MICROSTRUCTURAL INVESTIGATIONS ON THE SELF-HEALING ABILITY OF ENGINEERED CEMENTITIOUS COMPOSITES INCORPORATING DIFFERENT MINERAL ADMIXTURES

Ahmed Alyousif
Ryerson University, Canada

Khandaker M. Anwar Hossain
Ryerson University, Canada

Mohamed Lachemi
Ryerson University, Canada

Mustafa Sahmaran
Gazi University, Turkey

ABSTRACT

The present study investigates the impacts that self-healing has on the microstructure characteristics of microcracked Engineered Cementitious Composites (ECC). These have two contrasting maturity levels and, furthermore, they involve three varying mineral admixtures that have very different chemical constituents. The impact of self-healing on the transport characteristics was examined by employing rapid chloride permeability tests (RCPT). The findings indicated that, if the appropriate mineral admixture type and conditioning were chosen, it would be possible to enhance the majority of the chloride ion penetrability levels following a 30-day period of water curing. As a result, the majority of the findings were in range of the low penetrability level over the 30 days, as set by ASTM C1202. The microstructural indications corroborated the findings from the experiments and provided weight to the notion that the causal factor of the healing was the appearance of calcium carbonate and C-S-H. These served to fill the crack owing to the hydration of the cementitious particles. In summary, the results indicate that the degree of self-healing is subject to variance in accordance with the contrasting chemical compositions that dominate within a certain infrastructure type over the course of its service life.

Keywords: Engineered Cementitious Composites (ECC); Mineral admixtures; Microstructure; Self-Healing.

1. INTRODUCTION

It is widely acknowledged to be the case that the way in which concrete mixtures perform is not just associated with mechanical property characterisation. In addition to this, it is considerably impacted by the parameters that influence the extent to which the material is durable. The durability feature of concrete, reinforced concrete, and pre-stressed concrete structures has a significant effect on the extent to which the material is economic and serviceable, thus making this a central consideration. Despite this, elements of public infrastructure are frequently impacted by environmental factors and/or mechanical loads. Notably, the extent to which these structures are durable is compromised as a result of processes like cracking. Having occurred, it is not a straightforward matter to restore the untouched features of the concrete that were there prior to the cracking. This is because the cracking processes establishes a range of pathways that have the effect of accelerating the conveyance of a range of resources into the material, including aggressive ions, gaseous substances, and water. As these media are conveyed, the possibility for disruptive mechanisms including sulphate and acid attack, corrosion, and freeze/thaw exposure is heightened substantially, meaning that the concrete is subject to rapid and severe deterioration. In numerous contexts, degradation caused by cracking or others processes should be attended to and renovated urgently. Despite the urgency with which these operations must be carried out, the maintenance applications can be costly and complex.

In certain instances, the expense incurred to restore the concrete can exceed the original expense. Witmann (1998) explains that, combined with the economic concerns, the atmospheric effect that restoring deteriorated infrastructure can have can serve to hinder the progress of such projects. In light of these concerns, the innate self-healing capacity of cracks in concrete, favoured by the establishment of cracks with reduced widths, increases in attractiveness as a way in which to heighten infrastructure durability and regain mechanical properties.

Over the past years, considerable progression has been seen in the concrete sector in such a way that contemporary notions relating to high performance fiber reinforced cementitious composites (HPFRCC) have moved forward as opposed to the notion of subjecting the brittle nature of simple cementitious materials to modification (i.e. mortars and concretes). ECCs, a novel category of HPFRCC, are marked by considerable advantages when one considers the heightened damage tolerance and ductility that are the products of the spacing multiple microcracks close together. An additional innate feature of ECC is its micron-sized cracks that have widths of less than 100 µm level; notably, this is self-controlled and free of rebar ratio. When one takes into account the fact that ECC has a well-controlled tight crack formation, it is possible the most difficult to locate resource that could have a positive impacted on the serviceability of structures. This is owing to the way in which issues relating to durability are solved by applying it. Despite this, the applicability of these resources should be explained with reference to a range of durability viewpoints in order for ECC to be utilised comprehensively in the building process.

Concrete is the building resource that is the most frequently utilised across the globe. In light of this, it should be noted that the generation of Portland cement, one of the primary components of concrete, is, in part, a contributor to greenhouse gas emissions. In this way, it makes substantial contributions to the onset of climate change. As a result of these considerations, it is now mandatory that state governments take regulatory decrees and CO2-emission policies into account. In the context of worldwide sustainable development, the employment of supplementary cementitious materials (SCMs [i.e. fly ash, slag etc.]) as an occasional replacement for cement could serve to lessen the ecological damage that is caused be cement manufacturing. In combination with the environment-based effects, the employment of SCMs could have the effect of lessening the costs incurred by concrete mixtures. This is because, when considered in relation to Portland cement, the cost of SCMs is considerably reduced. Notably, Wang and Li (2007) explained that the inclusion of increased volumes of fly ash within the ECC systems results in the reduction of crack widths to up to 10 µm levels. The researchers argue that this could serve to improve the extent to which certain structures are durable.

In the past ten years, self-healing applications have been increasingly discussed among researchers. Despite the fact that a range of self-healing approaches have been utilised in order to functionalise the mechanism, Li and Herbert (2012) explain how the majority of the attention has been focused on the self-reparation of instances of damage, namely cracks, without external involvement. The capacity of concrete to self-heal the damage it develops is primarily related to the formation of calcite and, additionally, C-S-G gels in those instances where no extra healing actors are employed. Although each mechanism is effective to some degree in crack plugging, transformations in conveyance characteristics are associated with calcite formation in a closer way. This is central in the context of structures that will be exposed to H_2O over the course of their service lives. In light of these considerations, the current research focuses primarily on the rapid chloride permeability tests (RCPTs) from pre-cracked and viable ECC samples prior to and following their being exposed to environmental conditioning for crack healing. Furthermore, over the course of producing ECCs, mineral admixtures (Mas) marked by varying chemical constituents were utilised. Notably, the chemical composition can be very important in terms of the self-healing ability of the mixtures. Microstructural variance was examined inside the cracks by employing scanning electron microscopy (SEM) in combination with energy dispersive X-ray spectroscopy (EDS).

2. EXPERIMENTAL PROGRAM

2.1 Materials, Mixture Proportions and Basic Mechanical Properties

The components used for the generation of the ECC mixtures were as follows: Conventional Portland cement (PC); silica sand with a maximum aggregate size (MAS) of 400 µm and a water absorption capacity of 0.3%; water; poly-vinyl alcohol (PVA) fibres with a diameter of 39 µm, nominal tensile strength of 1610 MPa, and specific gravity of 1.3; and a high-range water reducing admixture (HRWRA). Additionally, the mixtures also involved varying mineral admixtures (MA) that were representative of widely differing chemical constituents. Contrasting MAs were chosen, including one type of ground granulated blast furnace slag (S, [ECC_S]) in combination with two varying fly ashes (FA), a low lime fly ash ([FA-L], ECC_L) and a high lime fly ash ([FA-H], ECC_L). The chemical and physical characteristics of the Portland cement and mineral admixtures are illustrated in Table 1, and the particle size distributions of the solid constituents are presented in Figure 1. The ECC mixtures were generated with a water to cementitious materials (PC+MA) ratio (W/CM) of 0.27, and a mineral admixture (i.e. FA or S) to Portland cement ratio (MA/PC) of 1.2, by mass. Table 2 presents information relating to the mixture proportions.

Foundational mechanical property characterisations of the ECC mixtures were carried out by employing 50 mm cubic specimens for compressive strength and 360×75×50 mm prism (length×depth×width) specimens for flexural parameters. Following a period of one day within the moulds at 23±2 °C, 50±5% RH, each example was conveyed to a plastic bag in order for curing to take place 23±2 °C, 95±5% RH for a one-week period. After the first week-long curing period, specimens were maintained in a lab environment at 23±2 °C, 50±5% RH for another three weeks. The foundational mechanical properties (i.e. compressive strength and flexural parameters [flexural strength and flexural deformation]) of the ECC samples obtained by taking the average of six samples at minimum can be found in Table 2. It is clearly seen that the average 28-day compressive strength findings of the ECC_S mixture (77.2 MPa) represented the peak, and this in turn was accounted for with reference to the increasing cementing ability and heightened specific surface area of the slag particles. The smallest average compressive strength finding was acquired from the ECC_L mixture (55.5 MPa). This result displayed a relationship with the increased pozzolanic capacity of low lime fly ash particles, where the extent to which they were effective was predicated at a later age. The average flexural strength findings of the ECC mixtures ranged from 10.2 to 11.6 MPa. An interesting finding to note is that the variance in flexural strength results was not as pronounced as the variance among compressive strength results. This is accounted for with reference to the intricate material features, including tensile first cracking strength, ultimate tensile strength, and tensile strain capacity that determine flexural strength findings (Qian et al., 2009). Table 2 also presents flexural deformation values, which shed light on how ductile the ECC materials are. The table shows that, in the context of the range of mixture types, the ECC_S mixture displayed the smallest average flexural deformation value at the end of the 28-day period (2.0 mm). At the same time, the ECC_L mixture was over twice as large as that of the ECC_S samples with 4.3 mm mid-span beam deformation level. The heightened ductility of the ECC_L samples was accounted for with reference to the tendency of low lime fly ash particles to lower the toughness of PCA fibre/matrix interface chemical bonds and matrices. At the same time, as stated by Wang and Li (2007), this increased the interface frictional bond in an attempt to acquire an increased tensile strain capacity.

Table 1: Chemical and physical properties of PC and different SCM types

Chemical Composition, %	PC	FA_L	FA_H	Slag
SiO_2	20.77	57.01	41.8	35.06
$Al2O_3$	5.55	20.97	18.78	10.4
Fe_2O_3(T)	3.35	4.15	6.44	0.79
MnO	-	0.032	0.019	0.387
MgO	2.49	1.76	4.66	12.24
CaO	61.4	9.78	21.77	38.34
Na_2O	0.19	2.23	1.74	0.12
K_2O	0.77	1.53	0.63	0.37
TiO_2	-	0.68	1.5	1.08
Loss on Ignition	2.2	1.25	0.68	1.12
Total		99.48	98.88	97.66
Physical Properties				
Specific Gravity	3.06	2.02	2.61	2.87
Blaine Fineness (m^2/kg)	325	290	315	430

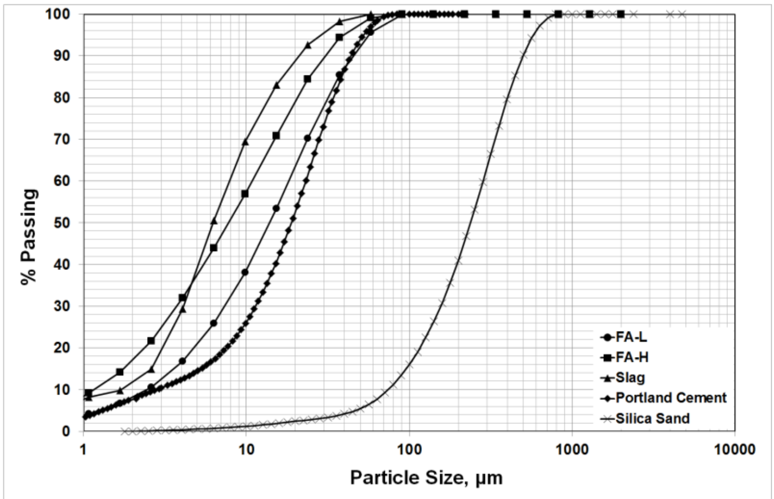

Figure 1: Particle size distributions of solid ingredients

Table 2: Mixture proportions and compressive strength results of ECC mixtures

Mixture Proportions	Mix ID.		
	ECC_L	ECC_H	ECC_S
Cement	1.0	1.0	1.0
Sand	0.80	0.80	0.80
FA/PC	1.2	1.2	-
S/PC	-	-	1.2
W/CM	0.27	0.27	0.27
PVA, (kg/m3)	26	26	26
HRWRA (kg/m3)	3.9	4.6	5.3
Mechanical Properties (28 days)			
Compressive strength (MPa)	55.5	58.7	77.2
Flexural strength (MPa)	10.2	11.6	11.5
Flexural deformation (mm)	4.3	2.7	2.0

2.2 Sample Preparation, Pre-Cracking and Methods for Self-Healing Evaluation

In order to track the nature of the self-healing process, RCPTs were carried out in line with ASTM C 1202. Following a one-day curing period in a lab environment at 23±2 °C and 50±5% RH, Ø100×200 mm cylindrical specimens were taken from the moulds and, following this, were placed into plastic bags at 23±2 °C and 95±5% RH until the end of 7 and 90 days. Following the first aging, a diamond blade saw was utilised in order to divide Ø100×200 mm cylinders were into Ø100×50 mm pieces. Prior to the samples being pre-loaded, identical processes to those applied in the context of the prisms were adhered to in order to define the ultimate splitting tensile deformation capacities of varying mixtures under splitting tensile loading. The findings ranged from 1.3 mm to 1.9 mm, contingent on varied MAs and their associated first curing periods. Following this, in an attempt to generate microcracks, Ø100×50 mm ECCs were pre-loaded up to 80% of their splitting tensile deformation capacities at the ages of 7 and 90 days in the context of a splitting tensile loading at a loading rate of 0.005 mm/s. For the RCPTs, six cylinders from every mixture were utilised, where three of these were sound and three were subjected to pre-loading. These experiments were carried out again after 30 and 90 days of CW (continuous water curing) exposure beyond the initial curing times. This repetition occurred in order to witness the self-healing performance of ECCs.

3. RESULTS AND DISCUSSION

3.1 Rapid Chloride Permeability Test (RCPT)

3.1.1 Unhealed Specimens

In order to measure the self-healing capacity of the ECCs with varying mineral admixtures, it was necessary to employ the RCPT. It should first be noted that the RCPT is not engaged in in order to find measurements associated with the permeability of concrete. Rather, the purpose of the test is to measure the resistance of the concrete to an electrical current. This is a valuable piece of information to find as there is a correlation between the extent to which the concrete is resistant and the degree to which it is permeable. Table 3 presents the findings of the RCPT in relation to varying ECC mixtures, and these present a fair picture of the specimens' resistivity against chloride ion ingress. The figures observed in Table 3 were all determined by calculating the average of three specimens. It is clear that there was considerable variance among the results, but this is not surprising when one takes into account the maturity levels and the types of mineral admixtures employed. In terms of the RCPT findings gathered from the seven-day-old specimens, the values were 7169, 4863, and 6397 C for the ECC_L, ECC_H and ECC_S mixtures respectively. Despite the fact that the ECC_S examples were anticipated to provide reduced findings, particularly over the beginning phases of hydration, the collected findings from the ECC_H mixture contradicted this prediction as a result of the improved cementing ability and high specific surface area of the slag particles when compared to varying fly ashes. Notably, RCPT is an electrochemical test process that has been impacted significantly as a result of the transformations in total porosity of the concrete material and chemical constituents of the pore solution. Thus, it is possible to state that, when assessing the findings collected from RCPT, the aspects ruling the chemical state of the pore solution (i.e. calcium silicate hydrate [C-S-H] gels, CH, and alkalis) should be watched closely. It is commonly regarded to be the case that the appearance of sodium and potassium ions in cementitious matrices, in combination with sulphates or hydroxides, results in the speeding up of early hydration (Juenger and Jennings, 2001). Juenger and Jennings (2001) continue to note that this is accompanied by the deceleration of late hydration. Furthermore, a number of researches, including Richardson (2004), have found evidence to support the notion that alkalis can effectively modify the morphology of calcium silicate hydrate (C-S-H) gels. In turn, Richardson (2004) describes how this results in the development of lath-like products that have a greater extent of crystallinity. As stated by Bentz (2006), the development of lath-like C-S-H gels when higher quantities of alkali are present is the causal factor of the depercolated (disconnected) capillary pore network. Although enhancements do take place over the course of the early hydration phases, it is possible that these microstructural modifications are the cause of the alterations in the transport characteristics of cementitious systems. This is important as it can shed light of the lower RCPT results that were collected from the ECC_H samples that had increased concentrations of alkali ions when considered in relation to ECC_S. Despite the fact that it is considered to be impactful to a lesser degree, the relatively decreased specific gravity of FA-H particles in comparison to slag, which result in the increased obtainability of these particles in the matrices per unit volume, could explain why more compact systems and lower RCPT results were acquired with the seven-day-old ECC_H specimens compared to ECC_S.

Table 3: Rapid chloride permeability test results of ECC specimens

Mix ID.	Initial Curing Age	Virgin	Pre-loaded	Initial Curing +	
				30 days	90 days
ECC_L	7 days	7169	8318	2475	511
	90 days	375	1308	478	246
ECC_H	7 days	4863	6289	639	258
	90 days	859	1511	399	330
ECC_S	7 days	6397	7888	1599	997
	90 days	1195	3686	1284	909

As anticipated, extending CW curing led to substantially enhanced RCPT findings owing to the incessant development of the cementitious composites over time. Despite the fact that the improvements in RCPT findings were in near to one another, the findings associated with composites that had a low lime fly ash were lower on the whole when the 90-day period was over. Table 3 shows that the enhancement in chloride ion penetrability of pre-loaded ECC_L samples was 81% beyond 90 days of early curing and up to the point where the 90-day period of CW curing was over. In addition, logged values for the ECC_H and ECC_S composites were 78% and 68% respectively. More noticeable improvements were logged in the RCPT findings from composites that incorporated FA-F particles. This has been accounted for with reference to the increased pozzolanic capacity and, furthermore, to the power that low calcium fly ash particles have to stay for long stretches of time with no chemical interaction in the matrices. Although enhancements in the RCPT findings varied according to the mineral admixture type, each of the 90-day-old findings relating to sound samples, apart from the ECC_S composite, resided in the range of very low chloride ion penetrability levels, according to ASTM C 1202. The ECC_S composite was in the low range. When pre-loading was applied, chloride ion penetrability results rose to a specific level regardless of the original curing period of composite type. For example, the seven-day average RCPT finding for the ECC_L mixture rose from 7169 coulombs to 8318 coulombs in those instances where specimens were pre-loaded up to 80% of their splitting tensile deformation capacities. This phenomenon was more exaggerated when the specimens were older. Taking the ECC_S specimens as a case study, it is clear that pre-loading resulted in a 23% rise in chloride ion penetrability in relation to the specimens that were seven days old. However, the rising RCPT finding reached 140% of the original figures in the specimens that were aged for 90 days. It is possible to attribute this phenomenon to the improved matrix maturity of the mixtures as a consequence of the elongated curing time; this resulted in rising matrix fracture toughness figures and, furthermore, activated the developed of contained cracks with greater widths rather than steady-state multiple microcracking (Wang and Li, 2007). It should also be noted that the increased percentage increments acquired with the employed pre-loading can be attributed to the notion that the working out took place on the basis of the considerably reduced RCPT findings recorded at increased ages (i.e. 90 days). The chloride ion penetrability levels of ECCs (according to ASTM C 1202) prior to and following the cracking process can be taken into account in order to acquire in-depth knowledge relating to the application of pre-loading on RCPT findings. Although the average RCPT findings of the 90-day-old ECC samples rose, recorded figures resided within the medium- or low-level range prior to and following pre-loading. The above results can be cited as proof that, dissimilar to water permeability as discussed by Lepech and Li (2009), the chloride ion permeability of ECC samples is significantly impacted by the appearance of microcracks.

3.1.2 Effects of self-healing

The variance in the RCPT findings of ECC samples pre-loaded up to 80% of their splitting tensile deformation capacities following a 7- and 90-day period of initial aging and, furthermore, a 30- and 90-day period of CW curing, is displayed in Table 3. In addition to this, Table 3 displays that, based a number of factors (including initial curing time, type of mineral admixture, and extra curing time), self-healing, with reference to the enhancements in RCPT findings, was witnessed in each mixture that had a minimum level of 20%. This is a testament to the efficacy of CW conditioning on crack sealing. Self-healing was discovered for all mixture types following a 30-day period of CW conditioning, regardless of whether the mixture was first cured for a 7- or 90-day period. As aforementioned, RCPT, as an electrochemical experiment, is impacted considerably by a range of factors. Although it is straightforward to carry out, it logs the progression of every ion as opposed to only measuring chlorides. Additionally, voltage applied for ion movement creates thermal energy; this can be considerably high and, furthermore, it can heighten the total findings for immature samples. Notably, the electrical conductance of the concrete is a central consideration in RCPT, and this can be altered dramatically by any conducting resource (i.e. alkalis, free carbon content, among others) where its presence in the pore solution is likewise reliant on the extent to which the samples are mature. It was found that, when CW curing extends to more than a 30-day period, self-healing in terms of RCPT began to decrease in intensity. For instance, in the context of seven-day-old ECC_L samples, the average RCPT findings fell from 8318 to 2475 C level following the initial 30-day period of CW curing. Minor decrements was observed when the curing time was extended to 90 days, and the same findings were observed in relation to 511 C. Samples that were originally cured for a longer period of time were subject to the same phenomena, and this was also the same for the remaining composites that incorporated varying mineral admixtures. This correlation was no unexpected, and it was attributed to the abundance of anhydrous materials in the initial phases and, accordingly, reducing initial crack volumes at later ages. It should be noted that this could have served to restrict the extent to which the marked self-healing was visible. Although the specific healing periods was different in terms of the admixture type that was utilised, evidence of self-healing was easier to find on the samples that were cured for a seven-day period. Dissimilar to what the researchers had anticipated, samples that were originally cured for a 90-day period failed to display marked variance in healing rates. This was the case for all ECCs. Here, it should be noted that this observation could address the old question relating to cementitious composites, that of the efficacy of late-age self-healing in contrast to early-age. Nevertheless, it will be necessary to conduct follow-up studies to corroborate this finding; these studies could, among other things, examine samples that have been cured for extended periods of time. In terms of the impact that varying mineral admixtures had on RCPT findings about pre-cracked ECC samples, it is possible to present the general notion that each mixture had a comparable healing rate to all others. Notably, ECC_S samples displayed anomalously reduced figures. Although there was extensive variance in the RCPT findings as a result of the varying chemical constituents and initial curing ages of the composites, it is imperative to note that the 30-day CW curing period is suitable for the majority of seriously degraded ECCs to indicate reduced levels of chloride ion penetrability according to ASTM C 1202.

3.2 Microstructure Observations of Self-Healed ECC Mixtures

SEM-EDS was used to analyse the microstructure of healed crack lines that developed on pre-loaded specimens. This took place following a 90-day period of healing. Figure 2 presents the SEM micrographs and the EDS information relating to the self-healing products on the surface layers of ECC_L, ECC_H, and ECC_S.

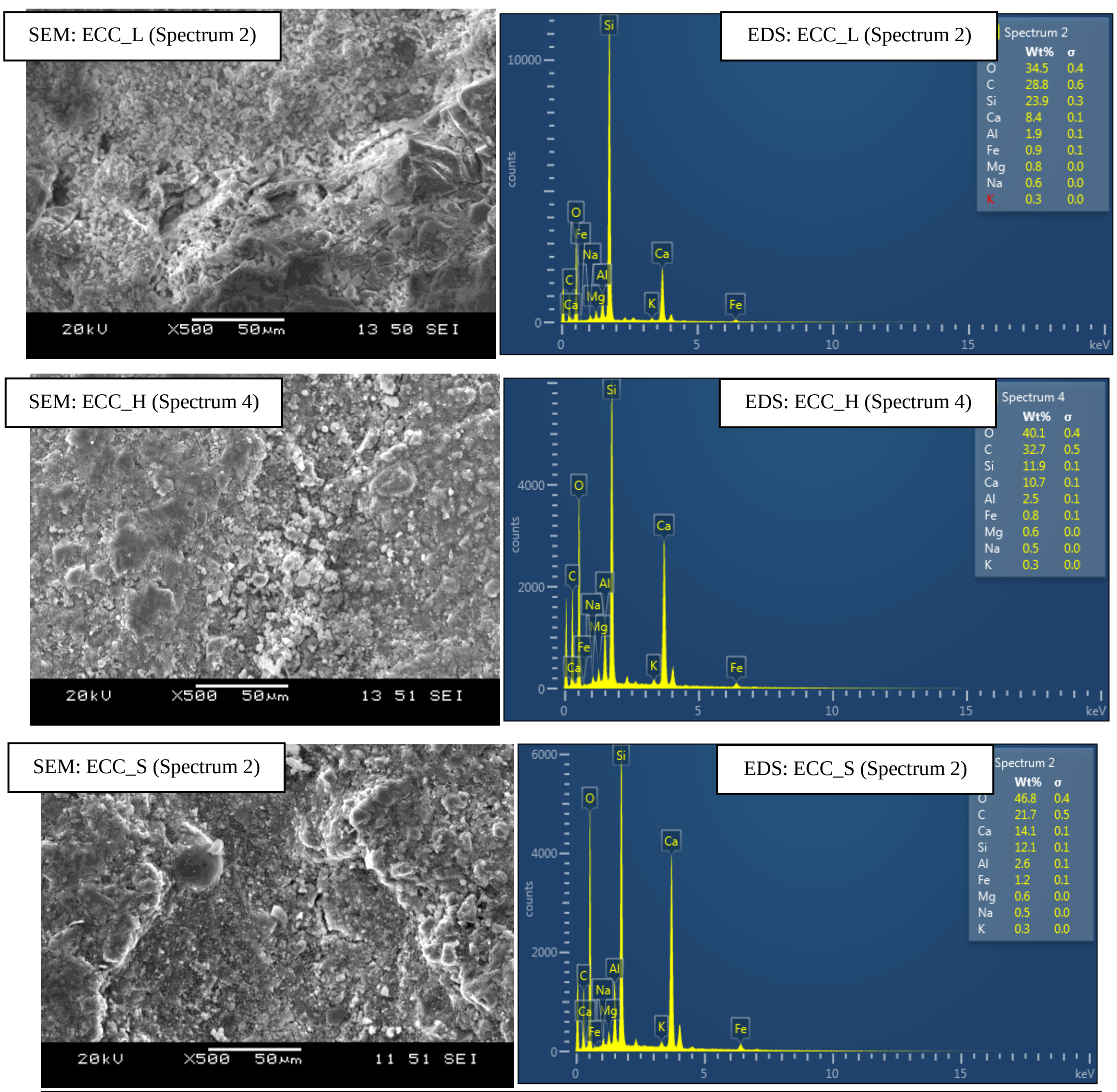

Figure 2: SEM micrograph with EDS pattern of products in self-healed cracks of the surface layer of ECC_L, ECC_H, and ECC_S

According to the SEM images relating to the healed cracks in Figure 4, the surfaces of ECC_L, ECC_H, and ECC_S seem to have been healed entirely; additionally, the crack line has been completely plugged. EDS findings were indicative of a number of aspects, including the high calcium peak, the presence of oxygen, silica, carbon, and a reduced aluminium peak. These observations confirmed that calcite, in combination with the mixed C-S-H/$Ca(OH)_2$, is the primary healing component in terms of the surfaces of ECC_L, ECC_H, and ECC_S. This is supported by the work of numerous authors, including Kan et al. (2010), Wua et al. (2012), and Fan and Li (2015), who have presented the notion that calcite is the main product on healed crack surfaces. Ozbay et al. (2013) demonstrated that, when water is present, Ca^{2+} from hydration products percolates from the solid matrix into cracks; following this, a reaction between it and CO_2 takes place, producing $CaCO_3$ crystals.

An additional notion that must be investigated further is the impact that varying mineral admixtures have on the microstructural characteristics of ECC composites. ECCs that had low lime fly ash particles (i.e. ECC_L) performed more effectively in terms of self-healing than other composites, especially in those cases where they were subject to initial curing for a relatively short period of time, for example a week. Given the enhancements in the findings associated with the sound samples, the performance of low lime fly ash particles was succeeded by that of high lime fly ash (i.e. ECC_H) and ground granulated blast furnace slag particles (ECC_S), generally speaking. Despite this, when one takes into account the self-healing rates of pre-loaded samples, slag particles seemed to outperform high lime fly ash and even low lime fly ash in certain instances; this was often the case when they were initially cured for a limited time. The way in which the ECC_S composites performed in terms of self-healing was a surprise to the authors owing to the fact that it had been assumed that the samples incorporating slag would yield significantly reduced quantities of anhydrous materials. In addition, it was thought that there was an increased matrix maturity in combination with a higher quantity of crack openings upon pre-loading. Sahmaran et al. (2013) arrived at the conclusion that, owing to the fact that slag particles contain reduced quantities of SiO_2 when considered in relation to alternative mineral admixtures, reduced rates of pozzolanic reactivity is expected. This would mean that portlandite (as the product of cement hydration) would stay for a longer period of time and in larger quantities in the cementitious matrices. It is important to note that this could result in the increased pH of the pore solution. In the instances where the pH figure for a pore solution is increased, carbonic acid (as a product of the reaction between water and CO_2) has the capacity to disassociate at a more rapid rate when it is in the form either of bicarbonate (HCO^{3-}) or carbonate ions (CO_3^{2-}). Notably, these are employed in calcite development by joining these with the percolated Ca^2+ ions from C-S-H gels and, additionally, portlandite. As discussed by Jooss (2001) and Edvardsen (1999), this should take place when CO_2 abundant water is present. As such, the heightened self-healing capacity observed in relation to the ECC_S samples has been accounted for, to a great degree, with reference to calcite development. This phenomenon was also visibly observable as a result of the fact that a by-product of the calcite formation was a white deposit on the microcracked samples. This determination concurs with the RCPT findings gathered from sound and pre-loaded samples.

4. CONCLUSION

The purpose of the current paper has been to present the assessment of the self-healing processes in cementitious composites that are constituted of mineral admixtures that have considerable variance in terms of their chemical compositions. Over the course of the investigation, the researchers focused on the task by taking RCPT measurements and microstructural observations into account. As a result of carrying out the evaluation, a number of conclusions were determined as follows:

1. The chloride ion penetrability findings relating to the ECC composites were heightened considerably when microcracks were present. Despite this, the degree of this was contingent on the maturity level and, additionally, the kind of mineral admixture employed in the composites.
2. Self-healing facilitated by enhancements to the chloride ion penetrability when the samples were subjected to further CW curing generated extensive attention. The RCPT findings associated with the majority of the almost-failed ECC samples, according to ASTM C 1202, lowered to reduced levels when they had been CW cured for a 30-day period.
3. The cracking process has a significant impact on the chloride ion penetrability of the ECC samples. Although the RCPT results increased as pre-loading was applied, the finishing values when the 90-day period was over resided within the low or the medium levels, as presented by ASTMC1202.

4. Serving as an effective healing product for the ECC_L, ECC_H, and ECC_S samples, an increased presence of supplementary calcite and C-S-H in the surface layer was suggested by the microstructural analysis engaged in by SEM-EDS on the surface layer of healed crack lines.

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