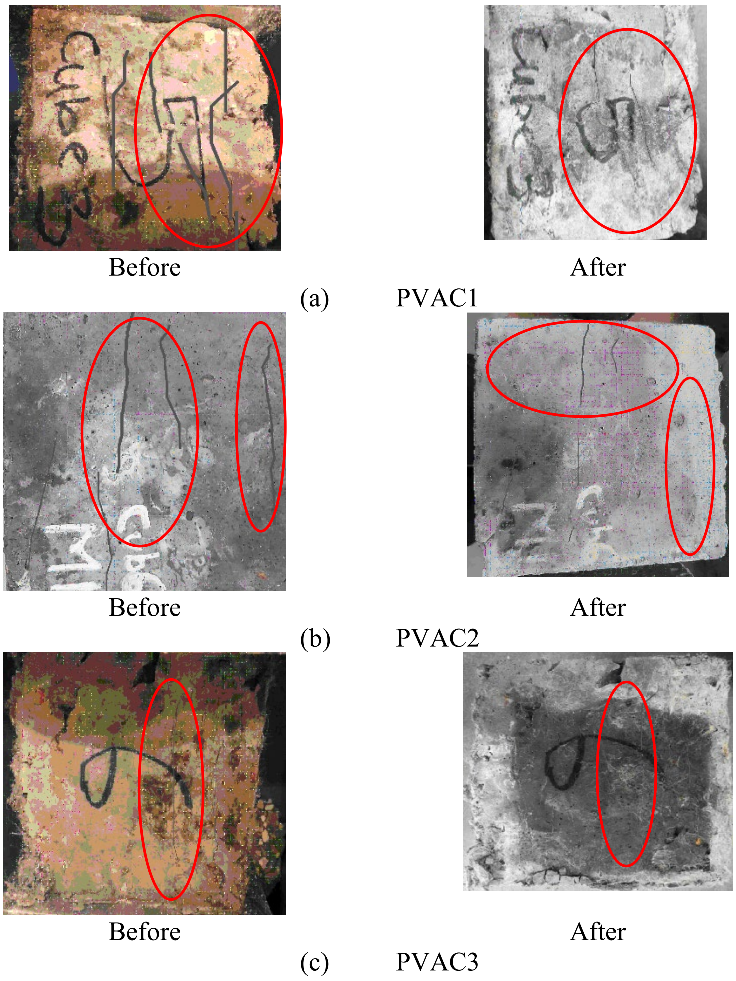
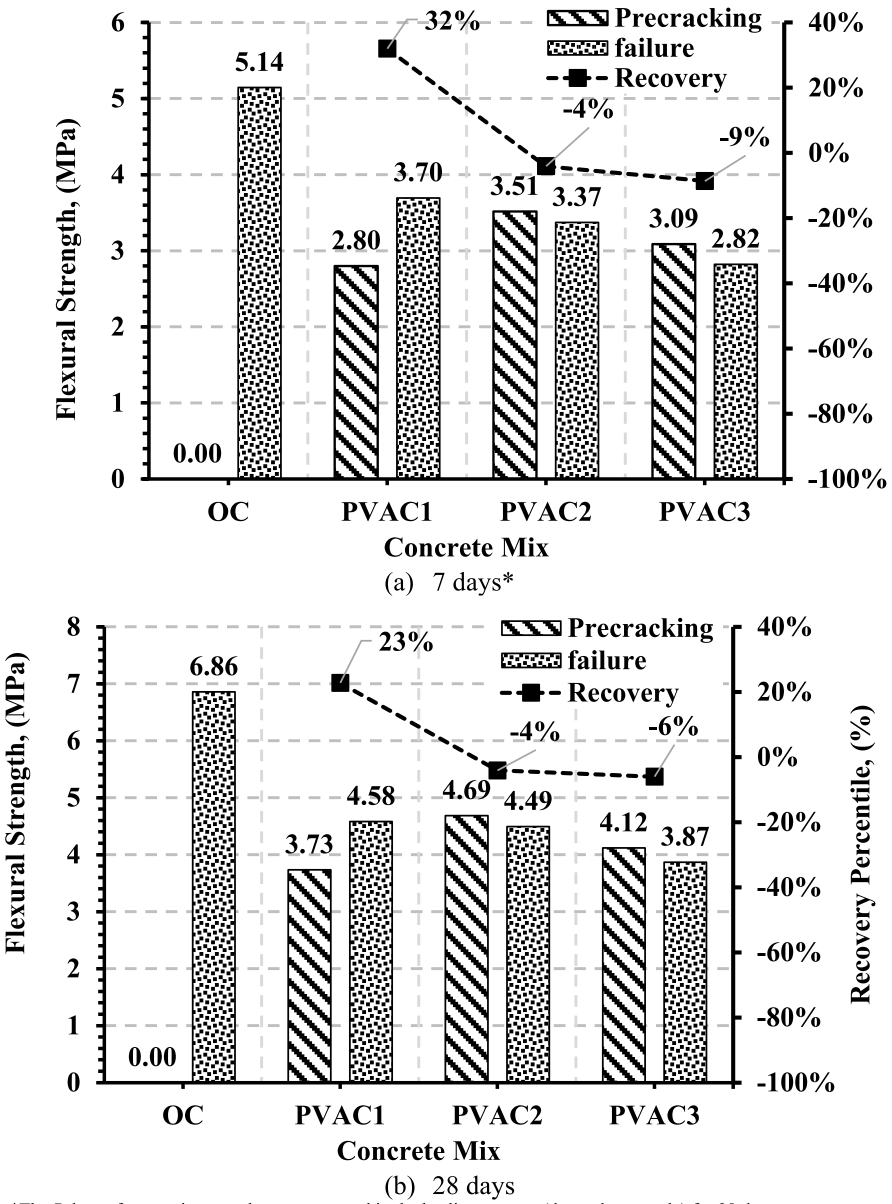


Fig. 7. Crack closure of cube specimens at initiating cracks and after applying the healing process at 28 days of age for mix (a) PVAC1, (b) PVAC2, and (c) PVAC3

Usually, the crack closure evaluates the influence of the healing process. Fig. 7 shows the initiated crack specimens before and after encountering the healing process. Based on Fig.7, the crack closure results revealed also unique trends. Mix PVAC3 showed the maximum crack closure and the disappearance of crack propagation onto the surface of the cube specimens as shown in Fig. 7- c. Similarly, the mixes PVAC1 and PVAC2 showed the healing of some cracks but in lower number and width than that of the other mixes. Cracks with a maximum width of 0.3 mm are not visible for all the specimens.

Flexural strength

Flexural strength is more crucial as most structure elements are subjected to cracking generated directly or indirectly by tension loads. Fig. 9 shows the results of the pre-cracking and failure prism specimens for flexural at 7 and 28 days of age. Compared with the control mix, it is clear from Fig. 8-a and b, that the pre-cracking specimens attain a value of 54, 68, and 59% for mixes PVAC1, PVAC2, and PVAC3 of the control mix at 7 and 28 days of age.

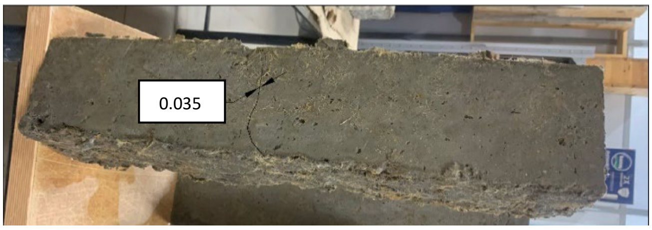


*The 7 days of age curing was then encountered in the healing process (dry and wet cycle) for 28 days

Fig. 8. Flexural strength results for the prism specimens for all mixes after hardening with (pre-cracking) and applying the healing process till failure at (a) 7 and (b) 28 days of age.

Feng et al. [32] explored the repaired area in prism specimens for those with PVA fibers through a prism specimen tested in bending to create mid-crack. The exploration revealed that the control specimens retained 31% on average of their crack repaired after 7 and 28 days of age which was attributed to the continuous hydration of cement paste carried out in the crack inner surfaces and carbonization reaction. However, the prism specimens with PVA fibers achieved about 44 to 50 % at 7 and 28 days of age indicating the improvement of the healing process using the PVA fibers.

Before



After

Fig. 9. Crack closure of prism specimens at initiating cracks and after applying the healing process at 28 days of age for mix PVAC1

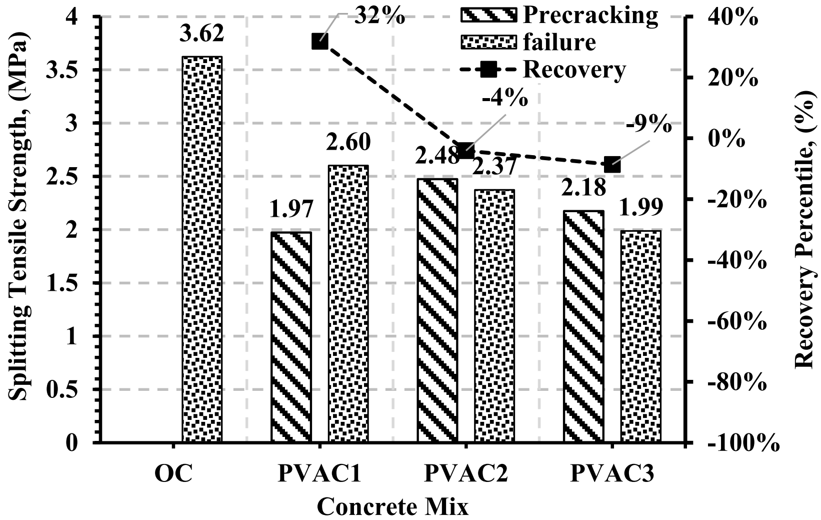
From Fig.8, the flexural strength of prism specimens, in the current research, for mix-added PVA fiber at 1, 2, and 3% of the recovery were 32, -4, -9, 23, -4, and -6%, respectively for mix PVAC1, PVAC2, and PVAC3 at 7 and 28 days of age. It should be mentioned that the OC mix might have provided a greater grade at failure stress than other mixes with PVA addition at 7 and 28 days of age. This behavior can denote that the PVA fiber along with fly ash provides the ability to heal although lower compressive strength may be attained as a result of ball formation and random distribution within the concrete mixture. This randomization creates voids that weaken the bonding behavior between the concrete matrix and PVA fiber (interfacial transition zone, ITZ)

The crack width was measured as shown in Fig. 10. The crack width closure reached nearly 86% of that of the original crack width. Similar findings were found in the literature [33 - 35] that the PVA fibers provided the most reliable healing and recovery enhancement among the other fibers (i.e., PP fiber, etc.). Due to the difficulty in measuring and getting more photos for the flexural prism specimens before and after the healing process, only mix PVAC1 is presented, as shown in Fig.9. The figure shows the closure of the crack of 0.25 mm after 28 days of curing exposed to wet and dry cycle have reached to 0.035 which means that nearly 86% of the crack width was closed and filled with PVA that possessed more calcites as illustrated by Zhang et al. [31].

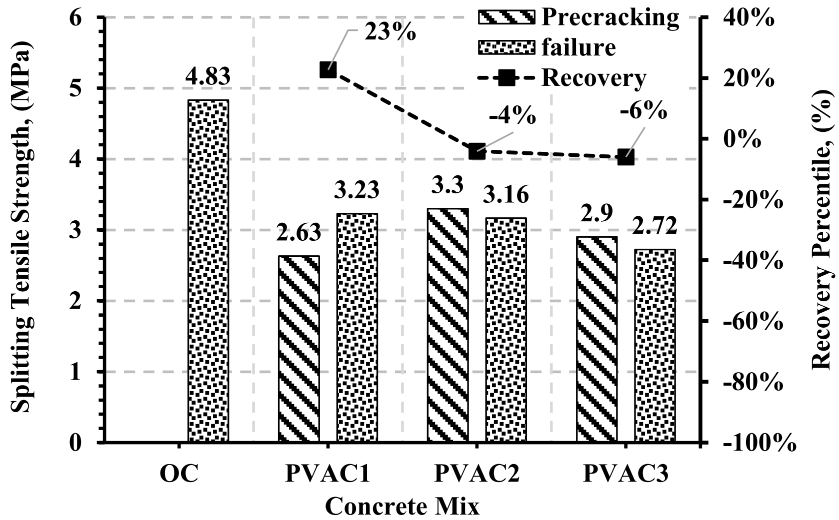
Tensile strength

Similarly, the tensile strength was measured for a critical structural member that requires control such as tanks. Fig. 10 shows the results of the pre-cracking and failure cylinder specimens for tensile at 7 and 28 days of age. Compared with the control mix, it is clear from Fig. 10-a and b, that the pre-cracking specimens attain a value similar to those of flexural strength for mixes PVAC1, PVAC2, and PVAC3 of that of the control mix at 7 and 28 days of age. The tensile strength reached similar to those of flexural strength but at lower values; for instance, the control mix revealed 5.14 and 6.86 MPa for flexural strength while for tensile strength was 3.62 and 4.84 MPa at 7 and 28 days of age. From Fig.10, the flexural strength of prism specimens for those mixes with added PVA fiber at 1, 2, and 3% the recovery at 7 and 28 days were 32, -4, -9, 23, -4, and -6%, respectively for mix PVAC1, PVAC2, and PVAC3.

Consequently, the OC mix might have provided a greater grade at failure stress than other mixes with PVA addition at 7 days of age. Due to the difficulty in measuring the cracks in the cylinder specimens before and after the healing process, just photos of the healing process and the crack's appearance were encountered, as shown in Fig.11. The figure shows the closure of the crack after 28 days of curing exposed to wet and dry cycle. The results seem to be compiled with those reported by Zhang et al. [36].



(a) 7 days*



(b) 28 days

*The 7 days of age curing was then encountered in the healing process (dry and wet cycle) for 28 days

Fig. 10. Splitting tensile strength results for the prism specimens for all mixes after hardening with (pre-cracking) and applying the healing process till failure at (a) 7 and (b) 28 days of age.

Before After

Fig. 11. Crack closure of cylinder specimens at initiating cracks and after applying the healing process at 28 days of age for mix PVAC1

Conclusion and key findings

Based on the results of the current investigation, the following conclusions can be drawn:

[1] In terms of fresh state properties, the addition of PVA fibers reduced the workability, and it was recommended to use the superplasticizer to compensate for the water required.

[2] The mechanical properties of the compressive, flexural, and splitting tensile strength revealed a similar trend. The best performance was revealed with a PVA addition of 1%.

[3] The PVA fiber addition self-healing mechanism facilitates pore closure in the concrete matrix by precipitating calcite crystals that grow and spread from nucleation sites on the bacterial cell walls.

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