GREEN ENGINEERED CEMENTITIOUS COMPOSITES: A DURABILITY POINT OF VIEW

Mustafa Sahmaran (1), Gurkan Yildirim (1), Hasan E. Yucel (1)

(1) Department of Civil Engineering, The University of Gaziantep, 27310, Gaziantep, Turkey

Abstract

Lack of durability has recognized a major concern in construction practices for the past decades. In order for safety requirements to be fulfilled, it is vital to know whether durability needs are ensured or not. One of the most severe concerns in the case of sharp decrease in durability associated with concrete cracking. Concrete may crack throughout the service life of a structure. The presence of cracks influence the mechanical properties and allows for aggressive ions to penetrate into concrete itself and reinforcing bars by creating additional pathways which can lead to further cracking and disintegration in time. Therefore, durability can be associated with the brittle nature of concrete. Engineered Cementitious Composites (ECC) is a special type of high performance fiber reinforced cementitious composites with substantial benefit in both high ductility and multiple micro-cracks as a result of mechanical loadings. In this document, emphasis is placed on the accumulated knowledge on durability performance of high volume fly ash incorporated (green - environmentally friendly) ECC under various types of aggressive environments and mechanical loading. The introduction of materials which provide both high ductility and promising durability can significantly impact the design of future, more durable infrastructures.

Keywords: Engineered Cementitious Composites (ECC); Durability; High Volume Fly Ash, Self-healing.

1. INTRODUCTION

In Design Codes, a service life time of 75+ for concrete structures is now generally required from large public works [1]. But experience has shown that under the combined effects of mechanical loads and environments, many infrastructures begin to deteriorate after only 20 or 30 years [2]. The short service life of concrete infrastructures has significant impacts due to materials production for repair and replacement of deteriorated infrastructure, along with fuel consumption and vehicle emissions from construction related traffic congestion. The poor durability of reinforced concrete infrastructure associated with concrete cracking is one of the main reasons for this short service life of concrete infrastructure [3].
Concrete may crack throughout the service life of a structure. They may be originated from external effects, harsh environment, poor workmanship or due to concrete itself in the case of restraining conditions. The formation of cracks coupled with a lack of crack width control in brittle concrete are primarily responsible for two damaging phenomena; reduce the strength and stiffness of the concrete structure, and accelerate the ingress of aggressive ions, leading to other types of deterioration such as corrosion, alkali-silica reaction (ASR) and freeze/thaw damage, and resulting in further cracking and disintegration [3]. Therefore, durability is vitally important for all structures, and it can be associated with the brittle nature of concrete.

During the last decade concrete technology has been undergoing rapid development. The effort to modify the brittle behavior of plain cementitious materials such as mortars and concretes has resulted in modern concepts of high performance fiber reinforced cementitious composites (HPFRCC). Engineered Cementitious Composites (ECC) is a newly developed HPFRCC with substantial benefit in both high ductility and multiple micro-cracks as a result of mechanical loadings. Yet to prove acceptable for many applications, these materials must show enhanced durability by exhibiting such characteristics as excellent protection of steel reinforcement, resistance to freeze/thaw cycles with/without de-icing salts, fire resistance, promising transport properties even in the presence of microcracking and demonstration of long term mechanical performance. In this article, emphasis is placed on the accumulated knowledge on durability performance of high volume fly ash (HVFA) incorporated ECC under various types of aggressive environments and mechanical loading.

1.1 Significance of Fly Ash in the Production of ECC

Lately, there are increasing concerns related to raw material depletion, global warming and climate change with the exponential growth of human population and industrialization. Because of these reasons, there is a growing trend to use industrial by-products as supplementary materials in the production of conventional, high-performance and high-strength concrete mixtures. Among the various supplementary materials, fly ash (FA) is one of the most commonly available mineral admixtures.

In production of ECC, the absence of coarse aggregates results in higher cement content. Therefore, partial replacement of cement with FA can lower the material cost, reduce environmental burden and enhance its greenness, since the production of these materials needs less energy and causes less CO₂ emission than cement. Additionally, improved workability, reduced heat of hydration and cracking at early ages, enhanced mechanical and durability properties especially at later ages can also be counted as the beneficial effects of FA. More recently, FA has become what some consider a necessary component of ECC. Recent studies have indicated that increasing the amount of FA (up to 85% replacement by weight of cement content) in HVFA-ECC tends to improve robustness of tensile ductility while retaining a long-term tensile strain of approximately 3% [4]. Moreover, it has been observed that with an increase of the FA amount, the crack width is reduced from about 60 µm level to 10-30 µm level or sometimes even lower than 10 µm level, which may benefit the long term durability of HVFA-ECC structures.
2. TRANSPORT PROPERTIES

2.1 Salt Ponding and Chloride Diffusion

The corrosion of steel in concrete is one of the major problems with respect to the durability of reinforced concrete structures, and the penetration of chloride ions into concrete is considered to be the major cause of corrosion. Along this line, Sahmaran and Li conducted ponding tests on ECC specimens containing different amounts of Class-F FA in order to observe the effects of mineral admixture replacement rate on the chloride diffusion [5,6]. According to their research, two different ECC mixtures were investigated namely ECC-1 and ECC-2 having FA-Portland cement ratio (FA/PC) of 1.2 and 2.2, respectively. Specimens that were pre-loaded to different deformation levels under four-point bending loading exposed to NaCl solution for 30 days. As a result, it was concluded that, the crack width of all specimens even at large imposed deformation level was lower than 50 μm, while the number of cracks on tensile surface of the ECC specimens increased. Figure 1 shows the relationship between the effective diffusion coefficient of chloride ions and the beam deformation level for ECC specimens. As seen from the Figure 1, the effective diffusion coefficients of ECC-1 increase at a steady rate with the imposed deformation value (or number of cracks), which is in agreement with research findings by Konin et. al [7]. On the other hand, for the higher deformation level (>1 mm), the effective diffusion coefficients of ECC-2 increase suddenly at higher deformation levels. It is speculated that this sudden increase in effective diffusion coefficient of ECC-2 is associated with the increase in the number of extremely tiny cracks, which were not detected during cracks characterization due to their closing on specimen unloading. Since the micro-cracked specimens are almost dry when they are first exposed to salt solution in accordance with AASHTO T259, the presence of even almost closed tiny cracks may affect the chloride penetration significantly because of capillary suction.

![Figure 1: Effective diffusion coefficient versus pre-loading beam deformation level](image)

Compared to PC mortar (Figure 1), the reason for the relatively low effective diffusion coefficient of cracked ECC specimens is not only due to the tight crack width but also the presence of self-healing of the microcracks. Microcracks of ECC can be easily closed by a self-healing process even after exposure for 30 days to NaCl solution [6,8]. The observed self-healing in ECC can be attributed primarily to the large FA content and relatively low water to binder ratio within the ECC mixture [6,8]. Moreover, even though ECC-2 (FA/PC=2.2) has
tighter crack width compared with ECC-1 (FA/PC=1.2) specimens, the effective diffusion coefficients of ECC-2 for the virgin and micro-cracked specimens were observed to be higher than that of ECC-1 specimens, at given beam deformations. Normally, it is accepted that increasing FA content is an effective means for reducing the coefficient of effective chloride diffusion due to both its chloride binding effect and pore refinement [9]. These benefits, however, are usually manifested at later ages with little improvement being observed after ages of 28 days or so [10].

2.2 Absorption

Transport of liquids in porous solids due to surface tension acting in capillaries is called water absorption. Absorption is related not only to the pore structure, crack density and crack size, but also to the moisture state of the concrete. Since concrete structures in exposed conditions are generally subjected to the drying actions of wind and sun, they are rarely fully saturated when in service. Under dry or partially saturated condition, permeability and diffusion may not be the dominant transport processes in concrete materials, but capillary suction or absorption is [11]. The relationship between tight crack width and capillary suction indicated that the water absorption increase is fairly high as the number of cracks on the surface of the ECC specimens increases implying that micro-cracked ECC specimens would be more vulnerable to attack than virgin specimens [12]. Therefore, to determine how load-induced micro-cracks of ECC affect the capillary suction, sorptivity test was conducted by Sahmaran and Li [6,12]. Two mixtures employed were ECC-1 and ECC-2 with FA/PC ratios of 1.2 and 2.2, respectively. In Figure 2, the relationship between the sorptivity over six hours and the number of cracks, for ECC specimens was shown. As seen from Figure 2, the presence of micro-cracking in ECC significantly alters the transport properties measured as a function of the number of micro-cracks. The water absorption increase is fairly high as the number of cracks on the surface of the ECC specimens increases. As the number of cracks along the specimen grows, the sorptivity of ECC increased exponentially. It should be noted that because of the closing of many tiny cracks in the unloaded stages, the crack number, especially in the case of the pre-cracked ECC-2 specimens, is likely undercounted. As a result, the correlation between the crack density and sorptivity value may be different, and therefore should be interpreted with care.

![Figure 2: Sorptivity versus number of crack](image-url)
2.3 Rapid Chloride Permeability Test (RCPT)

Misra et al. [13] have shown that chloride permeability as measured from RCPT can be used for quality control of concrete. It can be stated that, the total charge passed, in coulombs, is related to the ability of ECC specimens to resist chloride ion penetration. Sahmaran and Li have shown in their work that increasing FA content from 55 to about 70% reduces the resistance to chloride-ion penetration of ECC [6]. The data given in that study exhibited that standard ECC mixture (FA/PC=1.2) showed excellent resistance to chloride ion penetration with the total charge exceeding 501 coulombs at the age of 28 days while this value was increased to 1178 coulombs for ECC-2 (FA/PC=2.2) specimens. This trend is in stark contrast to that observed from previous studies; HVFA (up to 70%) can considerably improve the performance of concrete in terms of reduced chloride-ion penetration according to ASTM C1202 test method. The reason for the observed lower resistance to chloride ion penetration in the case of ECC-2 may be attributed to the fact that specimens were cured in air after 7 days sealed curing, and because of lack of curing, most of the FA particles in the matrix remain without any chemical reaction. Since ECC-2 has more FA content than ECC-1, it has been more negatively affected by the lack of curing. The benefits of using Class-F FA in concrete in terms of improved durability properties such as chloride-ion penetration resistance is usually manifested at later ages with the continuous supply of moisture [14].

3. FROST RESISTANCE WITH/WITHOUT DE-ICING SALTS

It is well known that the cyclical freeze-thaw cycles and the use of de-icing salts during winter are two of the major causes of rapid degradation in concrete pavements, bridge decks, parking structures, and similar structures. ECC used for this kind of structures must be resistant to cyclical freezing and thawing, and the effects of de-icing agents. It is known that a proper air-void system is generally needed in normal concrete to avoid internal cracking due to freeze-thaw cycles and scaling due to freezing in the presence of deicer salts.

Due to HVFA content used in the mixtures as in the scope of this paper, it is important to test the performance of ECC exposed to freezing/thawing cycles in the presence of de-icing salt. Salt scaling resistance of non-air-entrained sound and mechanically pre-loaded ECC specimens was evaluated by Sahmaran and Li in accordance with ASTM C672 [15]. As a result, the ASTM C 672 scaling test results non-air-entrained sound ECC made with HVFA performed satisfactorily. For the sound ECC specimens, scaled-off particles less than 0.40 kg/m² were determined. For the pre-cracked ECC specimens, the magnitude of beam deformation level was found to have little detrimental effect since even for a 2 mm beam deformation level, very good salt scaling resistance was obtained. Only the mass of scaling residue of ECC mixtures with FA/C ratio of 2.2 and beam deformation value of 2.0 mm exceeded the 1 kg/m² acceptable limit in this severe scaling test.

The field performance of ECC generally indicates that it has a good frost resistance, however, it is also important to have an understanding on the frost durability of HVFA-ECC mixtures with tighter crack widths. To account for this, Sahmaran et al. have conducted a research to assess the effect of FA and micro PVA fibers on the microstructure and frost durability of the non-air-entrained ECC [16]. In this study, ECC mixtures with two different FA to cement (FA/C) ratios (1.2 and 2.2) were prepared. To determine the effect of PVA fibers and ductility of ECC, ECC matrix mixtures of the same composition but without PVA fibers were also produced and tested for the frost resistance. Based on experimental results, it
was concluded that although the control ECC matrix mixtures specimens rapidly failed in freezing/thawing cycles (after 60 cycles, the ECC-2 matrix (FA/C=2.2) specimens and after 210 cycles, the ECC matrix (FA/C=1.2)), both ECC mixtures showed excellent performance when exposed to freezing/thawing cycles, even after 300 cycles. Increasing levels of FA lead to higher reductions in the mechanical performances compared with standard ECC mixture due to the lower maturity – lower compressive strength at the time of testing. Apart from the slight reductions in ductility and strength capacities and higher residual crack width, the results presented in this study largely confirm the durability performance of ECC material incorporating HVFA under frost exposure.

4. FIRE RESISTANCE

HVFA-ECC has been adopted in North America, Europe and Asia for high-rise buildings, bridges, tunnels, highways, and other forms of infrastructures. Fire remains one of the main threats to reinforced concrete structures, and the increasingly intensive use of HVFA-ECC in construction industry makes it necessary to fully understand the effects of fire on it. It has been pointed out in the author’s another work that “standard” ECC mixture (FA/PC=1.2) has acquired similarly or better performance than those of plain concrete and fiber reinforced concrete after exposure to high temperatures [17]. The influence of HVFA and PVA fiber on the fire and spalling resistance of ECC mixtures was also studied by Sahmaran et al. to observe the effects of FA replacement ratios in the case of high temperature exposures [18]. The outcomes of this study indicated that when exposed to high temperatures up to 400 °C, the residual properties of ECC mixtures regardless of FA replacement ratio drop slightly, followed by minimal microcracking on the surface, when compared to values obtained from unheated specimens. Increasing FA content from 55 to about 70% provide ECC with better residual mechanical properties after exposure to temperatures from 200 °C to 600 °C. Thus, it may be feasible to increase the allowable “working” temperature for ECC by incorporating a HVFA into mixes, which means that a larger proportion of structures exposed to high temperatures can remain serviceable. On the other hand, the effect of the addition of FA diminished when the exposure temperature was raised to 800 °C.

5. UNIAXIAL TENSILE BEHAVIOR

5.1 Under High Alkali Exposure

One of the most important environments that could affect the microstructure and composite properties of ECC is a high alkaline environment. In addition to high alkaline matrix pore water solution, ECC can come into contact with alkaline media through interaction with a variety of alkaline chemicals, soil (or solutions diffusing through soil) and sea water. Even though no deleterious expansion has been expected due to alkali silica reaction because of the high volume fly ash (HVFA) content, small sand particle size and micro-fibers in ECC [19], durability of HVFA-ECC must be evaluated under high alkaline environments. Alkalis will penetrate through micro-cracks or even the uncracked matrix that could lead to modifications in the material microstructure and hence changes in the composite properties. Sahmaran and Li investigated the durability of HVFA-ECC under highly alkaline environment [6,19]. According to results taken from their study, the tensile strain capacity of sound and pre-cracked ECC specimens exposed to 1 N NaOH solution at 38°C for 90 days averaged between 2.44% and 2.80% for ECC-1 (FA/PC=1.2) and 2.07% and 2.79% for ECC-2 (FA/PC=2.2),
respectively. Increasing levels of FA led to higher reductions in the tensile strain capacity compared with standard ECC mixture. The reduction in tensile strain capacity of ECC specimens stored in NaOH solution at 38 °C compared with ECC specimens cured in laboratory air may be attributed to changes of the fiber/matrix interface. In the case of higher FA content (ECC-2), alkalis may more easily penetrate through matrix because of lower matrix strength and compactness especially at early ages, and that could lead to more modifications in the material microstructure and hence changes in the composite properties. Despite a reduction in ductility, however, both of the ECC mixtures after 90 days of alkali solution exposure are found to retain tensile ductility at least more than 200 times that of normal concrete and FRC with no environmental exposure.

5.2 Under Sodium Chloride Exposure

ECC structural members may be exposed to marine environments (referred to as NaCl solution for this study) and NaCl solution will penetrate through micro-cracks or even the uncracked matrix that could lead to modifications in the material microstructure and hence changes in the composite properties. Due to the delicate balance of cement matrix, fiber, and matrix/fiber interface properties, the strain capacity of ECC may change under marine exposure conditions. Therefore, the durability of composites (fiber plus matrix – ECC) must first be evaluated before it can be used in real field conditions. This concern is addressed directly in the study conducted by Sahmaran and Li by measuring the tensile properties of virgin and pre-cracked HVFA-ECC materials in presence of NaCl solution [6,20]. Based on the results of this study, the specimens (pre-cracked and uncracked) stored in NaCl solution showed a slight reduction in ultimate tensile strength over the 180-day exposure period regardless of FA/PC ratio which may be attributed to the effects of damage on the fiber/matrix interface due to immersion of humid environment. The other reason of slight reduction in the tensile strength of ECC specimens when exposed to NaCl solution may be attributed to the effects of leaching of calcium hydroxide from the specimens. Water not saturated with calcium hydroxide may affect test results due to leaching of lime from the test specimens. Moreover, for uncracked specimens, tensile strain capacity was found not to be affected up to 90 days of NaCl exposure and for the pre-cracked specimens, exposure to NaCl appears to be similarly affected such that the influence of pre-cracking even up to 1.5% for ECC-1 (FA/PC of 1.2) and 2.5% for ECC-2 (FA/PC of 2.2) does not exacerbate the deterioration. However, after 180 days NaCl solution exposure period, both uncracked and cracked specimens showed a reduction of up to 30% in their tensile strain capacity, but their tensile strain capacity were still higher than 2%. Both of the ECC mixtures showed also almost the same percentage of reductions in terms of tensile properties, and therefore, the increase in the FA content did not change the behavior of ECC specimens exposed to continuous NaCl solution.

6. CONCLUSION

The results found in the studies summarized in this paper largely confirm the durability performance of HVFA-ECC material under accelerated aging (exposure to freeze-thaw cycles with/without de-icing salts, continuous sodium hydroxide at 38 °C and sodium chloride solutions at room temperature (marine environment), and humid environment) even in cases where the material experiences mechanical loading that deforms it into the strain-hardening stage prior to exposure. It may be possible to further extend FA volumes in ECC production. However, it is important to note that there is likely to be an upper limit, beyond which
compressive strength of HVFA-ECC cannot reasonably match that of structural concrete, and there is no further benefit with respect to its durability properties.

REFERENCES


