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Engineered Cementitious Composites for Modern Civil Engineering Structures in Hot Arid Coastal Climatic Conditions

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Abstract

Engineered Cementitious Composite (ECC) is an exclusive type of cement mixture with unique composition of low volume fibers and different composites so as to impart high ductility, high tensile strength besides ability to repair. Conventional concrete and fiber reinforced concrete has brittle nature and hence crack easily under environmental and mechanical loads affecting durability of structures. Efforts to modify the brittle nature of conventional concrete resulted in development of ECCs offering durability under a broad range of environmental exposure, low embodied energy, and negative carbon footprint making it environmentally sustainable construction material with self–healing potential. ECCs demonstrate tight crack width and development of these cracks in fact increase ability of ECCs to resist effects of hot, frost and humid weather conditions besides its low permeability coefficient and higher resistance to steel corrosion compared to other common substitutes. The paper attempts to discover suitability of ECC in a typical hot arid coastal region experiencing extreme harsh climate. It bear upon an in depth review to investigate potential of ECC, influence on pertinent engineering properties and its impact on construction industry in hot arid coastal climatic conditions.

Keywords: ECC; Composites; Durability; Self-healing; Sustainability.

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1. Introduction

The advances of sustainable construction and the green building movement of past decade have encouraged detailed assessment of construction practices and building materials. Globally, a number of sustainable initiatives emphasize on development and procurement of green materials, design of low energy demanding materials, procedures and construction practices that result in requiring lesser resources and energy and produce minimum waste. One such recent exploration in this realm has been development of Engineered Cementitious Composites (ECCs). ECCs are designed to produce a strong and ductile material that can be used in several applications where fiber reinforced concrete may not be appropriate. Generally, brittleness of concrete increases with increase in compressive strength, which is a potential restriction on the use of high strength concrete in structures. The advent of ECCs envisaged development of highly ductile cementitious materials as valuable constituent for structural and infrastructural applications having characteristics of high strength concrete besides increased tensile strain capability compared to normal or fiber reinforced concrete. Many studies focusing mechanical characteristics like residual strength, stiffness, and strain hardening of ECCs and its self–healing capabilities are carried out either in natural environmental exposures to very mild conditions where temperatures typically range from -14 to 28°C or at elevated temperatures of the order 200°C to 800°C or [1, 2, 3]. The structural characteristics of ECC in a hot arid coastal region with extreme harsh environmental conditions such as varied temperature range and humidity conditions has not been thoroughly explored. The paper presents an in depth review to investigate potential of ECCs, influence on engineering properties, and its impact to construction industry in such environmental conditions. The paper is not meant to be an exhaustive literature review of the subject matter but instead focuses on showing the diversity and breadth of this versatile and integrative material intersecting construction industries in hot humid coastal areas where temperatures remain above 45°C and humidity averaging over 90% for many days during summer, while round the year humidity averages between 50% and 60%.

Concrete is the most widely used structural construction material causing significant social, economic and environmental impacts. Globally, cement production accounts for 5% of greenhouse gases and various pollutants like significant levels of NO_x and particulates in to atmosphere [4]. It is therefore crucial that a sustainable and durable construction material like ECCs should be effectively used in any given environmental conditions so as to synergize a sustainable interaction between natural and built environment. ECCs have been identified as material greening component with overall goal of improving environmental sustainability. ECCs are high–performance fiber reinforced cementitious composites designed to resist large magnitudes of tensile and shear forces while remaining compatible with ordinary concrete in almost all other aspects such as volume usage, compressive strength and thermal properties.

2. Durability of ECC in hot and humid environments

Freeze–thaw tests are generally designed to simulate temperature changes in winter conditions. A study by Lepech and Li [5] included freeze–thaw exposure as per ASTM C666A [6] on companion series of ECC and normal concrete specimens – both without any air entrapped, as concrete durability is considered to be very sensitive to amount of air entrainment. These tests evaluated the effect of freeze–thaw conditions on strain capacity of composites. The performance resulted in a durability factor of 10 for concrete compared to 100 for ECC with both sets of specimens exhibiting a strain capacity of approximately 3%, well above the capacity needed by most structural applications.

To examine long term effects of hot and humid environments, Li et al. [7] included hot water immersion tests on the specimens. The effects were comprehensively examined on individual fibers, single fibers embedded in ECC matrix, and composite ECC specimens. These specimens were cured for 28 days at 60°C prior to hot water immersion for 26 weeks. After 26 weeks a small difference was seen in fiber properties such as strength, modulus and elongation. Interfacial properties, however, experienced significant changes, particularly between 13 and 26 weeks. During this time the chemical bonding between fiber and matrix increased, but the fiber apparent strength decreased. A drop in interfacial strain capacity from 4.5% at 13 weeks to 2.75% after 26 weeks of hot water immersion was seen. Hence, it was concluded that 2.75% of strain capacity (nearly 250 times greater than concrete) as seen after 26 weeks of accelerated conditioning, which can practically be considered equivalent to 70 years of hot and humid exposure is acceptable for almost any structural application. As a result, it should be noted that ECC exhibits exceptional behavior under freeze–thaw cycles, hot–cold temperature cycles, carbonation exposure, fatigue loading and long term mechanical performance.

Concerning the durability of fibers itself, Horikoshi et al. [8] studied durability of polyvinyl alcohol (PVA) fibers in cementitious alkaline water environment at elevated temperatures ranging from 20–70°C. The study recommended a threshold temperature of 50°C, as below this temperature fill strength is retained and predicted to be maintained at more than 95% over 100 years, but beyond this threshold tensile strength loss was evident. Magalhães et al. [9] studied thermal durability of PVA fibers subjected to temperatures ranging from 90°C to 250°C. Figure 1 show tensile strength of PVA fibers as a function of exposed temperature. It was observed that after initial heating up to 90°C tensile strength reduced approximately by 8%. The figure clearly shows that as peak temperature increases from 90 to 145°C tensile strength drop to approximately 83% compared to unheated reference samples. For samples subjected to temperatures in the range of 220-250°C the deterioration was quite significant. PVA fibers at 250°C melted and therefore tensile tests could not be performed.

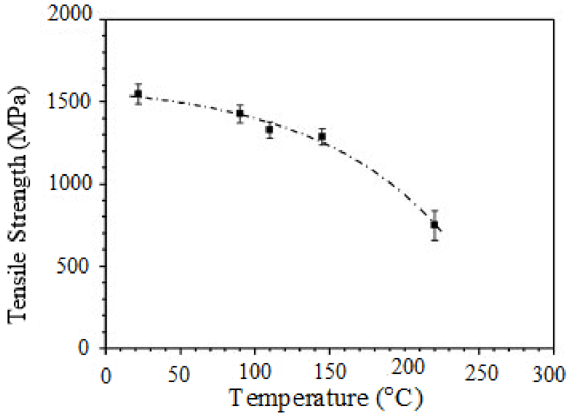

Fig. 1. Tensile strength of PVA fiber at various temperatures [9]

3. Permeability and Crack Resistance of ECC

It is well known that freeze–thaw cycles and the use of deicing salts during winter are two major causes of rapid degradation due to formation of cracks in concrete pavements, bridge decks, parking and similar structures. A proper air void system is generally needed in normal concrete to avoid internal cracking resulting from freeze–thaw cycles and scaling due to freezing with deicing salts. Lepech and Li [10] examined effect of crack width (CW) and crack frequency on durability of reinforced mortar and ECC as quantified by water permeability – an ability that protect steel reinforcement from corrosion continuously.

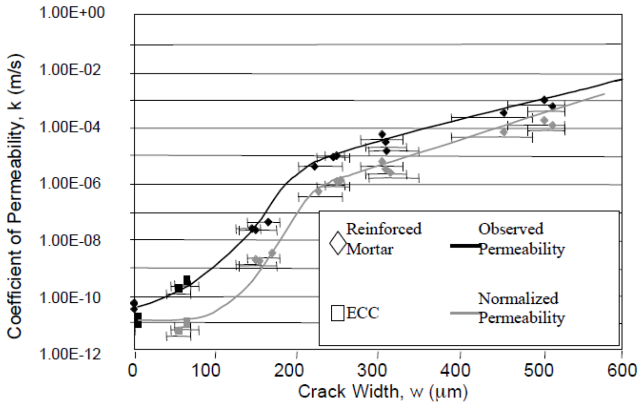

Fig. 2. Coefficient of permeability vs. crack width for ECC and reinforced mortar [10]

As it is generally agreed that regardless of effect of CW on corrosion rate, limiting the ingress of water, deicing salts, aggressive soil conditions and usage of sea water will improve durability of any concrete structure. It was observed that irrespective of strain level, ECC specimen with self-controlled crack widths averaging 60μm demonstrate nearly the same permeability as sound concrete, even when strained in tension to several percent as seen in Figure 2. In this study both ECC and reinforced mortar specimens were stretched to identical 1.5% deformation resulting in variety of crack widths and number of cracks among various specimens. It can be clearly seen that there is a drastic rise in permeability with increasing CW and also a comparable permeability of cracked ECC with referred sound material become more apparent. In contrast, cracks larger than 150μm were produced in reinforced mortar specimens. These larger crack widths result in significant increase in water permeability of reinforced mortar despite smaller number of cracks.

4. Self–healing characteristics of ECC

Structures exposed to the natural environment are vulnerable to cracking mainly because of excessive loading, restrained shrinkage, and harsh weather conditions. Cracks influence durability of concrete by allowing penetration of hazardous agents in concrete or steel reinforcement bars resulting in reduced stiffness loss of water-tightness. Studies have shown that cracked concrete has ability to heal itself over time when in contact with water, however healing of concrete is a complex process involving several chemical and physical mechanisms [7]. The magnitude of self–healing in cracked concrete depends on CW, with smaller cracks healing faster compared to large cracks. Thus specimens with small CWs may heal completely, increasing the durability resulting mechanical properties of the damaged material. Granger et al. [11] studied self-healing of cracks having width between 5μm and 15μm through mechanical tests on prismatic beams of size 50x100x500 mm^3. The ultra-high performance concrete specimens in this study were cured for 2 days at 20°C and 100% relative humidity to assess the behavior in hot and humid environment. The study included four different periods of ageing after pre-cracking phase. Table 1 shows evolution of gain in stiffness for different ageing periods in water. It was noticed that consequences of self-healing are more important for longest periods of exposure to water. Beams after 10 weeks of storage in water recovered their initial stiffness as the new hydrates with stiffness equivalent to hydrates from normal hydration process have crystallized in cracks decreasing even the length of the crack.

Table 1. Evolution of average reloading stiffness of healed concrete with time of storage in water (Granger et al, 2007).

Un-cracked Specimen	Specimen stored in water for			
	1 week	3 weeks	6 weeks	10 weeks
0.307kN/mm	0.209 kN/mm	0.283 kN/mm	0.301 kN/mm	0.306 kN/mm

Yang et al [12] studied magnitude of self–healing in ECCs exposed to different environments and found that crack damaged specimen show effective self–healing when subjected to wet–dry cycles. The study also discovered that resonant frequency (RF) recovery can be used as a method to quantify healing process of ECCs as it was directly proportional to recovery of mechanical properties. The study used RF to verify if self–healing was taking place, however the study did not look at chemical and morphological categorization of healing products. Kan et. al. [13] carried out classification of self–healing products in ECC materials using an environmental scanning electron microscope equipped with an energy dispersive spectroscopy and other microscopy equipment like X-ray diffraction and analytical electron microscope. The cyclic outdoor environment such as rainy days followed by clear days was simulated by immersing the ECC specimens of size 300x76x12.5 mm^3 in water at 20°C for 24 hours and then drying same specimens in air at 20±1°C (relative humidity of 50±5%) for 24 hours. The water was replaced during each cycle to avoid leached calcium deposits. The experimental results of the study suggest that ECC with benefits like self–controlled CW and high-tensile ductility has many characteristics contributing towards its self–healing behavior. Wet–dry cycles resulted in self–healing of ECCs shown by rapid RF recovery after four to five cycles, and RF recovery was found to be more than 90% at 2% imposed tensile strain after 10 wet–dry cycles. The study identified self–healing products for different CWs – fiber like calcium–silicate–hydrate for CWs of 15μm and stone like $CaCO_3$ for CWs of 30μm was reported as main self–healing product. CW of less than 50μm showed quick and almost complete self–healing due to hydration and formation of $CaCO_3$ crystals. Herbert and Li [1] investigated self–healing behavior of ECCs subjected to extreme environmental conditions including rain, snow and temperatures from -14 to 28°C for damaged specimens to their 0.5% tensile strain. The study quantified the rate and extent of self–healing products using uniaxial tensile tests and RF measurements. It was found that specimens recovered up to 90% of their original, pre-damaged RF values, and up to 31% and 68% of their initial stiffness after one and three months of exposure respectively . To measure extent of recovery specimens were reloaded after healing until failure and stiffness of specimens was recorded. Majority of healing products in cracks with width less than 10μm and up to 20μm were found. Although self–healing in the natural environment is quite likely, it was not that significant as observed under controlled laboratory conditions, as healing products can wash out easily in natural environment. In an extended study Herbert and Li [14] reported that stiffness, level of RF and first cracking strength recovery increases as duration of exposure of specimen to natural environment increases. Specimens undergoing multiple damage cycles showed level of recovery highly depending on average atmospheric temperatures and amount of rainfall between each damage. In this study all ECC specimens were exposed to natural environment for different time periods up to a period of one year recovered 95% to 105% of original RF values. For specimens that experienced multiple loading cycles, the extent of RF recovery decreased after each loading cycle. However, even after the third damage cycle the specimens strained to 0.5% were still be able to recover 88% and specimens strained to 1% recovered 84% of the RF value of control specimens. To address lack of information related to self–healing especially in case of multiple overloading conditions and to verify if it takes place in entire structure or is limited to certain areas Şahmaran et al [15] carried out experimental study on ECCs coupled with multiple micro crack formation under mechanical loading based on two basic toughness measures – repeatability and pervasiveness. The study observed that RF recovery rates were lower at middle portions of specimens compared to measurements taken from the surfaces probably because of difficulty in having moisture diffuse across longer distances. Even under repeated loading conditions, the self-healing mechanism is widely distributed over the entire area of the specimens rather than being limited to some specific portion(s). However, the self-healing was more prominent on a surface with easy exposure of cracks to water.

Several experimental studies show that ECCs can automatically regain their loss of performance resulting from cracks due to inherent phenomenon of autogenous healing. However, it should be noted that high temperatures may lead to damage and formation of micro-cracks during self-healing resulting in slower healing within a given specimen. High temperatures during self-healing can also lead to increase in ultimate strength and slight decrease in capacity of strain-hardening of ECC due to rapid but incomplete hydration of unreacted cement and fly ash. Overall, these studies propose that under certain environmental conditions, self-healing could be useful in real-life structures irrespective of age of specimen although more detailed studies are needed on the related topic.

5. **Mechanical Characterization of ECC**

ECC has been considered as a promising material for wide range of applications including structure repairs, seismic activity resistance, impacts and blasts due to their ultra-ductile, strain hardening, and high strain capacity behavior when subjected to tensile loading. ECC represents a family of materials with different functionalities. Self-consolidating ECCs are designed for large scale on site construction applications [16, 17,] high early strength ECC is designed for applications requiring rapid strength gain in transportation infrastructure [18], and light weight ECC is designed for applications where dead load of structural components needs to be minimized [19]. A summary of significant mechanical properties of ECC is given in Table 2. Much broader range of properties can also be expected through used of micromechanics tools.

Table 2 Mechanical Characteristics of ECC (Li, V.C., 2008).

Compressive Strength (MPa)	First Crack Strength (MPa)	Ult. Tensile Strength (MPa)	Ult. Tensile Strain (%)	Young's Modulus (GPa)	Flexural Strength (MPa)	Density (g/cm^3)
20 – 95	3 – 7	4 – 12	1 – 8	18 – 34	10 – 30	0.95 – 2.3

The compressive strength properties of ECC are not significantly different from normal to high strength concrete for compressive strength ranging from 30MPa to 90MPa with elastic modulus of the order 20–25GPa typically lower than concrete due to absence of coarse aggregates in ECC and compressive strain capacity of ECC is slightly higher around 0.45–0.65%. The tensile ductility of ECC is proven by its flexural response. A flexural strength in terms of modulus of rupture of 10–15 MPa is easily achievable and accompanied by a large extent of deflection hardening regime being an intrinsic property of ECC and not depending on geometry making it suitable for any shape of structural member.

Shang and Lu [20] studied impact of high temperature up to 800°C on compressive strength of ECC. This study followed two different cooling regimes – quenching in water and cooling in air. Figure 3 shows ratios of stiffness, strength and displacement of specimens subjected to high temperature to those of the control (or unheated) specimens. Residual compressive strength of ECC specimens was substantially influence by exposure to high temperatures; specimens showing increased 28–day compressive strength by 1% after being exposed to 200°C, while mean compressive strength decreased by 32% after exposure to 400°C. Beyond 400°C compressive strength dropped drastically by 62% and 77% at 600°C and 800°C, respectively. From Figure 3 it can also be seen that stiffness of post fire specimens shares a similar but more sensitive tendency with exposure temperatures. The mean compressive stiffness of ECC specimens increased by 0.5% after exposure to 200°C, while it decreased by 46%, 78%, and 85% respectively after exposure to 400, 600, and 800°C. The cooling regime of quenching in water helped the strength and stiffness recovery.

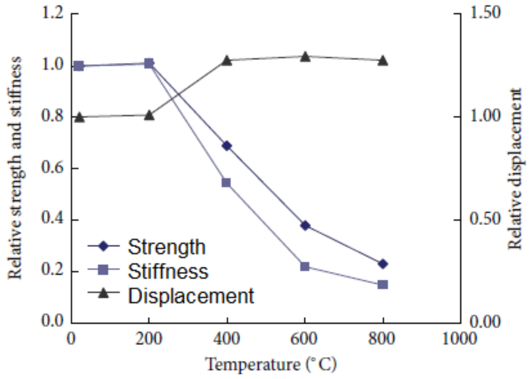

Fig. 3. Compressive strength, stiffness, and displacement at peak load with temperature (Shang and Lu, 2014)

Yu et al [21] also reported that cooling routines have a considerable influence on mechanical properties of post fire ECC specimens. Zhou et al [22] carried out uniaxial compressive tests on PVA fiber reinforced ECC with five different mix proportions and compressive strength ranging from 35 to 60MPa to obtain compressive parameters such as elastic modulus, engineering strain at peak stress, the Poisson's ratio and the toughness index. It was observed that with addition of PVA fibers, ECC becomes more ductile than mortar and the failure mode changes from brittle splitting to ductile shear failure. The elastic modulus of ECC increase with compressive strength, however strain at peak load had a little correlation with compressive strength. The study also proposed a new constitutive model to predict response of ECC under uniaxial compression. However, it should be noted that compressive strength of ECC increases with increasing fiber content requiring an optimum dosage as it starts decreasing with increase in fiber content.

6. Impact of ECC on construction industry

Construction activities propagate environmental pollution worldwide with CO_2 being prominent atmospheric pollutant causing climatic change. Over last decade, ECCs have emerged in full scale civil infrastructures – transportation, building, water and energy industry domains. ECCs have been used as cast in place with self-consolidation fresh property and in precast structural elements for both new and existing structures that require repair or retrofitting. Figure 4 shows a bridge deck with ECC link slab replacing a conventional expansion joint that typically requires frequent repairs in Michigan (USA) as it suffers severe weather conditions (freeze–thaw cycles in winter). ECCs with large deformable characteristics act like an expansion joint when deck needs to expand or shorten due to temperature change enhancing its service life. This link slab required a tensile strain value over 2% that normal or high strength concrete cannot withstand without fracture [23]. This ECC link slab provides an opportunity to study infrastructure sustainability as an advanced construction material is introduced.

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Fig. 4. ECC link slab in bridge deck replaces conventional expansion joints – Michigan (USA) [23]

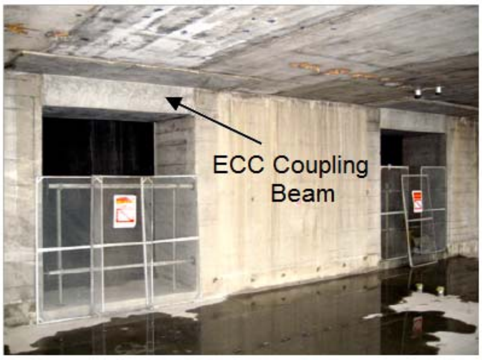

Fig. 5. ECC coupling beams for a 60-story reinforced concrete building – Osaka (Japan) [24]

Figure 5 shows use of ECCs in coupling beams for a 60-story reinforced concrete building located in Osaka Japan experiencing varied temperatures, humidity and rainfall. The high tensile ductility of ECC coupling beams enhance seismic safety and durability by absorbing energy during an earthquake [27].

Thus, the illustrative field applications of ECCs have different motivations–reducing maintenance cost and enhancing safety under natural hazards demonstrate wide applicability of this new ductile concrete.

Conclusions

Concrete is an extremely essential component of today's world being used in every structure in many different forms. Due to comparatively brittle nature of normal and fiber reinforced concrete not much can be done in terms of high tensile strain and load bearing applications. ECCs cater to these particular aspects and prove more beneficial in structural applications due to their distinct and diverse characteristics like self-healing capability, low permeability, high ductility and tensile strength besides being environmentally sustainable. The present paper demonstrates suitability of ECC in a hot arid coastal region having extreme harsh climate in terms of varied temperatures and humidity conditions by examining relevant experimental studies on durability, permeability, crack resistance, self-healing capabilities and vital mechanical characteristics like compressive and flexural strength of ECCs. The performance of ECCs is found to vary depending on ingredients and composition, heating rate and time, curing conditions and specimen types. However, this information is crucial as cracking and spalling under high temperature are induced by internal tensile stresses as many studies have established that tensile strength and strain capacity of ECC deteriorate under elevated temperatures of the order 200°C or little lower, due to degradation in fiber/matrix interferential properties. Compressive strength of ECC shows no reduction, it becomes more ductile under uniaxial compression, however failure mode changes from ductile 45 degree shear plane failure to brittle splitting crack failure. The elastic modulus of ECC is lower than concrete of same strength due to lack of aggregates. Durability performance as verified by various studies through interpretations on water ingress by permeability and capillary suction, and chloride penetration by diffusion in both cracked or uncracked ECC samples is found to be comparable or lower than normal sound concrete of same strength without any cracks.

A brief description on impact of ECCs on construction industry is also included. Experimental studies with ECCs are ongoing and application areas are increasing more than ever with an expectation that ECCs become more widespread in commercial concrete construction works.

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