THE EFFECT OF SELF-HEALING ON THE DURABILITY PERFORMANCE OF MICRO-CRACKED ECC

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Abstract: Increase in repair and replacement costs and poor performance of so-called conventional concrete materials force engineering society to pay serious attention to the durability issues. Many researchers agree on the general idea that cracking is vitally important if durability is of concern. Cracking of concrete under service conditions is inevitable due to several external factors and/or mechanisms occurring in concrete material itself. Therefore, elimination or minimization of cracking through various techniques arises great interest. One of the most effective techniques in eliminating cracks is self-healing phenomenon, which is commonly related with on-going hydration reactions or crystal formation in concrete. It is believed that the use of Engineered Cementitious Composites (ECC) may greatly promote the attainment of substantial self-healing, and accordingly increase the long term performance of concrete structures. In this study, the effects of self-healing on the durability performance of ECC were investigated in terms of mechanical property enhancement, chloride ion penetrability and frost resistance. The research results indicate that due to intrinsic self-controlled tight crack width, many durability challenges confronting concrete can be overcome by using ECC. The superior durability performances of micro-cracked ECC as a result of self-healing phenomenon are expected to contribute substantially to improving civil infrastructure sustainability by reducing the amount of repair and maintenance during the service life of the structure.

1 INTRODUCTION

Self-healing ability of cracked concrete is a frequently studied phenomenon. Both experimental research and practical experience have demonstrated that cracks in concrete material itself have a potential to seal themselves especially under the conditions where water and CO_2 are present. Self-healing is generally attributed to the hydration of previously unhydrated cementitious materials, calcite formation, expansion of the concrete in the crack flanks, crystallization, closing of cracks by solid matter in the water and closing of the cracks by spalling of loose concrete particles resulting from cracking [1]. Self-healing of cracks should be taken into account when specifying tolerable crack widths. Jacobsen et al. [2], Reinhardt and Jooss [3], Edvardsen [1], Aldea et al. [4] and Clear [5] have proposed the maximum crack widths as 5 to 10 μm, 100 μm, 200 μm, 205 μm and 300 μm, respectively in order for a crack to seal itself completely. In all, it is pointed out that the most serious challenge for complete healing of a crack is tolerable crack width. Since conventional concrete has the tendency to deform in a brittle manner under mechanical loading, such small crack widths in conventional concrete could be a major concern to attain. Since the crack width was identified as a key factor in the self-healing of concrete, materials that can recover the drawbacks caused due to brittle nature of concrete came into prominence lately.

One of such materials called Engineered Cementitious Composites (ECC) was first developed by Li and coworkers during the last decade [6]. As a new class of High Performance Fiber Reinforced Cementitious Composites (HPFRCC), ECC is a ductile fiber reinforced cementitious composite micromechanically designed to achieve high damage tolerance under severe loading and high durability under normal service conditions. [6-8]. The most distinctive characteristic separating ECC from conventional concrete and fiber reinforced concrete (FRC) is an ultimate tensile strain capacity between 3% to 5%, depending on the specific ECC mixture. This strain capacity is realized through the formation of many closely spaced microcracks, allowing for a strain capacity over 300 times than that of normal concrete. These cracks, which carry increasing load after formation, allow the material to exhibit strain hardening, similar to many ductile metals.

While the components of ECC may be similar to FRC, the distinctive ECC characteristic of strain hardening through microcracking is achieved through micromechanical tailoring of the components (i.e. cement, sand, and fibers), along with control of the interfacial properties between components [6-9]. Fracture properties of the cementitious matrix are carefully controlled through mix proportions. Fiber properties, such as strength, modulus of elasticity, and aspect ratio have been customized for use in ECC. The interfacial properties between fiber and matrix have also been optimized in cooperation with the manufacturer for use in this material. While most HPFRCCs rely on a high fiber volume to achieve high performance, ECC uses low amounts, typically 2% by volume, of short, discontinuous fiber. This low fiber volume, along with the common components, allows flexibility in construction execution. To date, ECC materials have been engineered for self-consolidation casting, extrusion, shotcreting, and conventional mixing in a gravity mixer or conventional mixing truck [10-13].

Figure 1 shows a typical uniaxial tensile stress-strain curve of ECC material containing 2% PVA fiber [14]. The characteristic strain-hardening behavior after first cracking is accompanied by multiple microcracking. The crack width development during inelastic straining is also shown in Figure 1. Even at ultimate load, the crack width remains smaller than 100 μm. This tight crack width is self-controlled and, whether the composite is used in combination with conventional reinforcement or not, it is a material characteristic independent of rebar reinforcement ratio. In contrast, normal concrete and fiber reinforced concrete rely on steel reinforcement for crack width control. Given the intrinsically well-controlled tight crack width in ECC, the effect of self-healing of cracks on the durability and residual mechanical properties of cracked ECC specimens has recently been investigated under a number of commonly encountered environments by author. In this article, emphasis is placed on the accumulated knowledge on the effect of self-healing on the durability performance (mechanical property enhancement, chloride ion penetrability and frost resistance) of micro-cracked ECC.

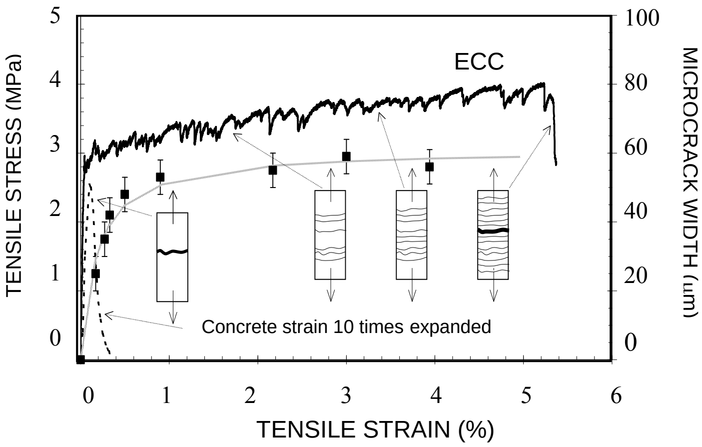


Figure 1: Typical tensile stress-strain curve and crack width development of ECC

2 EXPERIMENTAL PROGRAM

2.1 Materials, mixture proportions and basic mechanical properties

The influence of self-healing on durability performance of ECC mixtures was investigated in terms of mechanical property enhancement, rapid chloride permeability test (RCPT) results and frost resistance. To do this, ECC mixtures having water to cementitious material ratio (W/CM) of 0.27 and fly ash to Portland cement ratio (FA/PC) of 1.2 and 2.2, by mass (from now on ECC-1 and ECC-2, respectively) were prepared, details of which are given in Table 1. Type I ordinary Portland cement (C), silica sand with an maximum size of 400 µm, Class-F fly ash (FA) conforming to ASTMC 618 requirements, polyvinyl alcohol (PVA) fibers, and a polycarboxylate based superplasticizer (SP) were used. The chemical compositions and physical properties of the cement and FA are reported in Table 2. The PVA fibers had an average diameter of 39 µm, average length of 12 mm, a tensile strength of 1600 MPa, a density of 1300 kg/m^3, an elastic modulus of 42.8 GPa, and a maximum elongation of 6.0%.

Table 1 shows compressive strength test results of the ECC mixtures cured in an environmental chamber at a temperature of 23 ± 2 °C and a relative humidity of 95 ± 5% until the age of testing. The compressive strength was computed as an average of six 50 mm cubic specimens. As seen from Table 1, the compressive strength of ECC decreased with increasing FA content. However even at almost 70% replacement of Portland cement with FA (FA/C = 2.2), the compressive strength of ECC at 28 days can be more than 50 MPa.

Table 1: Mixture properties of ECC

Ingredients, kg/m^3		**ECC-1**	**ECC-2**
C		558	375
FA		669	823
Water		5.55	21.68
PVA		3.35	5.48
Sand		2.49	1.71
SP		2.49	0.34
FA/C		1.2	2.2
Compressive Strength, MPa	**14-d**	39.2	27.7
	28-d	62.5	54.1

Table 2: Properties of cement and fly ash

Chemical Composition	**C**	**FA**
CaO	61.8	5.57
SiO_2	19.4	59.5
Al_2O_3	5.3	22.2
Fe_2O_3	2.3	3.9
MgO	0.9	-
SO_3	3.8	0.2
K_2O	1.1	1.1
Na_2O	0.2	2.7
Loss on Ignition	2.1	0.2
Physical Properties		
Spec. Grav.	3.15	2.18
Ret. On 45 µm, %	12.9	9.6
Water Req., %	-	93.4

2.2 Pre-cracking and methods to evaluate self-healing

Mechanical and chloride ion permeability properties

Ø100×200 mm cylinder specimens were prepared to define ultimate splitting tensile load carrying capacity of the ECC mixtures. At the end of the 28 days, three 50 mm thick discs were extracted by using a diamond blade saw from the central portion of the cylinder specimen. From each mix, six disc specimens were tested under the splitting tensile loading up to failure of the specimens using a closed-loop controlled material testing system at a loading rate of 0.005 mm/s, and average ultimate splitting tensile load carrying capacity and deformation level of the mixtures were defined. The remaining disc specimens of the both mixtures were pre-loaded to 0.75, 1.00 and 1.25 mm deformation level under splitting tensile loading to achieve various amounts of microcracks before exposure to different curing regimes.

In addition to splitting tensile properties, at the age of 28 days, the rapid chloride permeability testing (RCPT) of the ECC specimens, based on the ASTM C1202, was conducted on the pre-cracked and virgin ECC specimens to determine whether microcracking due to mechanical pre-loading affects chloride ion penetration resistance or not. After, the pre-loaded ECC disc specimens together with some uncracked (virgin) disc specimens without pre-loading were subjected to different exposure conditions at room temperature for additional 30 and 60 days. Three different conditioning regimes (CA – continuous air, W/D – wet/dry cycle and CW – continuous wet) were used to simulate different environmental exposures and to investigate their influences on the chloride ion permeability of ECC mixtures at different ages by using three disc specimens at each age. In addition to chloride ion permeability resistance of pre-cracked and virgin ECC specimens, residual mechanical properties (under splitting tensile loading) of ECC specimens preloaded to 0 mm (virgin) and 1.25 mm deformation level were also tested at the ages of 28+60 days.

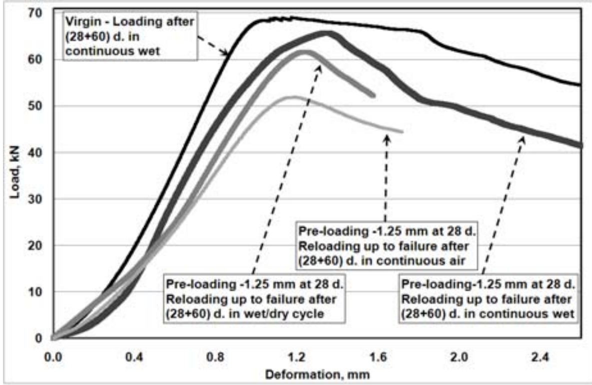
Frost durability properties

From each ECC mixture, fourteen 400 × 100 × 75 mm prisms for the freeze-thaw test were prepared. All specimens were demolded at the age of 24 h., and moist cured in lime-saturated water at 23±2 °C for 13 days. Fourteen days after casting, from each mixture, six prism specimens with a span length of 355 mm and a height of 75 mm were tested under the four-point bending test up to failure, and the average ultimate flexural strength, mid-span beam deflection capacity and flexural stiffness of each mixture were determined. The deflection capacity was defined as the deflection at which point the bending stress reaches maximum (MOR). At the same age, six prisms were pre-loaded up to 2.5 mm deformation level and then load released; just after that three of those preloaded beams were reloaded up to failure to observe the effect of damage by pre-loading. The deflection of 2.5 mm is below ultimate deflection capacity of both ECC mixtures (> 3.44 mm) with no localized fracture. Tests were conducted on a closed-loop controlled material test system with 100 kN capacity under displacement control at a rate of 0.005 mm/s. LVDT was fixed on the test set-up to measure the flexural deflection of the specimen. The crack widths were measured just after load released by using a video microscope. The widths of the crack were measured on the tension surface of the beam specimens along the span length. Then from each mixture three pristine and three preloaded specimens were transferred into the freeze-thaw chamber in accordance with ASTM C666 Procedure A, and subjected to between five and six freeze-thaw cycles in a 24 h. period in the unloaded state. After completing the 300 freeze-thaw cycles (F/T), beam specimens were also loaded up to failure under flexural loading and decrements due to frost action in flexural properties were determined.

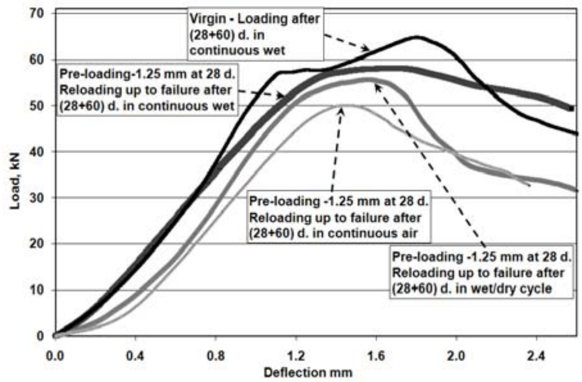
3 RESULTS AND DISCUSSION

3.1 Mechanical properties

In this section, only the mechanical properties of ECC specimens preloaded to a deformation level of 1.25 mm after 60 days of further curing regimes were tested. In Figure 2, the influence of curing conditions on splitting tensile load – deflection behavior of ECC mixtures pre-loaded to 1.25 mm deformation level was displayed for further 60 days of curing after 28 days moist curing. As it is clear from the figure, there was a significant recovery in load carrying capacity, deflection capacity and stiffness within 60 days of further curing implying significant amount of self-healing attainment. The recovery was found to be more pronounced in the case CW and W/D curing conditions compared with CA curing. This result suggests that damp environments are much more influential when marked self-healing is of concern. The occurrence of self-healing was also supported by visual observations during the splitting tensile loading so that at the time of retesting, the failure of ECC specimens was not always initiated from the first cracking points. The probable reason for this trend was primarily correlated with higher amounts of cementitious material and lower W/CM ratio of ECC mixtures that would trigger further hydration reactions in an attempt to seal the microcaracks on the specimens [15,16]. Another reason for marked self-healing in the case of CW and W/D curing conditions can be attributed to the formation of calcium carbonate since moist curing provides much higher concentration of CO_2, both as a dissolved gas and as a bicarbonate solution, than that of the laboratory air curing, where the amount of CO_2 is limited [17]. In the case of air cured specimens, the reason for lower recovery is highly attributable to the widely acknowledged fact that hydration reactions stop when the relative humidity in the hardened cement paste falls below 80% [18].



ECC-1



ECC-2

Figure 2: Effect of curing regimes on splitting tensile load-deflection behavior of ECC mixtures

In Table 3, mechanical properties of ECC specimens pre-cracked to a deformation level of 1.25 mm after 60 days of further curing regimes along with the results obtained after initial 28 days curing were displayed. When the effect of FA content is examined, it can be seen that there is a reduction in ultimate splitting load carrying capacity with pre-deformation level of 1.25 mm so that at the end of 28 days the decrease was around 14% and 7% for ECC-1 and ECC-2 mixtures, respectively. The decrease in the values diminished with further 60 days of moist curing to 9% and 4%. This may be attributed to the higher tensile ductility, tighter crack width and higher amount of unhydrated cementitious material available for further hydration in ECC-2 mixtures. From the observations made, it was, therefore, concluded that the amount of FA is an important parameter in realizing the effects of mechanical pre-loading and self-healing capacity [15].

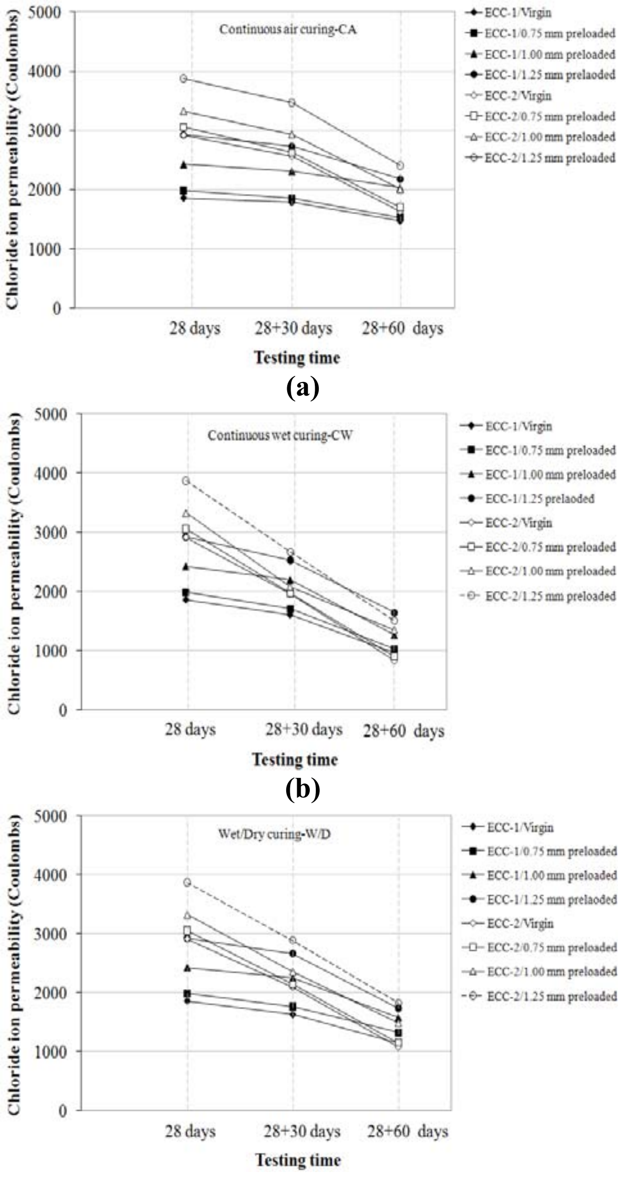
Table 3: Mechanical properties of ECC mixtures under different exposure conditions

Curing Condition		Pre-def., mm	Def. Cap., mm	Ult. Split. Load, kN
ECC-1				
7 days CW + 21 days AC		0.00	1.58	57.6
		1.25	0.77	49.8
28+60 days	CW	0.00	1.46	70.7
		1.25	1.32	64.6
	W/D	1.25	1.21	60.0
	AC	1.25	1.03	51.6
ECC-2				
7 days CW + 21 days AC		0.00	1.73	51.8
		1.25	0.88	48.1
28+60 days	CW	0.00	1.66	63.7
		1.25	1.64	61.1
	W/D	1.25	1.53	56.6
	AC	1.25	1.21	50.2

3.2 Rapid chloride permeability test (RCPT)

As another way of measuring the extent of self-healing under different curing conditions and pre-deformation levels, rapid chloride permeability tests (RCPT) were run on sound and pre-cracked ECC specimens [15]. The results were expressed in terms of the total electrical charge in Coulomb, which provides an indirect measure of the resistance of ECC mixtures to chloride ion penetration. Figure 3 shows the chloride ion permeability changes of ECC mixtures, which were cured in CW (a), CA (b) and W/D (c) at different ages. As seen in figure, chloride ion penetration decreases with time irrespective of the applied further curing conditions. Chloride ion permeability of virgin ECC-1 specimens after 30 days further curing decreased from 1863 to 1610 coulomb under CW, 1863 to 1785 coulomb under CA and 1863 to 1633 coulomb under W/D. For ECC-2, after 30 days further curing, chloride ion permeability decreased from 2921 to 1961 coulomb under CW curing, 2921 to 2567 coulomb under CA curing and 2921 to 2105 coulomb under W/D curing. Decrease in chloride ion permeability of the virgin specimens was much more evident after 60 days further curing. For instance, chloride ion permeability of virgin ECC specimens decreased to as low as 963 coulomb for ECC-1 and 829 coulomb for ECC-2 when exposed to CW, confirm the high resistance of HVFA-ECC to chloride-ion penetration. This means that compared to the results of virgin specimens at 28 days of age, the decrease in chloride ion permeability was around 48% and 72% with the 60 days further CW curing for ECC-1 and ECC-2 specimens, respectively. As also seen in Figure 3, at the end of 28+60 days further curing, chloride ion permeability values of the ECC-2 specimens are nearly equal to or less than that of the ECC-1 specimens' chloride ion permeability values for both virgin and preloaded specimens. As mentioned earlier, contrary to the expectance, with the increase of FA content from 55 to 70% increased the chloride ion permeability of the ECC at the 28 days as a result of inadequate moist curing. However, further 60 days CW and W/D curing, unhydrated cement and FA particles are hydrated, reduced pore sizes and densified the matrix and decreased the chloride ion permeability values of the ECC-2 specimens drastically.

For the different curing regimes, the decreasing trend of chloride ion permeability against curing age can also be seen in Figure 3. As seen in Figure 3 (a), chloride ion charge-testing age slope of ECC-1 specimens was very low and close to zero under the CA curing irrespective of preloading deformation level. However, change in chloride ion charge-testing age slope of ECC-2 specimens was explicit and became more evident when the preloading level increased. For CA curing, chloride ion charge-testing age slope variation of ECC-2 specimens between at 28 and 28+30 days and between 28+30 and 28+60 days was quite different from each other; decrease in chloride ion penetration increased remarkably after 28+30 days.



(a) (b) (c)

Figure 3: Chloride ion changes of ECC mixtures due to different curing regimes and testing ages

In Figure 3 (b) and (c) shows the variation in the chloride ion charge-testing age of ECC under CW and W/D curing regimes. As seen in both figures, for ECC-1, a slight decrease in the slope of chloride ion charge-testing age was observed with the further curing of 30 days due to continued hydration of the cementitious material. In general, there was no meaningful variation in the chloride ion charge-testing age slope due to the applied preloading deformation level; the decreasing trend was fairly similar for ECC-1 specimens. However, for ECC-2 specimens, chloride ion penetration decreasing trend was continuous and drastic without regard to the preloading deformation level. Moreover, the keenest decrease in the chloride ion penetration and the highest chloride ion penetration-testing age slope values were observed at the 1.25 mm preloaded ECC-2 specimens. As mentioned before, increasing the preloading deformation level increased the number of cracks, and so as the number of cracks increases, the recovery of cracks also increases. This means that the more damage experienced in the form of crack numbers, the more opportunity of crack healing the specimen presents. However, the ultimate self-healed condition may not be as complete as in specimens strained to a lower deformation. This is likely due to the probabilistic existence of larger crack widths that limit the amount of self-healing for highly strained specimens. Test results also supports the above mentioned modality, at the end of the 28+60 days CW curing, chloride ion penetration values of the virgin and 1.25 mm preloaded specimens were 963 and 1649 coulomb for ECC-1 and 829 and 1512 coulomb for ECC-2 specimens, respectively.

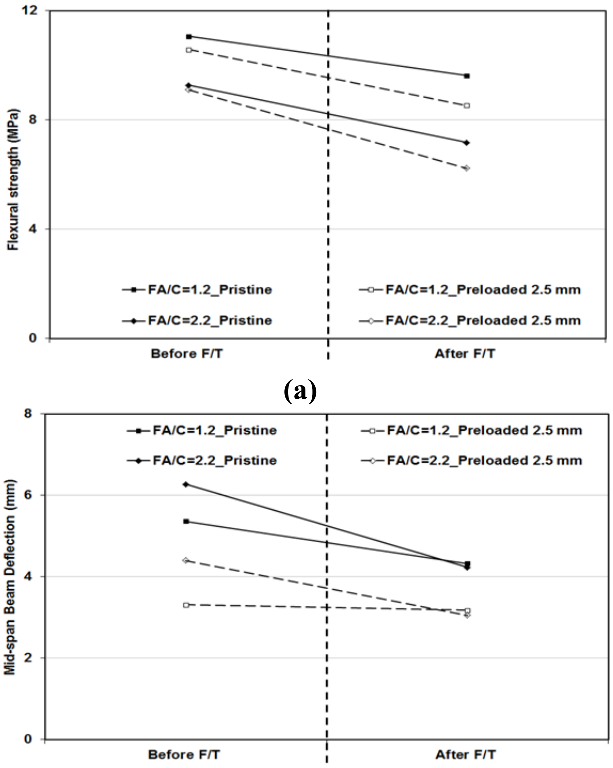
3.3 Frost durability

Table 4 shows the test results of pristine and preloaded ECC specimens in terms of ultimate deflection capacity, flexural strength, stiffness and residual crack width after subjected to 300 freeze-thaw cycles. Each reading represents the average value of three specimens. As seen from Table 4, it is noticeable that both of the flexural strength and deflection capacities of all ECC mixtures reduced due to the 300 freeze-thaw cycles, however, the impression of frost action is considerably low. After subjected to freeze-thaw cycles, under flexural loading, all ECC specimens demonstrate the strain-hardening behavior and multiple cracking. As in the non-frost deteriorated specimens, the first crack started inside the mid-span at the tensile face. The flexural stress increased at a slower rate, along with the development of multiple cracks with small crack spacing and tight crack widths. Micro-cracks developed from the first cracking point and spread out in the mid-span of the flexural beam. Bending failure in the ECC occurred when the fiber-bridging strength at one of the micro-cracks was reached; resulting in localized deformation once the modulus of rupture was approached.

Table 4: Flexural properties of ECC mixtures

Mix. ID		**Pre-def. level, mm**	**Mid-span def., mm**	**Flex Str., MPa**	**Res. CW., µm**	**Flex. Stif., MPa/ mm**
Cured 14 days moist curing	FA_ 1.2	0.0	5.36	11.1	~60	11.1
		2.5	3.31	10.6	~60	8.8
	FA_ 2.2	0.0	6.27	9.3	~40	8.6
		2.5	4.40	9.1	~40	7.6
After 300 F/T cycles	FA_ 1.2	0.0	4.33	9.6	~80	10.7
		2.5	3.18	8.5	~80	8.0
	FA_ 2.2	0.0	4.23	7.2	~80	7.8
		2.5	3.05	6.2	~80	5.7

In Figure 4, the variation of flexural strength and deflection capacity of ECC mixtures before and after subjected to frost action was demonstrated. The results obtained after 300 F/T cycles was found to be surprising so that flexural parameters of virgin and pre-cracked specimens were close to each other implying that mechanical preloading did not have significant effect on the residual mechanical properties. The drop in the flexural strength and mid-span deflection values were fairly close to each other. In the case of virgin and 2.5 mm – preloaded ECC-2 (FA/PC=2.2) specimens the decrease in the mid-span deflection values were 32.5% and 30.6% and these values were 13.0% and 19.4% for flexural strength, respectively. This suggests that slight healing of microcraks took place during freeze-thaw cycles. The probable reason behind this behavior could be in relation with high amounts of cementitious materials present in ECC specimens. During the thawing period, healing of microcracks caused due to mechanical preloading is more likely to take place leading to the development of further hydration processes [19, 20]. Therefore, it can be stated that self-healing in the case of F/T cycles is only valid for pre-deformed specimens. These findings are in line with those discussed in the literature [21, 22]. In literature it was concluded that the formation of re-hydration products in micro-cracks is possible during freeze-thaw cycles. In ECC, the re-healing process is especially aided by the innately tight crack width.



(b)

Figure 4: Variation in flexural parameters of ECC mixtures due to freeze-thaw cycles (F/T)

4 CONCLUSIONS

The influence of self-healing on durability properties was investigated in terms of improvement in mechanical properties, chloride ion permeability test results and frost resistance. For the disturbance of specimens, deformation levels of 0.75, 1.00 and 1.25 mm under splitting tensile loading and 2.50 mm under four point flexural loading were chosen depending on the pre-determined testing procedure. After pre-cracking of the specimens on the specified days, continuous wet (CW), continuous air (CA), cyclic wet-dry (W/D) and cyclic freeze-thaw (F/T) curing conditions were applied. From the results obtained, the following conclusions can be drawn:

1. With the effect of applied further 60 days CW and W/D curing regimes, mechanical properties of the preloaded ECC specimens can be close to, or almost reach to the mechanical properties of the same age virgin specimens cured in damp environment. Preloading deformation affected the chloride ion penetration of the ECC specimens. When the FA content used in the production of ECC is increased, the increase in chloride ion permeation properties is less influenced from the mechanical pre-loading. This may be attributed to the fact that an increase in the FA content in ECC production caused a reduction in the residual crack width from about 70 µm level to 40 µm level.
2. CW and W/D cycles contributed, and speeded up the healing process of the cracks and decreased the chloride ion permeability of the HVFA-ECC drastically, especially at the 28+60 days of age.
3. Mechanical properties of pristine and pre-cracked ECC specimens were found to be quite close to each other after 300 F/T cycles. The main reason for this trend was correlated with the possibility of healing of microcracks during thawing period and higher amounts of unhydrated cementitious materials in ECC systems.

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