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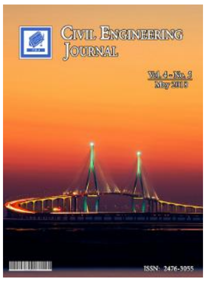

Self-Healing Ability of High-Strength Fibre-Reinforced Concrete with Fly Ash and Crystalline Admixture

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Abstract

The aim of this study is to analyse the self-healing capability of high-strength fibre-reinforced concrete (M70) with fly ash and crystalline admixture (CA) in four types of environmental exposures i.e. Water Immersion (WI), Wet-Dry Cycles (WD), Water contact (WC) and Air Exposure (AE). Specimens for four mixes are cast, one mix containing 1.1% of CA and three mixes with 10%, 20% and 30% partial replacement of cement with fly ash and additions of 1.1% CA. The specimens were pre-cracked at 28 days, in the range of 0.10-0.40 mm and the time set for healing was 42 days. The result shows that all the mixes have considerable amount of closing ability and strength-regaining capability for all exposure conditions. The concrete with 20% fly ash and 1.1% CA has complete crack closing ability and 100% strength-regaining capability for WI and WD cycle conditions. From SEM analysis, it is confirmed that self-healing products are CaCO3 and C-S-H gel.

Keywords: Self-Healing; Fly Ash; Crystalline Admixture; SEM; FTIR.

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1. Introduction

In recent years, with the development of economy and growth of urban population, more and more buildings have been constructed and this has led to the vast concentration of people and goods. Currently, construction material such as concrete is highly used because it has high compressive strength, notable fire resistance, better casting and lower expense than other construction materials. However, a major problem with the concrete is that it is vulnerable to cracking due to its relatively low tensile strength [1-2]. The cracks will reduce the capabilities of anti-permeability, anti-chloride-corrosion and anti-carbonisation greatly, which can make the corrosion of interior reinforcements much easier and can lower the carrying capacity and durability of the structure. If the repair of concrete cracks is not completed in time, it will affect the normal use of concrete structure, resulting in total destruction and even collapse.

High-strength concrete with self-healing system based on the combined action of fly ash and CA has been developed in order to seal developing cracks, which improves durability of concrete. Self-healing admixtures are those which have the capability of repairing small damages or cracks. The main reason for investigating the properties of self-healing admixtures is that constructions built with them will have increased service-life; likewise, structures with difficult or expensive repairs will benefit from self-healing their own damages. Thus, self-healing concrete will lead to an increase in the sustainability of the structures. In concrete, microcracks cannot be avoided completely and responsible for their failure in strength. This is even more important when it comes to infrastructure, as this type of construction requires high level of user performance, high durability and minimum ecological impact possible. Many works for the public

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services built in the second half of the last century are rapidly reaching high levels of degradation, reducing its function due to the deterioration of materials. Moreover, the continuous increase in population has caused an increase in demand for infrastructure capable of ensuring a high level of performance in service.

When a material degrades due to some damage, a special agent present within the material recovering the damage is called self-healing repair [2]. Self-healing is different from self-sealing in which the property which is recovered may vary [1-2]. From the natural process, bones and trees are the best examples that recover and repair their own strength [3]. Structure and shape of the material changes during self-healing which leads to the improvement of service life at low cost and also avoidance of complicated repair for the entire life [4]. To repair the crack, the research on self-healing is based on duration, mechanical strength and recovery property which depend on the structure. In some cases, both durability and mechanical based recovery are required; for example, water tightness is a property which is required for the structural stability and it prevents harmful substances that accelerate or activate corrosion, thus leading to load-bearing loss. Even though the self-healing concrete is popular in recent years, it was also known in earlier days. Neville [5] discussed the autogenous healing, and Fernández Cánovas [6] mentioned it as “cicatrization”. Moreover, it is observed that concrete composition such as historical lime and lime-pozzolana mortars are featured to improve self-healing capabilities. Such process has advantages for tighter cracks [7-9], as the process is fastened and healed in smaller volume. Many self-healing approaches, including autogenous, adhesive-based, mineral admixtures-based, and bacteria-based methods, have been developed [7]. There are two mechanisms for self- healing in concrete such as autonomous healing and autogenous healing [10-12]. Autogenous healing is a natural process which heals small cracks depending upon the composition of the concrete. Calcium carbonate and unhydrated cement are the additional ingredients, including other processes that help with self-healing [13]. Autonomous healing is another healing process based on engineering that improves the self-healing properties. Moreover, engineered healing is further classified as ‘active’ and ‘passive’ modes [11, 12, 14]. To activate the active mode, human help is required, but for ‘passive’ mode, no such help is required. In most of the cases, healing effects of autogenous healing are unreliable. Hence, engineered healing concepts are focussed in the recent years by incorporating self-healing agents, such as microencapsulated healing agents [15-17], bacterial concrete [18-19] and CAs [20-23]. The main objective of this project is to determine the self-healing ability of high-strength concrete (M70) with fly ash and CA in different exposure conditions.

2. Materials and Methods

The materials used for this research were cement, coarse aggregate, fine aggregate, water, fly ash, CA, super plasticizer and steel fibres.

The type of cement used was OPC 53 grade. Aggregates of size (12-10mm) were selected as coarse aggregate, and river sand was used as fine aggregate. The coarse aggregate and fine aggregate are well-graded aggregates (Figure1 and 2). For making the crack controllable while avoiding excessive branching of cracks, the quantity of steel fibre was fixed at 40 kg/m^3. In the concrete with CA, the CA added was 1.1% weight of the binder. Further, three mixes with partial replacement of cement with fly ash 10%, 20% and 30% and additions of 1.1% CA by weight of binder were cast and designated has FA$_{10}$CA, FA$_{20}$CA and FA$_{30}$CA respectively. The mix proportions are shown in Table 1.

Table 1. Mix design of self-healing concrete mixtures by weight

Mixes	Fly ash (%)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Fly ash (kg/m^3)	Water (lit/m^3)	Super plasticizer (lit/m^3)	Crystalline admixture (kg/m^3)	Steel fibers (kg/m^3)
RC	0	494	700	1136	0	148	4.94	0	9.88
CA	0	494	700	1136	0	148	4.94	5.434	9.88
FA$_{10}$CA	10	444.6	700	1136	49.4	148	4.94	5.434	9.88
FA$_{20}$CA	20	396	700	1136	98	148	4.94	5.434	9.88
FA$_{30}$CA	30	346	700	1136	148.2	148	4.94	5.434	9.88

The self-healing performance of the concrete cubes was evaluated by performing regained compressive strength. The crack was initiated in concrete cubes after curing in water for 28 days by applying compressive loads using compressive testing machine (CTM) as show in Figure 3. Then, the cracked specimens were cured for four different curing conditions (Table2) for 28 days and 42 days. Four different environmental conditions were considered in order to determine the influence of water availability on the self-healing capability of tested specimens. Then, the cured specimen was tested for compressive strength and results were presented in Figure 4.

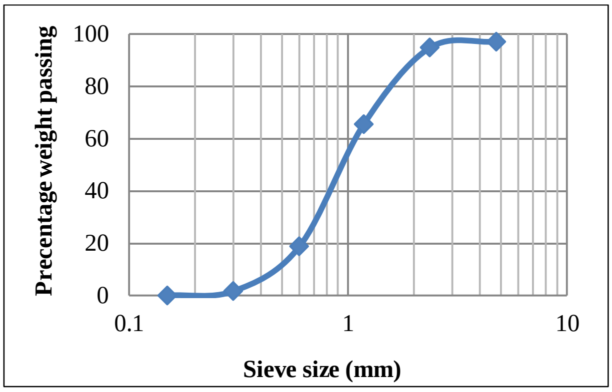


Figure 1. Grain size distributions of Fine Aggregate

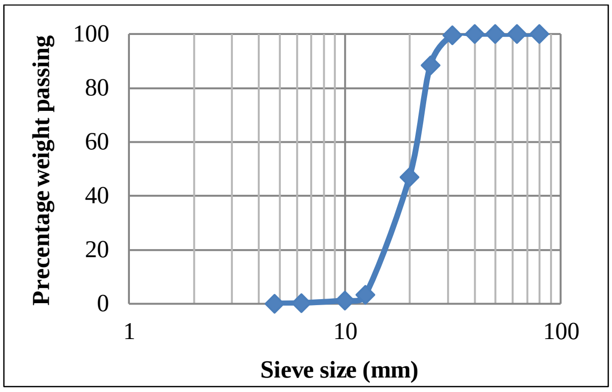


Figure 2. Grain size distributions Coarse Aggregate

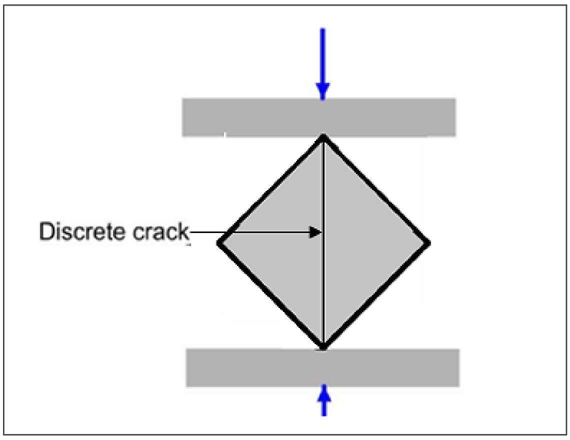


Figure 3. Test setup for crack initiation

Table 2. Types of Exposure simulation

Exposures	**Conditions**
Water Immersion (WI)	Continuous immersion in tap water.
Wet-Dry Cycles (WD)	3 days water immersion and 3 days air exposure.
Water Contact (WC)	Immersion in 2 cm of water layer.
Air Exposure (AE)	Open exposure to air

2.1 Evaluation of the regained strength properties

Since the self-healing properties are projected to increase, a corresponding increase in the value of stiffness and cracking loads are expected from the stage of initial loading to reloading. Recovery of comperssive strength (R) was employed to calculate the improvement in self-healing strength using Equation (1) given below.

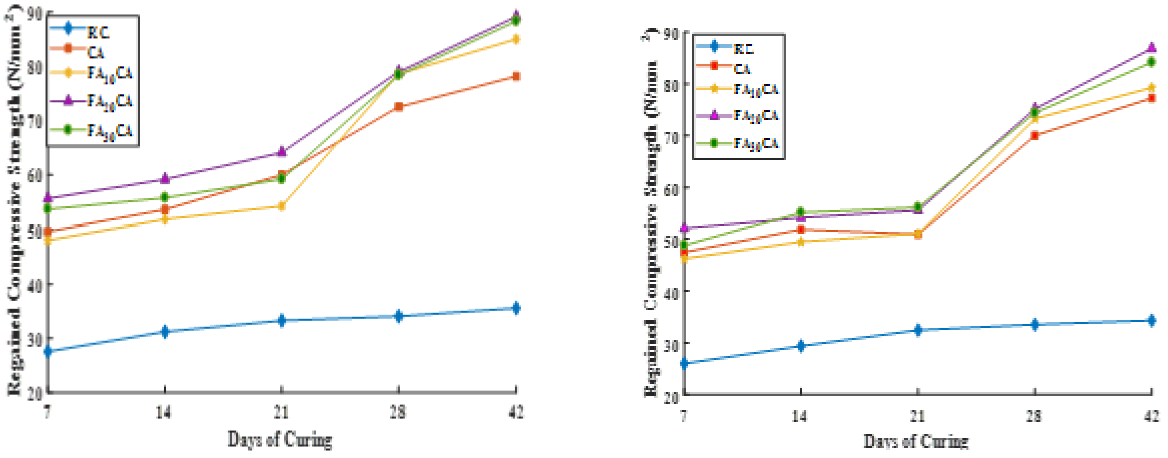
$$R=\frac{\text{Regained Compressive strength after healing}}{\text{original compressive strength}}\times 100 \tag{1}$$

3. Results and Discussion

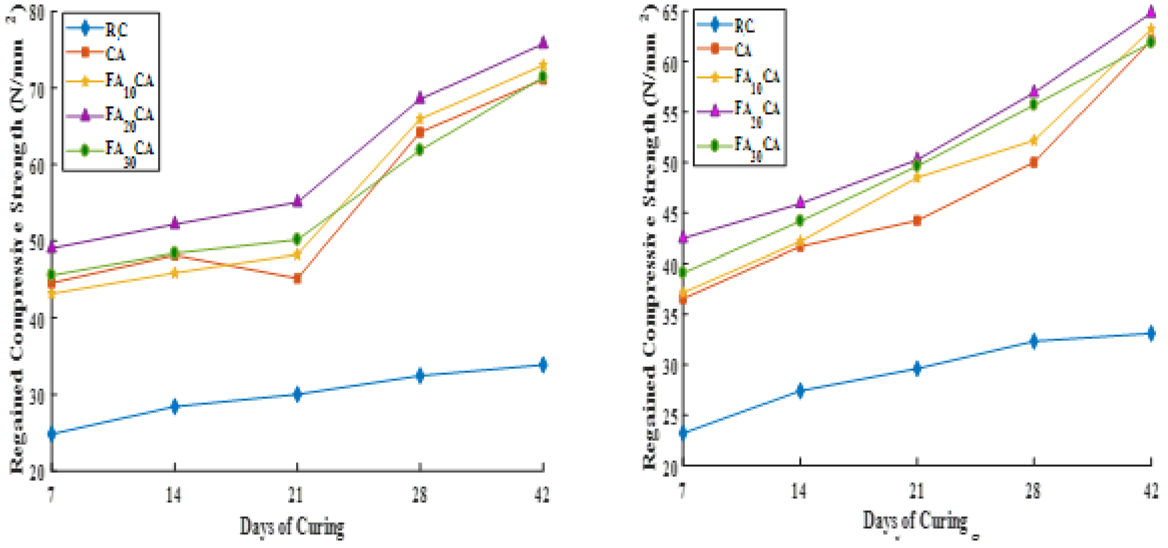
3.1. Recovery of Compressive Strength

Self-healing efficiency is to evaluate whether the material was able to recover some of its strength after acquiring some minor damages. Concrete with CA increasing the self-healing efficiency at all ages i.e. 7, 14, 21, 28 and 42 days for all the specimens were shown in Figure 4 and 5. It can be clearly observed that catalytic reaction between calcium ions and byproducts of cement hydration and unhydrated cement particles forming the C–S–H and $CaCO_3$ content. CAs acted as a bridge between cracks thus actuating considerable mechanical strength recovery. Self-healing was evident, as the healing materials proliferation in the sample exposed to the WI and WD curing conditions was much higher compared to the samples exposed to WC and AE curing conditions. Crack healing efficiency i.e. crack opening area reduction over time was found to increase from 28 to 42 days.

Self-healing efficiency of sample with CA is 91%-102% for WI, 87%-101% for WD, 79%-84% for WC and 69%-74% for AE from 28 days curing to 42 days curing. The self-healing capability of samples with WI and WD are better than that of WC and AE. Even though the self-healing efficiency of the sample with WC conditions is less than that of WI and WD conditions, it is still higher than that of RC specimens. Self-healing efficiency samples with CA and 20% fly ash are 94%-104% for WI, 92%-101% for WD, 82%-88% for WC and 72%-75% for AE from 28 days curing to 42 days curing. The self-healing capability of samples with WI and WD are better than that of WC and AE. Even though self-healing efficiency of the sample with WC conditions is less than that of WI and WD conditions, it is still higher than that of CA specimens. This was due to the participation of unhydrated minerals present in the crack surface in the re-hydration process for the self-healing, which improves filling of voids by $CaCO_3$ and C–S–H content in the concrete cracked specimen. CA in concrete is also able to absorb moisture from the atmosphere, thus resulting in considerable amount of self-healing i.e., 70% in AE conditions. Out of the four exposure conditions, self-healing in WI and WD conditions are efficient. Similarly, response from early researchers [20-23] has showed the importance of water in the development of healing materials regardless of the minerals used for samples. For each test series under water curing condition, one representative crack location was chosen and the change in surface crack width was represented in Figure 6. It can be observed that the crack sealing at 42 day curing was better than that of 28 day curing. It can also be observed that formation of $CaCO_3$ is the main reason for crack sealing. It is also possible that more on-going hydration might have occurred inside the cracks of mixes in which more unhydrated binder material was available.



(a) Water Immersion **(b) Wet-Dry Cycles**



(c) Water Contact **(d) Air Exposure**

Figure 4. Variation of Regained Compressive strength with respective to days of curing for four different curing conditions

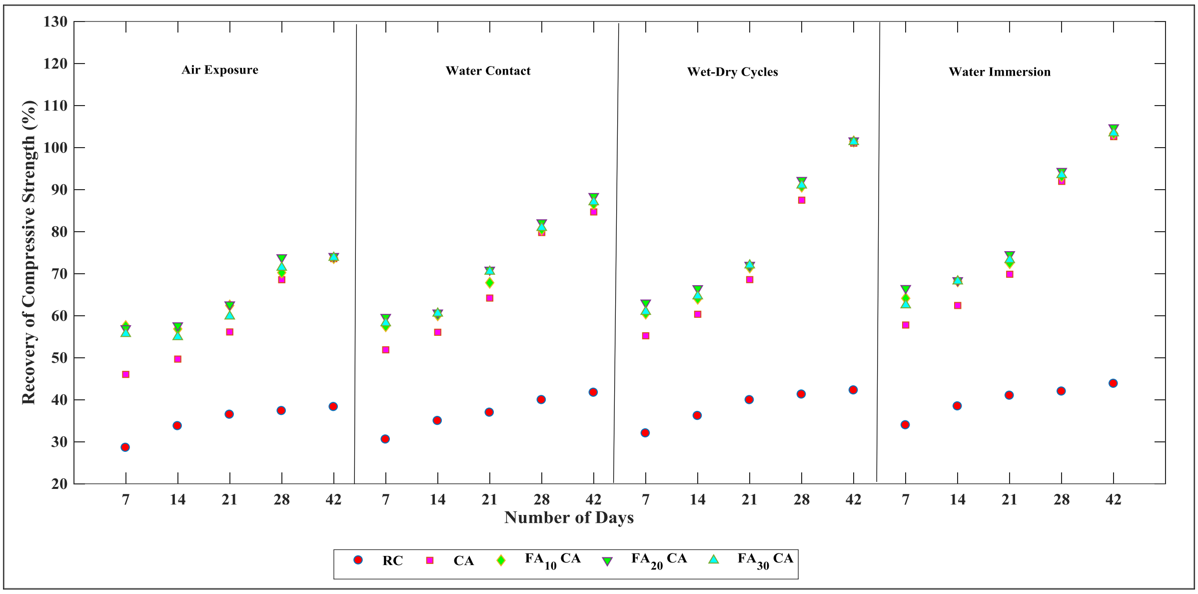


Figure 5. Percentage recovery of compressive strength with respective to days of curing for four different curing conditions

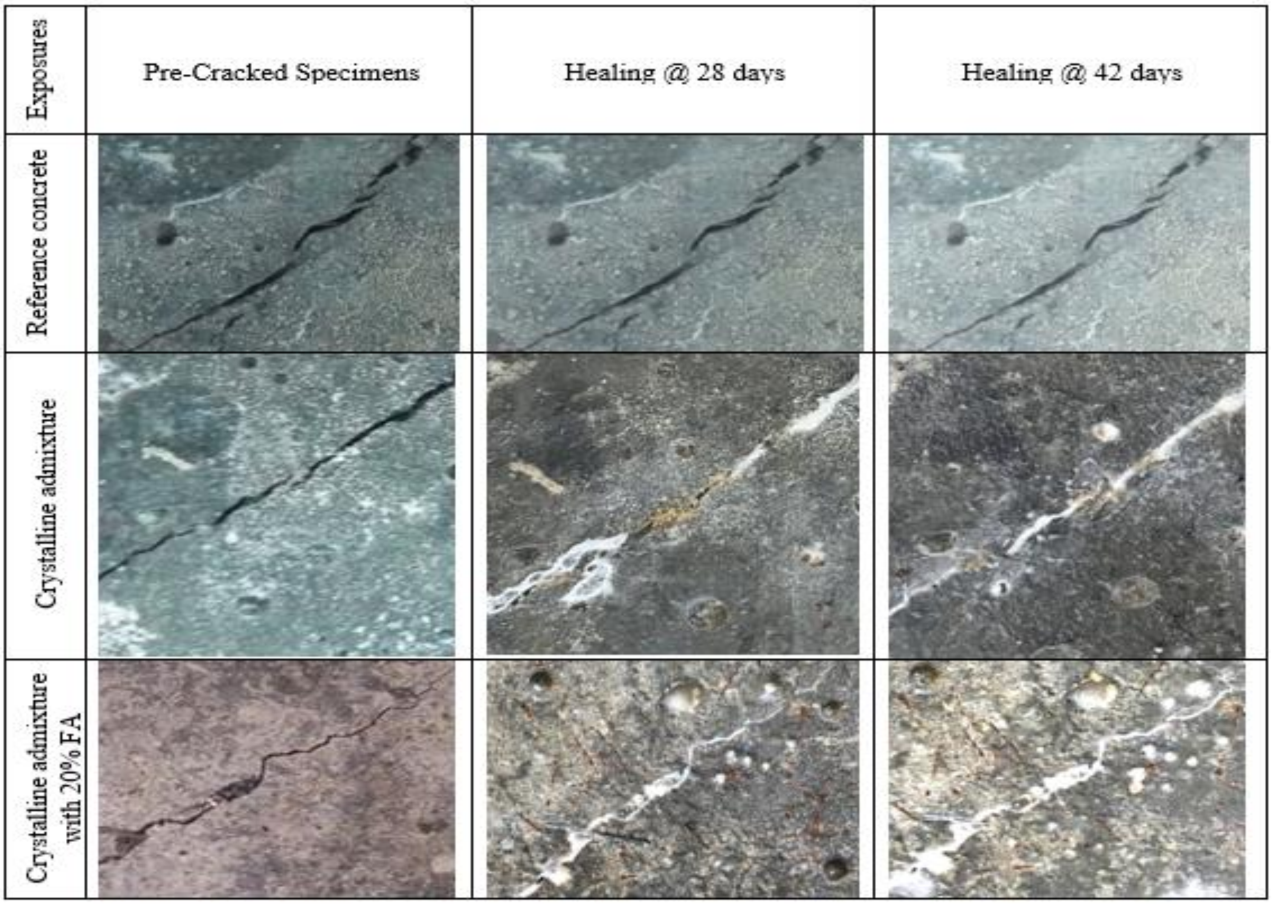
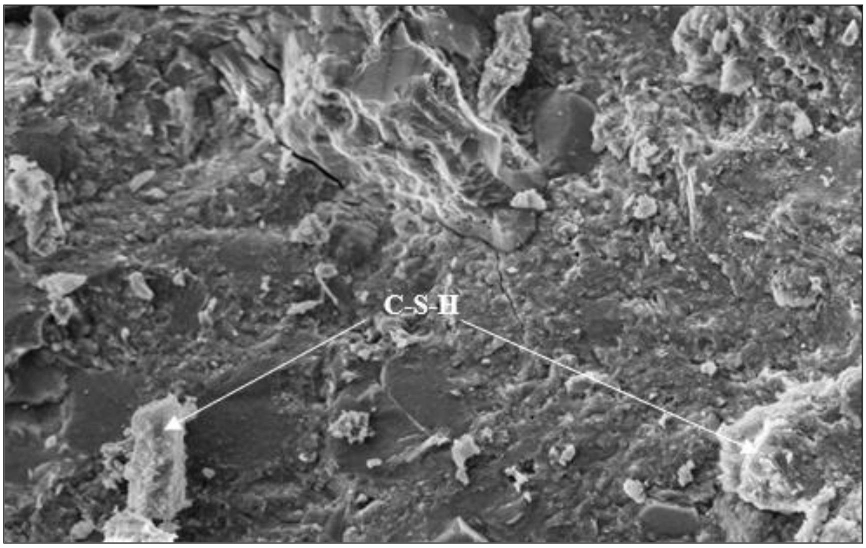


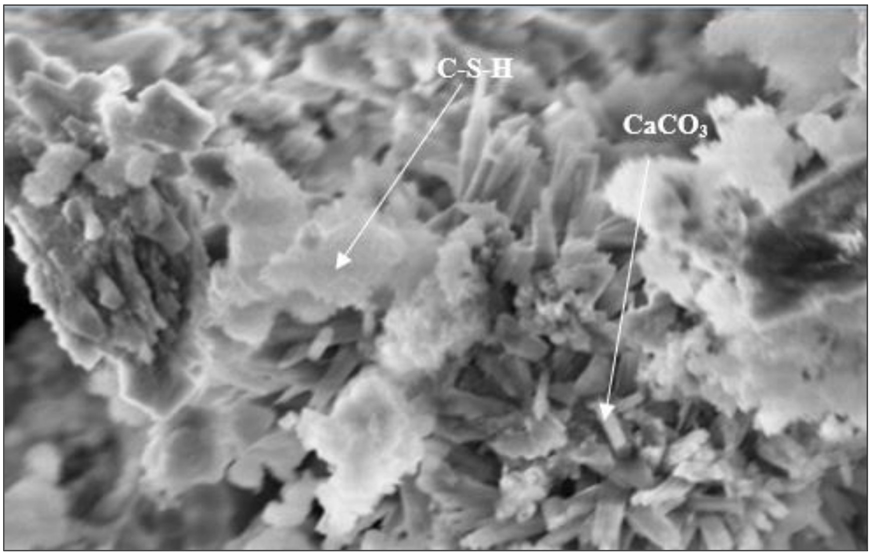
Figure 6. Crack sealing patterns under the water curing condition

3.2. Microstructural Analysis

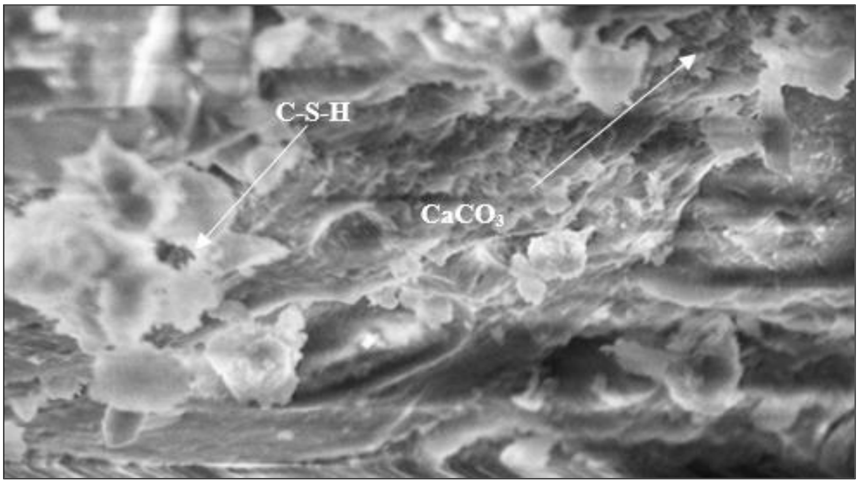
The self-healing material microstructure characterisation based on SEM analysis is presented in this section. It has been observed that concrete with CA shows better performance and hydration products are denser than that of reference concrete. Microstructural investigation of CA concrete specimen shows that C-S-H gel and $CaCO_3$ are self-healing products. The SEM micrographs shown in Figure 7 indicates a reduction in calcium hydroxide crystals ($Ca(OH)_2$) with a corresponding increase in the formation of amorphous C-S-H gels and $CaCO_3$ in concrete with CA. This gives rise to more strength and durability for the concrete.



(a) Reference concrete



(b) Concrete with crystalline admixture



(c) Concrete with crystalline admixture and 20% fly ash

Figure 7. Microstructural morphology of the self-healing concrete under SEM investigation

3.3. FTIR Analysis

FTIR analysis has been done for attaining further particulars regarding the components of reaction products after self-healing. FTIR transmission spectra of RC, CA, FA_{20} CA are presented in Figure 8.

A small broad band at 1600 cm^{-1} was because of vibrations by the bending-in-plane of –OH group of low concentration that is free of water molecules. Furthermore, the FTIR spectrum revealed two discrete peaks at 1320 cm^{-1} and 820 cm^{-1}, equivalent to the stretching and bending-in-plane ambiences of the carbon–oxygen bonds of CH and calcium carbonate ($CaCO_3$), subsequent to the reaction between calcium hydroxide ($Ca(OH)_2$) and carbon dioxide in the air. The intensity of the 1320 cm^{-1} band is anticipated to be closely associated with the ratio and depth of carbonation. The broad band detected at 3711 cm^{-1} in the infrared spectroscopy of OPC linked to overlap stretching vibrations of both the structural and free hydroxy groups of CH and water respectively. FTIR spectra of RC, CA, FA_{20}CA which have been defined as fingerprint evidence for the degree of polymerization with the formation of calcium-silicate-hydroxide phase due to hydration [24] having strong band observed at 900 cm^{-1} and the band observed at 520 cm^{-1} were associated with the bending-in-plane vibrations of the Si–O bonds in C_3S (tricalcium silicates) and C_2S (dicalcium silicates) [25-28]. The intensity of these bending–in–plane vibrations of the Si–O bonds decreased as calcium-silicate-hydroxide crystals formed [24,29]. Therefore, it is evident that the intensity of calcium-silicate-hydroxide gel and $CaCO_3$ crystals are much higher in FA_{20}CA and CA while comparing with RC in that order. Below-mentioned reactions may be the cause for self-healing mechanisms:

The atmospheric gas CO_2 liquefies very easily in H_2O.In the dissolution process, CO_2 reacts with the water molecules in forming H_2CO_3 (carbonic acid).

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2\,H^+ + CO_3^{2-}$$

The free calcium hydroxide within set concrete can further dissociate into Ca^{2+} and hydroxide (OH^-) ions.

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$$

Calcium (Ca^{2+}) reacts with bicarbonates and carbonate forms water insoluble pre-blocking precipitated crystals as calcium carbonate ($CaCO_3$).

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

$$Ca^{2+} + HCO_3^- \rightarrow CaCO_3 + H^+$$

The mechanism of healing in concrete with CA is the expansion by volume of the products, i.e., $CaCO_3$ and C-S-H in hydration. The enhancement in the durability is because of rehydration product's densification that is accomplished by triggering more self-healing material formation.

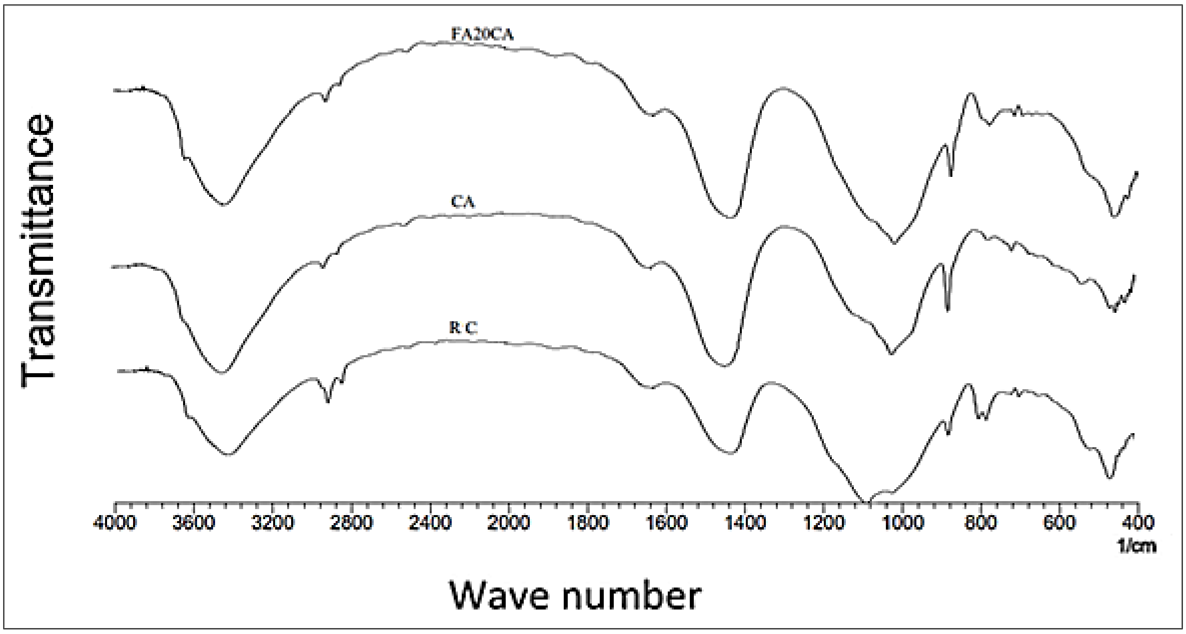


Figure 8. FTIR analysis

4. Conclusion

In this paper, a study on the self-healing ability of high-strength fibre reinforced concrete with fly ash and CA cracked specimens has been presented. The analysis is focussed on the recovery of regained strength of the cracked specimens by quantifying the self-healing effectiveness of CA and comparing the result of concrete specimens with and without fly ash under four different environmental exposures and the following conclusion are drawn.

- Concrete with CA immersed in water achieved 102% of self-healing efficiency and concrete with 20% fly ash and CAs in the WI exposure has achieved highest self-healing efficiency i.e. 104% at 42 days of curing.
- Concrete with CA in AE is also able to absorb moisture content from atmosphere, thus resulting in considerable amount self-healing i.e. 70%.
- From the SEM analysis, it is confirmed that C-S-H gel and $CaCO_3$ are the self-healing products.
- FTIR transmission spectra results showed the significant bond formation and mechanism of the self-healing property of the concrete with CA.
- From this work, it can be observed that the four exposures in order of decreasing healing rate are: WI > WD cycles > WC > AE.
- From this research work, it can be concluded that $FA_{20}CA$ under WI has an excellent self-healing ability.

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