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Monitoring Micro-crack Healing in an Engineered Cementitious Composite using the Environmental Scanning Electron Microscope

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Abstract

Environmental Scanning Electron Microscopy (ESEM) is used to study the origin of micro-crack healing in an Engineered Cementitious Composite (ECC). ESEM images were acquired from ECC specimens cut from pre-cracked, dog-bone samples which then subjected to submerged curing followed by exposure to the natural environment. The mineralogical and chemical compositions of the healing products were determined using the EDX facility in the ESEM. It is shown that the precipitation of calcium carbonate is the main contributor to micro-crack healing at the crack mouth. The healing products initially appeared in an angular rhombohedral morphology which then underwent a discernable transformation in size, shape and surface texture, from relatively flat and smooth to irregular and rough, resembling the texture of the original surface areas surrounding the micro-cracks. It is also shown that exposure to the natural environment, involving intermittent wetting/drying cycles, promotes additional crystal growth, which indicates enhanced self-healing capability in this environment.

Keywords: calcite; ECC; EDX; ESEM; micro-cracks; self-healing; wet/dry cycles.
1. Introduction

Cracking is one of the primary causes of deterioration in concrete structures. It can occur during the construction stage, when the concrete is still being cured, or at a later stage when the structure is in-service [1,2]. Early-age cracking generally occurs due to either restrained shrinkage [3–5] or poor construction practice such as inadequate curing [6,7]. Numerous factors can contribute to the development of cracks under service conditions, including poor design/detailing (e.g. inadequate cover thickness), differential settlement and unforeseen loading scenarios. With regards to the durability of reinforced concrete structures, it is cracking within the cover region that poses the most significant threat [8,9]. Surface cracking can negate the role of the concrete cover as the protective barrier to the steel reinforcement by creating direct paths for aggressive agents (e.g. chlorides) to enter the concrete and initiate corrosion of the steel reinforcement. Once initiated, corrosion of the steel can lead to further cracking or even spalling which can accelerate the deterioration processes. The problem originates from the brittle nature of concrete.

In an attempt to improve the long-term durability of concrete structures and, in particular, address the brittle nature of concrete, a novel cement-based material termed an Engineered Cementitious Composite (ECC) has been developed [10–12]. This cement-based material has been designed to exhibit high tensile strain capacity, typically in excess of 3%, whilst preserving the fundamental features of ordinary concrete such as high compressive strength [13]. The ECC's high tensile strain capacity originates from its ability to form a network of fine cracks when subjected to tension, which is in contrast to the behavior of ordinary concrete which is characterized by the formation of a few discrete cracks. Apart from its high tensile strain capacity, ECC also exhibits a controllable crack width, typically less than
0.1mm under service load, making it particularly suitable for applications where cracking and long-term durability are of primary importance [14,15].

With regard to the long-term durability of concrete, studies have shown that it may be possible to regain the loss in performance due to cracking through a process termed self-healing [16–18], with small crack widths being identified as a key factor in promoting the healing process [19–20]. The controllable crack width of ECC has proven desirable in encouraging self-healing with no reliance on any special admixtures and additives [21–26]. It has also been shown that crack healing in ECC is attributed primarily to further hydration of cement particles, thereby resulting not only in sealing effects but also a recovery in both strength and stiffness [22,25,27]. Healing products are often detected as white precipitates, suggesting the contribution of carbonation in addition to hydration. Sisomphon et al [28] demonstrated that the rate of crack healing in ECC is affected by the concentration of carbonate ions in the curing water, with a higher rate observed in samples subjected to cyclic wetting and drying with regularly refreshed water. Kan et al [21] were among the first to use the Environmental Scanning Electron Microscope (ESEM) to assess the process of healing on multiple cracks of different widths under wetting and drying cycles. They reported the formation of both fiber- and stone-like healing products which were considered to be, respectively, calcium silicate hydrate (C-S-H) and calcium carbonate (CaCO$_3$). Exposure to wet-dry cycles was found to be the most beneficial to the self-healing process.

Building upon these previous laboratory studies, the self-healing performance of ECC under exposure to the natural environment has been investigated [29], thereby providing a true picture of the self-healing capabilities of ECC. It was demonstrated that the UK’s mild and wet weather, which is characterized with intermittent rain, provides a suitable
environment for crack healing to occur. A large number of white precipitates were detected infilling the micro-cracks over the initial three weeks of exposure, with some cracks completely sealed in less than 6 days (see Fig. 1). It has also been shown that self-healing is achievable under controlled laboratory conditions, although the process appears to take longer [30].

This current paper presents an investigation into the origin of the crack healing. The ESEM was used to study three similar crack locations; by being able to observe the same cracks over a period of time, allowed a detailed picture of the evolving nature of crack-healing behavior. The Energy Dispersive X-ray (EDX) facility in the ESEM was also used to determine the mineralogical and chemical compositions of the healing products. The findings provide a new insight into the process of self-healing of micro-cracks in ECC which would, ultimately, assist to further engineer and optimize the healing process.

2. Experimental Program

To investigate the influence of environmental exposure on the progress of micro-crack healing, ESEM observations were undertaken on three ECC specimens over a period of four weeks subjected to the following exposure regime: submerged in water in a controlled laboratory environment (20±1°C) for 7 days; then a further 7 days with the water refreshed at the beginning of this exposure period and finally, natural (i.e. outdoor) exposure for another 14 days, with the specimens placed horizontally and the exposed surface facing upwards (and therefore directly exposed to rain). Fig. 2a presents the details of the test program over the four week period, whereas Fig. 2b shows the temperature and rainfall data during the final two week period when the samples were exposed outdoors. During this four week period, ESEM observations were undertaken at predetermined times as indicated on Fig. 2.
A total of eight dog-bone shaped samples with dimensions recommended by JSCE [31] (see Fig. 3(a)) were prepared: five were tested to failure to determine the tensile properties and the remainder were preloaded to 60% of the average tensile strain capacity, so that cracks could be observed in the ESEM. To prepare three specimens for ESEM imaging, the center region of each preloaded sample was wrapped with plastic tape and, from this portion of the sample, a specimen with dimensions of approximately 20×30×12 mm$^3$ was sawn. The tape was removed and the cut specimens were then conditioned before use to the regime detailed above. Specimens 1 and 2 were studied at Day 0, 1, 3, 7, 14, 21 and 28, with Day 0 representing the day at which they were preloaded, whereas Specimen 3 was studied from Day 7 onwards.

2.1. Materials

The ECC mix composition used within the experimental program is presented in Table 1. The binder comprised CEM I 52.5N cement to BS EN 197-1:2011 [32] blended with a fine fly-ash (Superpozz SV80 from ScotAsh) at a fly-ash-to-cement ratio of 1.8 (by mass), with a water-to-binder ratio kept constant at 0.28. Fine silica sand (RH110 from Minerals Marketing Ltd.) with an average particle size of 120µm was used at a constant sand-to-cement ratio of 0.6. The oxide composition of the FA and silica sand is presented in Table 2. A polycarboxylate high-range water-reducing admixture (MasterGlenium 315C from BASF) was used at a fixed dosage rate of 1% by weight of cement. Standard 12mm (long) polyvinyl alcohol (PVA) fibers (REC15 from Kuraray) were used at a fixed dosage of 2% by volume. The PVA fibers had an average diameter of 39µm and a tensile strength of 1.6GPa. The surface of the PVA fibers had a proprietary oil coating (1.2% by weight) to reduce any excessive fiber-matrix chemical bond strength due to their hydrophilic nature.
2.2. Test preparation and procedures

A 10-litre Hobart planetary motion mixer was used to prepare the specimens. After mixing, the ECC was cast in plexiglass molds and then covered with polythene sheeting to prevent moisture loss. The specimens were then left in a laboratory environment (20±1°C) and demolded after 24h; all specimens were then conditioned by placing in a small curing tank for a further 21 days. This curing length was determined according to the availability of the ESEM facility. The results presented in this paper are, therefore, relevant to the study of the self-healing performance of ECC in the early stages of service life where the risk of cracking is generally higher due to reduced strength.

Following this curing period, tensile testing was performed using a 100 kN Instron 4206 machine. Each sample was held using pneumatic grips and loading was then performed under a crosshead speed of 0.5 mm/min. Fig. 3(c) presents the tensile stress-strain results obtained from the five control samples, with the average strain at failure found to be 4.2%. Tensile stresses were determined from the installed load cell in the machine, whereas tensile strains were obtained from the two linear variable displacement transducers (LVDTs) mounted at both ends of the central region of the sample (Fig. 3(b)). For the preloaded samples, loading was stopped when the tensile strain reached 2.5% (or 60% of the average tensile strain capacity) and the grips were then released to unload the specimen.

2.3. Test equipment and procedures

A Philips XL30 Environmental Scanning Electron Microscope (ESEM), with LaB₆ filament, fitted with an Oxford Instruments X-Max 80 Energy Dispersive X-ray (EDX) detector was used for the study. The ESEM is capable of examining test specimens in their
natural wet state, without any preparation. However, owing to the relatively large size of the materials being examined, it was not possible to employ the full ESEM wet-mode facility, (which utilizes a Peltier cooling stage) but instead the low-vacuum mode was used. This allowed examination of relatively large surfaces, without the need for adding a conductive surface coating which was essential as the specimens were to be examined multiple times during the month long testing period. The only disadvantage of using a low-vacuum being that specimens underwent further drying under vacuum during examination. The ESEM operated at 20 kV, at a pressure of 0.7 to 0.8 Torr using a spot size of 5.2 and a working distance of between 7.5 and 10 mm. Images were recorded using a backscattered electron (BSE) detector, which was found most practical for locating cracks and viewing compositional contrasts.

It was possible to return to the exact locations previously examined by utilizing a specially fabricated steel mounting placed within the ESEM (see Fig. 4) which allowed repositioning of the specimen with an accuracy of approximately ±1 mm. The mounting remained in place throughout the testing program and it was therefore possible to study the same areas and re-acquire images from the locations that had been previously imaged (approximately at the middle strip of the 20×30 mm² surface).

3. Results and Discussion

3.1 Before healing (day 0)

Figs. 5(a) - (d) show the initial state before healing, with the micro-crack shown in Figs. 5(b) and (d) containing broken fragments of the matrix and fly-ash particles, the latter being spherical in shape. The micro-cracks can be seen as dark bands with widths ranging from 5-30μm, whereas the surrounding areas appear to comprise a large number of interconnected
small crystals which are much brighter (denoted by ‘S’ in Figs. 5(c) and (d)). EDX analysis of this surface presented in Figs. 6(a) and (b) displays a strong peak due to calcium and weak peaks due to silicon and aluminum, although the trace of other elements such as magnesium can also be detected. The high calcium content indicates that the crystals making up the surface surrounding the micro-crack are covered with a layer of calcium carbonate resulting from carbonation process, whereas the weak peaks can be associated with the presence of the hydration products directly underneath the carbonated surface layer. In some places, it is evident that the carbonated surface layer has flaked off, leaving darker patches (see Figs. 5(a) and (b)), with a composition shown in Fig. 6(c). These darker patches contain a large proportion of silicon and aluminum as would be expected in the bulk cement matrix, which is not dissimilar to the overall composition of the broken fragments of the matrix and fly-ash particles found within the micro-crack (see Fig. 6(d)).

3.2 Healing under submerged conditions (day 1 to 14)

This section presents the findings from the initial phase of the observations, with the specimens stored under water for 14 days and with the water being refreshed at the 7th day. In general, it was found that crack healing is most active during the initial three days of exposure. The findings from the ESEM tests carried out at the predetermined times are discussed below viz. 1, 3, 7 and 14 days.

Day 1. Figs. 7(a) and (b) show an example of the state of the micro-cracks in Specimens 1 and 2 after being submerged in water for one day. It is evident that the exposure to water has resulted in the precipitation of a large number of crystals nucleating along the length of the micro-cracks and on the dark patches. The crystals appear to vary considerably in both size and shape, with the majority having an angular rhombohedral shape, with smooth sides, and a
few perforations (see Figs. 7(c) and (d)). Analysis by EDX indicates that the crystals are primarily composed of calcium carbonate (Figs. 7(e) and (f)) and the rhombohedral shape would indicate the polymorph is calcite. It is evident that the width of the micro-crack remains virtually constant, suggesting no evidence of matrix swelling.

Day 3. At this stage, it is evident from Figs. 8(a), 9(a) and (d) that there is a marked increase in the crystal size and a discernable transformation in shape, from a rhombohedral shape to a rather elongated shape, with the growth following the longitudinal profile of the micro-cracks. In addition, there is a transformation in crystal surface texture, from a relatively flat and smooth appearance to a somewhat irregular and serrated one, resembling the texture of the surrounding surface areas (see ‘S’ in Fig. 5(c)). The texture does imply that this is a single crystal as there appears to be alignment of the cleavage planes, although the crystals forming at the top left of Figs. 9(a)- (c) appear to be a new addition to the rest.

The results obtained up to Day 3 indicate that carbonation reactions dominate the crack healing process. The precipitation of calcite crystals can be associated with the presence of carbonate ions from the curing water and the dissolution of Ca\(^{2+}\) ions primarily from the flanks of the micro-cracks into the water as well as that from the sawn (side) surfaces of the specimen, with the latter possibly being attracted to the crack mouth due to the high polarity of the PVA fibers. As demonstrated by [21] and [34] when studying the self-healing performance of ECC and fiber reinforced mortar in general, the presence of PVA fibers in a crack was found to promote the deposition of healing products on the surface of the fibers thereby enhancing the healing process. Furthermore, the precipitation of the calcite crystals along the cracks could be attributed to the exposure to further drying under vacuum during ESEM examination. It is anticipated that this would promote the dissolved Ca\(^{2+}\) ions within
the micro-cracks [33] to leach out to the top surface of the cracks, thereby creating a favorable environment along the length of the micro-cracks for crystal growth.

Day 7. Figs. 8(b), 9(b) and (e) show the progress of crack healing at the same locations as above. It is evident that the size and shape of the large crystals do not appear to change, indicating that a majority of the crystals have already reached their full size at 3 days. It was not clear whether this was either due to the diminution of Ca\textsuperscript{2+} ions resulting from reduced calcium leaching with time (e.g. from surface- to diffusion-controlled processes [33]), in combination with the dilution effect of water, or due to the depletion of the carbonate ions in the water near the top surface of the micro-cracks. It was for this reason that the water was refreshed after day 7.

Despite the similarity in morphology and texture of the existing crystals, precipitation of spherical smooth polymorphs was found in one area of Fig. 8(b), with the enlarged images shown in Fig. 8(d) for clarity. These polymorphs were observed after 7 days underwater and were very rare; it was also evident that they did not increase in size. Whilst their surface morphology was much smoother and different to neighboring calcium carbonate crystals, they had a similar composition, but with a trace amount of strontium. The growth of these spherical polymorphs are difficult to explain without further analysis (e.g. by Raman spectroscopy), in order to confirm whether different polymorphs of calcium carbonate, such as aragonite or vaterite, have formed.

Figs. 10(a) and (c) present an example of the state of the micro-cracks in Specimen 3 where very little indication of crystal growth was found. The lack of crack healing activity may be, in part, due to the fact that this specimen was placed inside the ESEM chamber for
the first time at day 7, exposing the specimen to only one drying cycle during ESEM examination. This finding would suggest that the significant healing activity observed earlier in Specimens 1 and 2 was attributed to the exposure to wetting/drying cycles. Apart from the lack in healing activity, it is interesting to note that the texture surrounding the micro-cracks was not quite the same to those observed in Specimens 1 and 2 (see ‘S’ in Figs. 5(c) and (d)), with the crystals at this location have grown in spherical patches. Calcium carbonate was present over the original surface.

Day 14. Figs. 8(c), 9(c), 9(f) and 10(b) show the state of selected areas after being underwater for 14 days. With reference to Figs. 8(c), 9(c) and 9(f), which show the micro-cracks in Specimens 1 and 2 where more frequent measurements were undertaken, it is evident that while the water was refreshed at Day 7, there were no significant differences in crystal morphology to that observed at Day 7. This finding would indicate that it was the limited amount of Ca\(^{2+}\) ions that is likely the cause of the termination in the crystal growth. This could be due to a combined effect of less dissolution of Ca\(^{2+}\) with time and the dilution effect of water. Nonetheless, it is evident that the majority of the micro-cracks have already healed, with only a few areas of the micro-cracks (e.g. between calcite crystals as indicated by triangles in Fig. 8(c)) still apparent. In contrast, no significant differences could be observed in Specimen 3 (compare Figs. 10(a) and (c) to Figs. 10(b) and (d)). As this specimen was kept underwater continuously and the water was refreshed at Day 7, it is likely that the lack of the healing activity was attributed to the shortage of Ca\(^{2+}\) ions.

3.3 Healing under natural environment (14–28 days)
This section presents the results of the same specimens exposed to an outdoor atmosphere for a further 14 days following the 14 days water exposure (see Fig. 2(b)), with observations made at Day 21 on Figs. 11(a), (c) and (e) and at Day 28 on Figs. 11(b), (d) and (f).

With reference to Figs. 11(a) and (c), it is evident that the exposure to a cyclic wet/dry atmosphere for a further 7 days (Day 21) caused the healing process to resume, as indicated by the precipitation of a great number of small calcite crystals along the two micro-cracks and on the dark patches (see the enlarged images in Fig. 13(a)). The same growth of crystals was also found in Specimen 3 presented in Fig. 11(e), where no healing activity was observed initially (see Fig. 13(b)). This is likely attributed to the frequent wetting/drying cycles over the 7 days of exposure to the natural environment (see Fig. 2(b)), highlighting the benefits of intermittent wet and dry exposure to crack healing. As Sisomphon et al [35] suggested, this could be due to the concentration of the Ca\(^{2+}\) and CO\(_3^{2-}\) ions increasing as the water evaporates cyclically.

It is interesting to note that there are different modes of growth between the submerged and the atmospheric phases of the observations. The exposure to atmospheric wet/dry cyclic conditions appears to result in the precipitation of a greater number of rhombohedral calcite crystals (see Figs. 11, 13(a) and (b)), but they are much smaller in size when compared to those precipitated during the underwater exposure (Figs. 8 and 9). This would imply that the exposure to the wet/dry cycles increases the rate of nucleation, but decreases the rate of crystal growth. In particular, there is no additional growth of the existing large crystals formed during the submerged phase of observations and all new crystals appear to precipitate on the surface and on the crack mouth that remained unhealed. It is possible that during the wet period, the surface is wetted with a thin water film; when Ca\(^{2+}\) ions are leached out from
the original surface and/or crack mouth and these ions may not be able to access the large crystals, leading to the apparent termination in growth of the large crystals. The precipitation of the large number of calcite crystals can be associated with the increase in the concentration of Ca$^{2+}$ and CO$_3^{2-}$ ions in the remaining dregs of water as the surface dries out. Overall, it appears that these small and numerous crystals are more effective in sealing the crack. If surface permeability tests were conducted at this stage using, for example, the Autoclam [36], this final material is likely to exhibit a lower permeability than that stored under submerged conditions over the initial 14 days.

With reference to Figs. 11(b) and (d) and the digital micrograph presented in Fig. 12, it is evident that after a further 7 days (Day 28), there appears to be little additional growth indicating that the major part of the healing process has occurred within the first 7 days of outdoor exposure. The same trend could also be observed from the micro-crack shown in Fig. 11(f), where, after 14-days, there were only a few areas where the cracks are detectable with the whole specimen looking well-sealed. Enlarged areas can be seen in Figs. 13(a) to (f) which also show the cracks to be well-sealed after 7 days atmospheric exposure with little further growth by 14 days.

4.0 Conclusions

Repeated ESEM observations have been undertaken at three very similar locations on pre-cracked ECC specimens to monitor the progress of crack healing with time, particularly with respect to the morphology of the healing products. EDX analyses were also performed to provide supporting information in relation to the elemental compositions of the healing products. The following conclusions can be drawn from the work presented:
1. The precipitation of calcite crystals was evident during the first three days following preloading. The crystals initially appeared in an angular rhombohedral morphology and then underwent a transformation in size, shape and surface texture, from flat and smooth to somewhat irregular and rough, resembling the texture of the original surface areas.

2. The precipitation of the calcite crystals can be associated with the reactions between the carbonate ions from the curing water and the dissolved calcium ions primarily from the water inside the micro-cracks.

3. The exposure to further drying under low vacuum during ESEM examination is expected to advance the overall mass transport of water and ions through the micro-cracks, allowing for the calcium ions to leach out to the top surface of the micro-cracks thereby creating a favorable environment for crystal growth. Crack healing was found to be less active in specimens kept underwater continuously.

4. The exposure to atmospheric environment involving intermittent wetting/drying cycles was found to promote the precipitation of numerous small crystals on the original surface as well as at crack mouth locations.

5. No appreciable further growth of the existing crystals either on the original surface or at the crack mouth was apparent. The termination in crystals growth would indicate that during the wet period, the surface was only covered with a thin layer of water which contained dissolved calcium and carbonate ions. It is likely that these ions were unable to access the large crystals, thereby leading to the apparent termination in growth of the large crystals.

6. The precipitation of the numerous small crystals during outdoor exposure appears to be more effective in sealing the micro-cracks.
Acknowledgements

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(c) C

(e) Weight (%)

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(f) Weight (%)

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**Fig. – 7.** The growth of calcite crystals after 1 day water exposure observed from (a) Specimen 1; (b) Specimen 2; (c) and (d) are enlarged images of (a) and (b); (e) and (f) are the compositions of the large angular crystals denoted by ‘C’ in (c) and (d), respectively.

**Fig. – 8.** The progress of micro-crack healing in the area shown in Fig. 7(a) after (a) 3 days; (b) 7 days; and (c) 14 days water exposure, with the triangles in (c) pointing to the locations where the micro-cracks have not completely healed; (d) some unusually shaped crystals found in (b).
Fig. – 9. The growth of the crystal shown in Fig. 7(c) after (a) 3 days; (b) 7 days; and (c) 14 days water exposure. The growth of other crystals shown in Fig. 7(d) after (d) 3 days; (e) 7 days; and (f) 14 days water exposure.
Fig. – 10. ESEM images of micro-cracks observed on Specimen 3: (a) and (b) after 7 and 14 days indoor water exposure; (c) and (d) are enlarged images of (a) and (b).
**Fig. – 11.** The progress of micro-crack healing after: (a), (c) and (e) a further 7 days outdoor exposure (Day 21); and (b), (d), (f) a further 14 days outdoor exposure (Day 28). (a) and (b) are from Specimen 1; (c) and (d) from Specimen 2; (e) and (f) from Specimen 3.

**Fig. – 12.** Digital micrograph of the same location shown in Fig. 11(b), with the image taken using a digital microscope equipped with a 12 MP digital camera.
**Fig. – 13.** The growth of the calcite crystals previously shown in Figs. 9 and 10: (a) and (b) after a further 7 days outdoor exposure (Day 21); (c) and (d) after a further 14 days outdoor exposure (Day 28); (e) and (f) are enlarges images of (c) and (d).
Table 1 – Materials mix proportions and mechanical property.

<table>
<thead>
<tr>
<th></th>
<th>CEM I (kg/m³)</th>
<th>FA (kg/m³)</th>
<th>Silica sand (kg/m³)</th>
<th>w/b</th>
<th>HRWR (kg/m³)</th>
<th>PVA (kg/m³)</th>
<th>F_{28} (MPa)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>454</td>
<td>818</td>
<td>273</td>
<td>0.28</td>
<td>4.54</td>
<td>26</td>
<td>34.8</td>
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</table>

Notes: binder includes cement and fly-ash; F_{28}: 28-day compressive strength determined on 50 mm cubes.

Table 2 – Oxide analysis and physical properties of fly-ash and silica sand (wt%).

<table>
<thead>
<tr>
<th></th>
<th>Fly-ash</th>
<th>Silica sand</th>
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<tr>
<td>Chemical analysis</td>
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<tr>
<td>SiO₂</td>
<td>52.7</td>
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<tr>
<td>Al₂O₃</td>
<td>26.6</td>
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<tr>
<td>Fe₂O₃</td>
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<tr>
<td>K₂O</td>
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<tr>
<td>CaO</td>
<td>2.4</td>
<td>–</td>
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<tr>
<td>MgO</td>
<td>1.2</td>
<td>–</td>
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<tr>
<td>Na₂O equivalent</td>
<td>1.7</td>
<td>–</td>
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<tr>
<td>SO₄</td>
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<td>–</td>
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<tr>
<td>Free CaO</td>
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<tr>
<td>Total phosphate</td>
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<tr>
<td>Loss on Ignition (LOI)</td>
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<td>Physical properties</td>
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<td>Specific gravity</td>
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<td>Surface area (m²/kg)</td>
<td>1300</td>
<td>–</td>
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<tr>
<td>Fineness (% retained on 25 μm)</td>
<td>&lt;25</td>
<td>–</td>
</tr>
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<td>Size distribution (μm) and cumulative retained (%)</td>
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<tr>
<td>500</td>
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<td>355</td>
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<td>250</td>
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<tr>
<td>90</td>
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<tr>
<td>63</td>
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Graphical abstract
Highlights
- ESEM with EDX used to characterize the origin of micro-crack healing in an ECC
- Evolution of healing precipitates studied at three specific locations over four weeks
- Specimens exposed to laboratory environment, followed by the natural environment
- Calcium carbonate is the main contributor to crack healing at the crack mouth
- Outdoor exposure involving intermittent rain promotes additional crystal growth