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ENGINEERED CEMENTITIOUS COMPOSITEAS AN INNOVATIVE DURABLE MATERIAL: A REVIEW

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ABSTRACT

This paper studies recent research on the durability properties of engineered cementitious composites (ECC). As the necessity for economic infrastructure increases worldwide to cater for the rehabilitation of concrete structures that are damaged by continuous wear and environmental conditions. The reviewed subjects for ECC and normal concrete include to characterize mix design, to explain age at cracking, to evaluate possible crack width and determine the interfacial bond strength and strength capacity which can lead to assess the durability of ECC. Several key parameters such as compressive strength, tensile strength, tensile relaxation, elastic modulus, drying shrinkage, bond strength and crack resistance were considered. Conversely, ECC displays superior tensile strain capacity compared to normal concrete. Unlike ordinary cement-based materials, ECC strain hardens after the first cracking and behaves similarly to ductile metals. The microcracking behavior contributes towards crack width control, whereby even under large imposed deformation, crack sizes remain relatively small (less than 100 µm). Under favorable conditions, it has been experimentally reviewedthat ECC has self-healing capability. Hence, the crack control and self-healing properties may take advantage of the durability issues that most concrete structures face today. All these characteristics suggest that ECC can be potentially used on a larger scale in the field of repair.

Keywords: engineered cementitious composite, durability, micro-crack, crack-width, tensile-strain capacity.

1. INTRODUCTION

Concrete is currently the widely used construction material for civil infrastructure and is likely the predominant material for foreseeable future because of its unique properties such as versatility, durability and easy to handle, due to these unique properties, concrete becomes the vast material that consumed annually throughout the world. Although concrete has its reputation as being a durable material, with a lifespan of 100 years and more, its performance when used with steel reinforcement, particularly in a marine environment, has proved to be a significant issue for many decades to many countries worldwide.

Many concrete infrastructures suffer from severe deterioration all over the world. Realdeterioration can be correlatedwithsomematters such as faulty design, poor skillfulness, environmental factors during the construction, and loading configuration[1]. Also, reinforcement deterioration also entails associated cracking and spalling [2]. When decorously protected from the external environment, reinforced concrete can be expected to maintain serviceability for decades. Thus inspection and maintenance procedures for concrete structures have therefore become the target of debating. However, the practice of continuous inspection and maintenance is difficult, specially in the case of sizable concrete structures like infrastructures, owing to the considerable amount of labor and funds required. Figure-1 illustrates the most common cause concrete deterioration and reinforcement corrosion [2, 3, 4]

On the other hand, repair may be difficult or impossible to be executed because of current conditions such as the location of the casualty in the affected structure. Many infrastructures, in an instance, highways and tunnels are also in continuous service and in such cases, repair work becomes challenging. Moreover, even if such repair work were attainable in principle, the cost and amount of labor required for identification of problem and repair work can be prohibitive in the case of large-scale infrastructures. Accordingly, the cost of maintenance and repair of deteriorated infrastructure can be expected to increase rapidly and have serious economic implications on future generations. Under such circumstances, high capability concrete, or automatic repair, self-healing, of serious cracks without capital requirements of affected structures could be of a great solution.

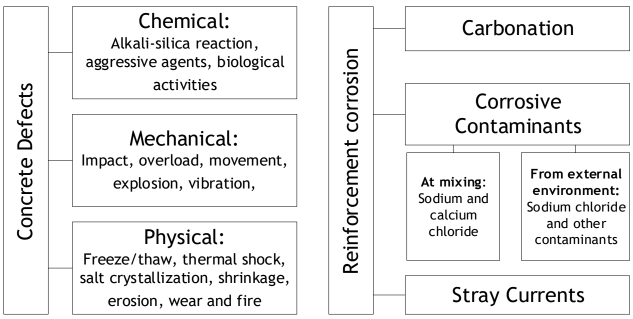

Figure-1. Typical causes of concrete and rebar deterioration[2].

1.1 Corrosion of reinforcement

The problem of rust or corrosion of reingorcement can be divided into two main processes namely the anodic and cathodic reactions. The anodic process (Equation 1) requires the oxidation of iron atoms to steely ions when the concrete cover at the outer of the reinforcement has been damaged.

The cathodic process (Equation 2) consists of the reduction of oxygen from the enclosing air as it response with water to structure hydroxyl ions. The gap between the anode and cathode can vary greatly calculate on on the position of the deteroration of the concrete cover. The cathode and anode areas may also subtitute along the length of a continuous reinforcing steel bar. Oxygen at the cathode devotes to the discharge of electrons that were detached from the oxidation of the iron in the steel bar at the anode. The flux of ions and electrons jointly can be used to measure the corrosion rate [5, 1].

Anodic reaction:

$$2Fe \rightarrow 2Fe^{2+} + 4e^{-} \quad (1)$$

Cathodic reaction:

$$O_2 + 2H_2 0 + 4e^{-} \rightarrow 4OH^{-} \quad (2)$$

Overall reaction:

$$2Fe + 2H_2 O + O_2 \rightarrow 2Fe\,(OH)_2 \quad (3)$$

Concrete reinforcing of steel in is covered opposite to corrosion mainly due to the alkaline environment resulting from the cement hydration reaction.It concedes the steel to shape a protective layer that avoids the anodic disintegration of the iron. As in considering this passive layer is sustained, corrosion will not occur. However, concrete is described as a porous material. Carbon dioxide in the air or chloride ions from the encircling environment can, therefore, penetrate the concrete through its pores and react with calcium hydroxide instantly. The reaction eventually causes a diminishing in the pH of the concrete thatcauses the protective layer around the steel to dissolve. Hence, the reinforcement becomes vulnerable to corrosion at the slightest damage to the concrete cover. The presence of moisture is usually required to sustain the corrosion reaction [1, 2, 5, 6].

1.2 Patch repair materials

Patch repair materials must meet specific performance criteria such as strength, size stability, limited permeability and good surface bonding with the concrete substrate [2]. As a main rule, repair mortars should have low shrinkage as possible and thermal coefficient similar to that of the substrate. Repair materials generally do not need to have high compressive strength as this material property has little significance to crack resistance. Vary to other methods of repair are available in the concrete rehabilitation industry such as grouting, epoxy injection, surfacecoatings, corrosion inhibitors and cathodic protection systems [7, 8].

The current of deteriorating state over worldwide infrastructure suggests many potentialuses of overlays. However, durability is still a significant concern and is dependent on several factors including shrinkage, surface preparation and ultimately bond strength. Durabilityis usually identified with crack width, whereby limited crack size will restrictand block the penetration of corrosive chemicals from the surrounding environment. Conventional patching materialremains brittle and, under the right conditions, repaired concrete structures will be subject to surface cracking. Debonding is also a common failure mechanism that is initiated at the substrate overlay interface as presented in Figure-2. Further cracking is induced that concede the penetration of corrosive substances which then accelerate the damage process. This bond substantiality issue leads to additional repair costs and reduced serviceability [9, 10].

The main goal of concrete repair is to restore theload-bearing capacity and rigidity of the concrete structure. For the repaired member to show maximum behaviour peformance, a monolithicbehavior should be achieved.

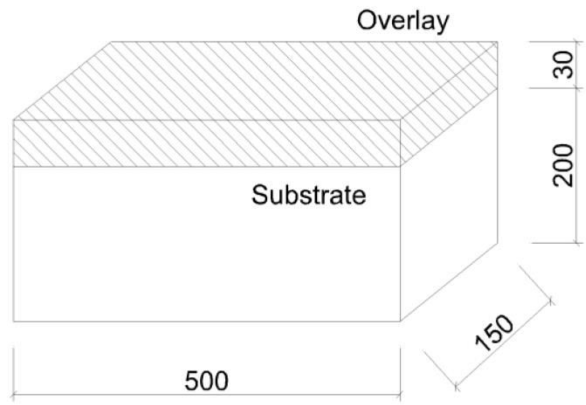

Figure-2. Repair material on the overlay composite beam and concrete substrate (unit in mm) [11, 12].

Hence, decent bonding should be created between the concrete substrate and overlay material. Bond strength may be expressed qualitativelyregardingthe bond concept and quantitatively scoped as the energy or stress compulsory to separate the two materials layers. However, in the case of concrete overlays, the bond strength is typically characterized as the tensile strength. Practicable applications, bond strength, is measured by coring and pull off tests. The stress at failure may be calculated by dividing the maximum force with thecross-sectionalarea of the specimen. Nevertheless, it must be emphasized that bond strengthequal failure stress only if a failure appear solely at the interface of the two materials[13, 11].

2. ENGINEERED CEMENTITIOUS COMPOSITE

In the recent past, the effort to adapt the brittle nature of ordinary concrete has resulted in modern concepts of ultra-high performance fiber reinforced cementitious composites, which are represented by tensile strain-hardening after first cracking. Depending on its contents, its tensile strain capacity can be up to several hundred times that of normal and fiber reinforced concrete. Engineered Cementitious Composites (ECC), designed to strain to harden in tension based on micromechanical principles, concede optimization of the composite for high performance represented by extreme ductility while decreasing the amount of reinforcing fibers, typically less than 2% by its volume[14, 15, 4].

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Unlike other concrete materials, ECC strain-hardens after first cracking, identical to a ductile metal, and determine a strain capacity up to 500 times greater than normal concrete (Figure-3). Along with tensile ductility, the particular crack development within ECC is critical to its durability. Contrasting from ordinary concrete and most fiber reinforced concretes, ECC shows self-controlled crack widths under increasing load. Even at extensive imposed deformation, crack widths of ECC remain small, less than 60 μm (Figure 3). In contrast, it is well known that firm crack width control using steel reinforcement is difficult to achieve in concrete structures. With intrinsically tight crack width and high tensile ductility, ECC peform a newconcrete material that offers significant potential to naturally resolving the durability problem of concrete structures [16]. A typical example mix design of ECC using poly-vinyl-alcohol (PVA) fiber reinforcements and plain mortar are given in Table-1.

The primary criterion that differentiates ECC from regularfiber-reinforcedcomposite (FRC) is the strain hardening that appears after early cracking. As the crack occurs inside the matrix, an increase in stress is examined followed by a rise in strain. In FRC, after the development of the first crack, the latter continues to open up as thefibers stretch and rupture. This condition is called tension softening and results in a decrease in overall stress-bearingcapacity of the composite. Under other conditions, tension softening in ECC occurs after a certain strain level is achieved and a stress-strain relationship related to that of a ductile metal is obtained[17]. The strain hardening behavior of ECC is shown in Figure-3 and the response of ECC under flexural loading presented in Figure-4.

Table-1. Typical example proportion of ECC and plain mortar mix design (kg/m^3) [18]

Material	ECC	Plain mortar
Cement	385	385
Water	385	385
SupplementaryCementitious Materials (Fly ash class F)	578	578
Fine aggregate (silica sand)	600	653
Fiber content-PVA (vol), %	26	-
Viscous agent (Methylcellulose)	1	1
Superplasticizer (Mapei dynamon SP1)	2	2
Sum	1974	2001
w/b	0.4	0.4
f/c	1.5	1.5
Total binder	963	963
Slump diameter (mm)	150	220

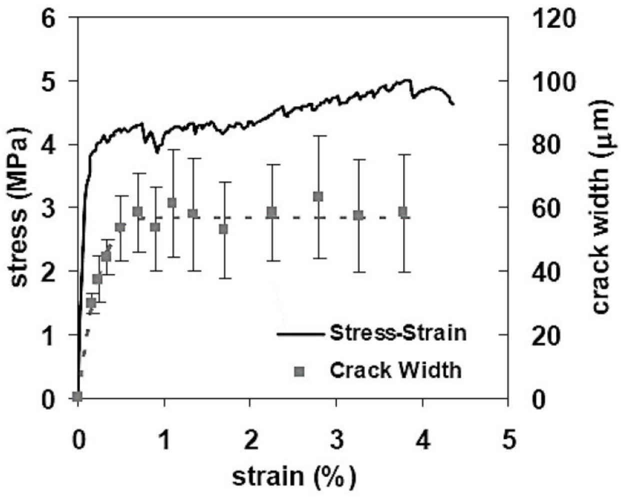

Figure-3. Tensile stress-strain curve behavior and crack width of ECC [19, 20, 21].

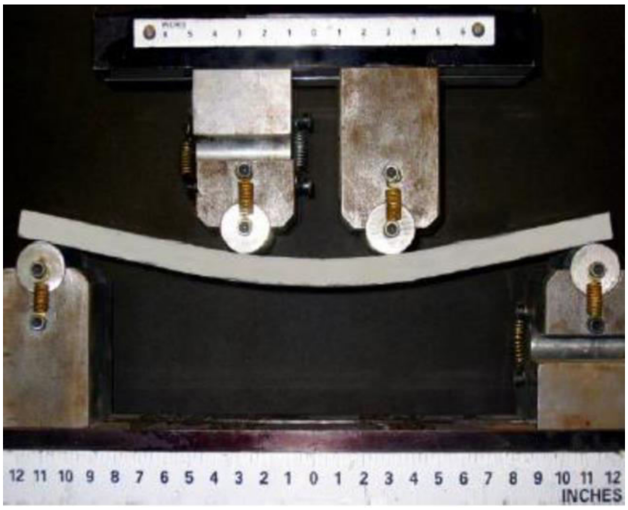

Figure-4. ECC plate under flexural loading [6].

Lately, increasing research has been conducted on the durability of ECC materials. This paper provides an overview of the recent investigations in ECC cracking and strength. The subjects include several experimental tests due to ECC cracking and ECC properties, corrosion resistance and ECC performance.

2.1 Micromechanics

On the contrary, the exceptional ductile capacity of ECC lies within the composite tailoring process. A fiber possesses characteristics such as length, diameter, strength, volume and elastic modulus. A cementitiousmatrix has properties such as fracture toughness, elastic modulus that require measuring. It is also important to consider the chemical and frictional bonds betweenfiber and concrete matrix.

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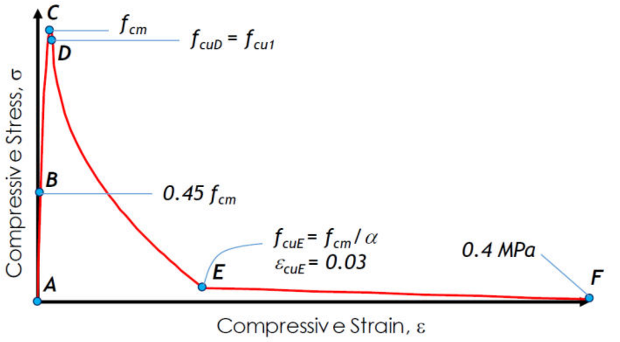
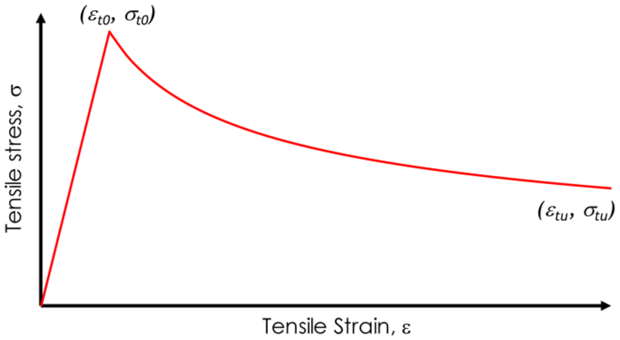
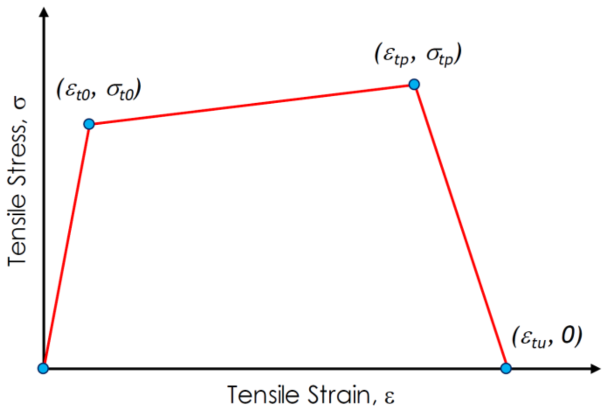


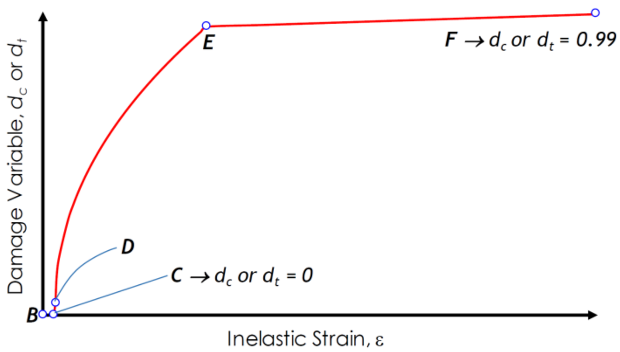
(a) Compressive behavior: concrete [20, 22]



(b) Tensile behavior: concrete [23]



(c) Tensile stress-strain: PVA-ECC material [24]



(d) Inelastic strain, ε [22]

Figure-5. Concrete constitutive model [20].

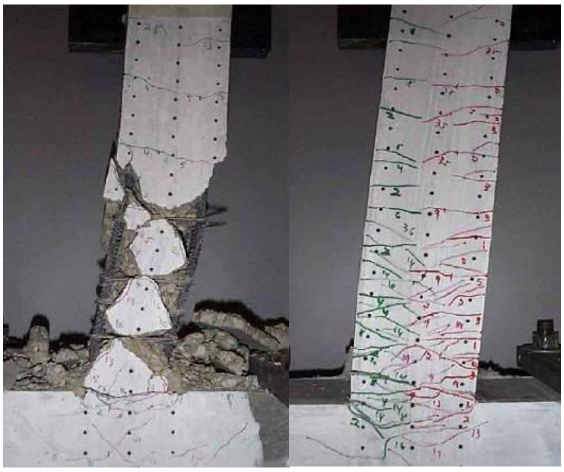
The tailoring procedure, therefore, accustoms the micromechanical properties according to the characteristics of ECC required. Micromechanical studies involve analyzing the composite regarding bond strength and interaction between the fiber, matrix and interface under certain loading conditions [14, 6].

2.2 ECC element performance

Aforementioned, ECC is a class of ultra-ductile fiber reinforced cementitious composite. As a result,the failure possibility by fracture is minimal in comparsion to conventional reinforced concrete. In regular structural concrete design, compressive strength is advised to be the main criteria for quality and safety. Hence, structural strength is mostly associated with material strength (compressive strength). However, this spread only if the failure mode is governed by material strength. For instance, if a failure occurs via tensile fracture, high compressive strength does not represent greater structural strength [6].

Along replacing conventional reinforced concrete with ECC for structuralapplications has significant implications on safety, durability and construction efficiency. ECC has the very high shear capacity and hence develops multiple cracks normal to the main tensile load. The extent of spalling is also minimized. After all, ECC has an ultra-ductile property; the shear reaction is alsoductile. This allows the elimination of normal steel shear reinforcement (stirrups). Further, ECC beams without shear reinforcement show sophisticated performance than high strength concrete beams with firmly spaced steel stirrups, implying that the reinforcement can be removed when the concrete matrix is replaced by ECC[25, 26]. This can add to significant cost savings on materials, especially inlarge-scale projects.

In addition to that, the strain hardening behavior and high tensile capacity enableECC elements to assist large deformations due to imposed loads. This is fruitful in situations where the concretedetailsare exposed to high stresses such as joints in concrete decks. The high ductility of ECC implements it to account for the deck movements due to shrinkage, creep or temperature changes. Theirs limits damage and promotes the sustainability of very costly infrastructure while improving the structural safety and integrity of buildings[15, 6, 27, 28].



(a) RC+stirrups (b) ECC+no stirrups

Figure-6. Damage response of reinforced concrete with stirrups vs. ECC [17, 18]

Likewise, in structure combination of reinforced ECC, both the ECC matrix and steel are designed to be plastic and elastic respectively. Hence, the two components can accommodate a large amount of strain and remain well-matched during deformation to a certain percentage of strain. Compatible deformation results indeficient stress levels at the bounds of ECC and steel. This is a distinctive aspect of reinforced ECC. The interface of these two materials is not as important as in conventionalreinforcedconcrete because of the high stress can be conveyed straight to the ductile ECC matrix. In contrast, in traditionalreinforced concrete elements, the stress accumulated must be transmitted to the concrete away from the crack location. After cracking, the latter discharges close to the crack site while the steel reinforcement accommodatesadditional load delivered by the concrete. The result is mismatched deflection with associated high-stress levels at the interfaceof steel and concrete. The broad failure modes hence observed are spalling of the concrete cover and bond separation[6, 13, 19]

Figure-6 shows that compatible deformation between ECC and steel reinforcement results in the enormousamount of microcracks onward of the element (higher crack density) rather than a large and critical crack as observed in conventional reinforced concrete.

Similiarly, when an ECC member is loaded and tested for flexure or shear past the elastic limit, plastic deformation occurs with associated microcracking. This ultimately increases theload-bearingcapacity of each part through these cracks. The microcrack wideness is generally dependent on the type offiber (PE or PVA) used and the steel and ECC bond strength [14]. A crack width of fewer than 100 micronsis usually achieved when PVA fiberis utilized. From Figure 6, crack width (μm) initially increases with rising stress percentage. However,the rate of gain reduces after nearly 1% strain and sustain about 80 μm crack size. After that point, there is no further serious rise in crack width despite increasing strain and deformation[6, 4].

2.3 Self-healing of ECC

Research suggests that cracked concrete, under favorable conditions, can heal itself over a certainperiodwhen unprotected to water. Literature studies further show that there is a steady decline in permeability of the distressed concrete as water flows through the cracks. This change in permeability can be associatedwith weaken crack width as the healing step happens. The healing concept can be itself described as a series of chemical and physical mechanisms as revealed in most of the literature studied; several possible causes can be responsible for the self-healing phenomena as schematically illustrated in Figure-7. Some of these measurements include the precipitation of calcium carbonate crystals (a), closing of cracks by impurities and concrete fragments from spalling of the internal aspects (b), hydration of unreacted cement (c), and enlargement of the hydrated cementitious matrix in the crack flanks (d). Notwithstanding, out of all these instruments, calcium carbonate precipitation is the most effective and add to the larger part of self-healing of cracks within the concrete matrix[29, 30, 31].

Besides, self-healing is described as the ability of a damaged material to repair itself through internal processes. This self-healingbehavior is dependent on several factors such as the presence of water pressure, crack width and crack stability [32]. However, the degree of self-healing in a cracked concrete sample is found to be intensely dependent on crack width. Smaller cracks are expected to heal faster and more efficiently than larger ones. For instance, in a certain position where there is a small crack width, the cracks may heal entirely. Hence, self-healing can likely increase the durability and safety of damaged infrastructure. Nonetheless, this is a rarephenomenon in most common concrete materials due to their brittle nature and larger crack widths [18]. A crack width smaller than 50 μm is suggested for self-healing process to occur methodically as microcracks lack less filling materials to connect the crack edges[18, 32].

Moreover, the multiple cracking and microcracking behaviorof ECC suggests that tight crack width control can be achieved. This further benefit the possibility of self-healing in ECC repair materials underfavorable environmental conditions. This can ultimately support the operationphase of repaired infrastructure and reduce long circumtances of maintenance costs. Thence, self-healing can potentially be a distinct property of ECC repair mortars, in addition to high ductility anddamageresistance. Nonetheless, further research is required on the self-healing property of ECC based repair patches.

3. EXPERIMENTAL INVESTIGATION OF ECC

The mix design for ECC Concrete is for the most part placed on micromechanics form. The principle of micromechanics is useful at thephysical constituent level which has an outstanding mechanical interaction among the fiber, mortar-matrix, and fiber-matrix interface. Naturally, fibers are of the structure of millimeters in length and tens of microns in diameter, and they may have

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a surface coating on the nanometer scale. The heights of the PVA fibers used by various researchers vary between 8 mm and 12 mm diameter of 40μm. The nominal tensile strength of the fiber was 1620 MPa, and the density was 1300 kg/m^3. The fiber content was 2 % of the total volume of mortar for all ECC mixes. The optimal mix proportion given in the literature determines thepercentageof various components. The tests on ECC are performed to assess thedifferent wet properties as well as hardened properties. The criteriaon hardened property mainly include flexural tests. The focus point has been made to present information about the work performed by various pioneers in developing this type of ductile concrete.

Some experimental works were divided by the reasons for carrying out the test mainly to know the durability properties. Summary of empirical investigation is presented in Table-2. The creation of ECC specimens required a number of material input which varied according to local availability. These included Ordinary Portland Cement (OPC), Class F Fly ash, Silica sand - crystalline Silica (Quartz), PolyVinyl Alcohol (PVA) fibers and water. Superplasticizer and viscous agent were also used to obtain the required consistency and workability. The selection of materials was based on previous work [18, 19, 20].

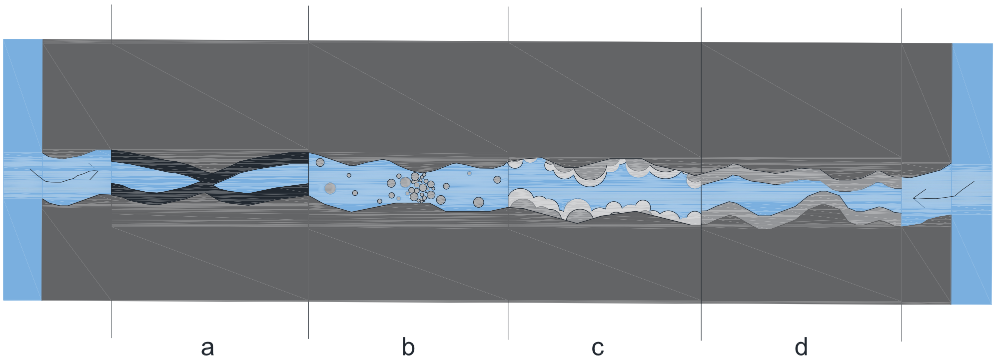


Figure-7. Possibility of potential mechanism for self-healing in concrete [30].

Table-2. Experimental investigation test summary [18].

Type of investigation test	Testing ages (days)	Number of specimens per mix	Result		Explanation
			ECC	Plain mortar	
Compressive	28	3	25, 25 MPa	32.5, 21.7 MPa	Influence of (w/b), influence of fly-ash content (f/c)
Direct tensile	28	3	3.7	2.6	Tensile strain capacity of ECC (2.4%) is about 3 times greater than plain mortar (0.8%)
Tensile relaxation	35	1	18.8 %	7.8 %	Influence of (w/b), influence of fly-ash content (f/c)
Elastic modulus	35	3	14.2 GPa	28.5 GPa	The lower elastic modulus of ECC, typically (15-34 GPa), is generally attributed to the lack of coarse aggregate and possibly due to the slippage of fibers at the matrix interface.
Accelerated drying	7	3	687 μ-ε	313 μ-ε	The higher shrinkage strain in ECC can be attributed to higher cement content and absence of coarse aggregates.
Ring test	Day by day	2	12 days	10 days	Monitor age at cracking (early cracking)
Direct shear	14	7	2.24 MPa	2.45 MPa	There is not a significant difference between the results of Mixing
Pull-0ff	14	6	1.41 MPa	1.65 MPa	The different workability of the two mortars affected the tensile bond strength.
Flexural	14	3	6.6 MPa	3.5 MPa	This result can be attributed to the high ductility (multiple cracking and strain hardening properties) of ECC

3.1 Compressive strength

These tests were examined on several specimens of 100 x 100 x 100 mm cured cubes of each overlay mix. These tests were carried out to determine the consequence of the compressive strength and hence characterize eachcombination. The results brougth about by something were also used in the elastic modulus test. Furthermore,to monitor the strength development of the material, the analysiswas carried out at standard ages of 3, 7 and 28 days orderly [33].

It is observed that ECC had lower compressive strength value than the plain mortar. This can be associatedwith the slippage of fibers at the matrix interface. Generally, higher w/b ratio makes the paste more porous as it consist of more water and air as the mortar dries up [34].

3.2 Direct tensile

Direct uniaxial tensile strength tests were analyzed on notched dog-bone shaped prismaticspecimens with extended dovetail ends. The prismatic section of the dogbone specimen had cross-sectional dimensions of 40 x 40 mm with a length of 170 mm and the total length including the dovetail ends was 270 mm. The built-in notch measure actually was 1 x 5 x 40 mm. The notching allowed failure to occur in the middle of the dog-bone specimens.

It is concluded that ECC displayed the highest tensile strength with 3.6 MPa compared to a plain mortar with 2.6 MPa. This result suggests that the inclusion of fibers in the mortar matrix increases the tensile strength of the composite. In addition, tensile strain capacity of ECC and plain mortar are explained as follows, 2.4% and 0.8%. It was about three times greater than plain mortar. The results agree with Li [4] which states that the typical tensile strain capacity of ECC varieties between 1-8 % depending on the desired ductility and mix constituents. Also, strain hardening was considered only in the ECC mix. The normal (plain) mortar failed through brittle failure.

3.3 Tensile relaxation

This tests were performed using dog-bone specimens with the same dimensions as the tensile strength test specimens other than that these were unnotched in this case. Each relaxation test was carried out for a period of 12 hours and only onesample per mix was analyzed at the standard age of 28 days [35]. The relaxation coefficient ψ (%) was attained from the following equation:

$$\psi = 100\ x\ \left(1 - \frac{\sigma_t}{\sigma_o}\right) \quad (4)$$

σ_o – original stress at the time of loading (MPa)
σ_t – remaining stress after 12 hours (MPa)

In order to compare the tensile relaxation potential of ECC to the plain mortar, it is observed that ECC had a significantly greater relaxation potential than plain mortar with 18.8% and 7.8%. This result ties with better improvement of performance of ECC in terms of cracking potential under restrained conditions. Comparable trends were obtained in previous experiments performed by Lim *et al.*[12, 31]

3.4 Elastic modulus

These tests in compression were utilized on cylindrical specimens with 100 mm diameter and height of 200 mm respectively. An Amsler compression machine was used to apply a load in suit-able increments and the strain was recorded with an extensometer with 100 mm gauge length. A stress-strain curve of the material was then plotted using the recorded values, and the elastic modulus was calculated as the gradient of the curve in the linear portion (between 0 and 40% of ultimate strength). Three specimens werecast per mix and tested at a standard age of 35 days.

As a result, the 35-dayelastic modulus of plain mortar achieved 28.5 GPa is higher than that of ECC which result 14.2 GPa for the given water to binder ratio and fly-ash content. Typical results were obtained in research undertaken by Li et al.[13, 36]. The lower elastic modulus of ECC, generally considered 15-34 GPa, is associated withthe lack of coarse aggregate and possibly due to the slippage offibers at the matrix interface.

3.5 Accelerated drying shrinkage

These tests were taken on 100 x 100 x 200 mm prisms to resolve the drying shrinkage strain. Three specimens were used per mix. All prismaticsamples were cured in a water basin for the same amount of time (7 days) beforetesting. Hence, the influence of curing regime on drying shrinkage was not examined[1].

The drying shrinkage strain (ε) of each specimen was calculated using the following formula:

$$\varepsilon = \left(\frac{L_o - L_n}{100}\right) \quad (5)$$

where L_o is the primary length between the strain targets before drying (mm), $L_n$is the final length between strain targets after drying (mm).

In order to compare and contrast the extent of drying shrinkage in ECC to the (plain) ordinary mortar, the result of ECC and plain mortar are analyzed. ECC displayed 687 μ-ε which relatively more drying shrinkage strain that the plain mortar 313 μ-ε. According to Li et al.[6], the higher shrinkage strain in ECC can be associatedwithhigher cement content and absence of coarse aggregates.

3.6 Ring test

The ring test provides a simple and economicanalysis for evaluating the cracking potential of mortar under restrained shrinkage conditions [34, 29]. Hence, it aids the selection of cement-based materials that are less likely to crack under restrained shrinkage. However, the ring test does have important limitations such as not accounting for the degree of restraint, the rate of property development, overlay geometry, curing and application [37].

Table-3. ECC vs plain mortar – material properties [18].

Material properties	ECC	Plain mortar
(w/b)	0.40	0.40
(f/c)	1.50	1.50
35 days elastic modulus (GPa)	14.2	28.5
7 days Tensile strength (MPa)	2.5	1.9
Tensile relaxation (ψ/%)	18.8	7.8
Drying shrinkage (ε/μ-strain)	687	313
Age at cracking (days)	12	10

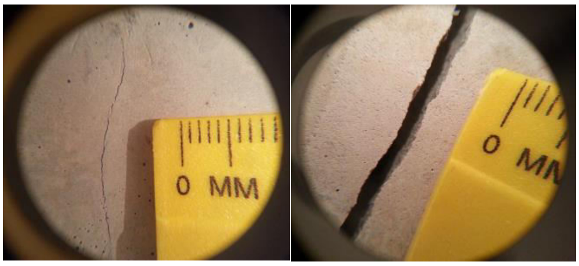
This test consists of casting a mortar ring around an inner steel ring. The latter provides the source of restraint to the shrinkage that the mortar experiences. This causes the development of internal stress within the ring specimen. Whenthese stresses exceed the tensile strength of the mortar, cracking occurs [37]. The age of cracking was measured from the day of casting and the crack width is measured using a crack meter. The crack width was measured at four different positions along the crack length for consistency of results.

The age at cracking of ECC relative to the plain mortar was analyzedby comparing the results of Mix 1 and Mix 6 respectively. ECC (12 days) took longer to crackconcerningthe plain mortar, suggesting a lower overall cracking potential. The results show that higher tensile strength (2.5 MPa), lower elastic modulus (14.2 GPa) andmore upper tensile relaxation (18.8%) of ECC compensatedfor its higher shrinkage strain (687 μ-ε). On the other hand, the lower age at cracking of the plain mortar (10 days) was influenced more by higher elastic modulus (stiffer mortar), lower tensile strength and tensile relaxation. Tensile relaxation is considered as the significant stress relief mechanism against restrained shrinkage cracking [34]. Table-4 illustrates the tolerable crack widths for reinforced concrete structures for durability under various exposure conditions.

Table-4. RC Structures crack width limitation for durability [32].

Exposure condition	Tolerable crack width (mm)
ACI 224R, 90	
Dry air or protective membranes	0.41
Humidity, moist air, soil	0.30
Deicing chemicals	0.18
Seawater and seawater spray; wetting and drying	0.25
Water retaining structures	0.10
ACI 318-89	
Interior	0.41
Exterior	0.33
ACI 350R-89	
Normal	0.27
Severe	0.22
CEB/FIP Model Code 1990	
Humid environment, deicing agents, seawater	0.30

Aforementioned, ECC is classified as an ultra-ductile fiber reinforced concrete with multiple and micro-cracking behaviorunder tension and bending. The total number of microcracks on the two rings was counted and recorded at a standard age of 28 days after the appearance of the first microcrack. For instance, it can be noted that there is a significant difference in crack width between ordinary (plain) mortar and ECC. The crack width of the ECC was limited to 51 μm while the crack size of the plain mortarwas 499 μm. Hence the average crack opening of the ordinary (plain) mortar was approximatelyten times greater than that of ECC. It is also approved by Tambusay*et al.*[38, 39].



(a) (b)

Figure-8. Cracking behavior; (a) Crack width of ECC, (b) Crack width of normal (plain) mortar [18].

3.7 Direct shear

The direct shear test was performedto evaluate and compare the interfacial bond strength between the overlay and substrate. This test involves applying a shear force directly at thesubstrate-overlay interface, without creating any eccentricities which may otherwise generate tensile stresses in the member. Seven 150 x 150 x 150 mm bonded overlay specimens were tested at a standard age of 14 days using an Amsler compression testing machine.

$$Shear = \left(\frac{k_{shear}F}{A}\right) \quad (6)$$

where,

k_{shear} – Coefficient for the shear load (53/67)

F – Failure load (kN)
A – Area of the interface (m^2)

The results of this test were hence used to compare the performance of ECC relative to the plain mortarregarding bond strength.

The interfacial bond strength between the overlay and substrate is slightly higher using plain mortar compared to ECC for the given water to binder and fly-ash to cement ratios. However, there is not a significant difference between the results of ECC and plain mortar.

This difference in bond strength may be associatedwith the workability of the mortar mix. The plain mortar had higher workability (220 mm) compared to ECC (150 -160 mm). Higher workability may result in the plain mortar overlay having a better mechanical interlock with the substrate and hence a slightly higher interfacial bond strength than ECC. After closer inspection, it was observed that the substrate would consist of a thin layer of overlay on its surface. Previous researchers have developed the term ‘overlay interface zone’ to describe the concrete which is found close to the interface of the present substrate [2]. The possible explanation for the creation of this weak interface zone within the overlay can be associatedwith the properties of the substrate as well as surface preparation [40].

3.8 Pull-off

Pull-off tests were carried out to determine the interfacial tensile bond strength between the overlay (ECC or plain mortar) and the concrete substrate. Six samples were cored from 150 x 150 x 150 mm mortar cubes and used to perform this test. Coring was done perpendicular to the interfacial bond between the overlay and substrate and resulted in cores consisting of both overlay and substrate material. The cored specimens were 50 mm in diameter and 150 mm in height. These were after that shortened for testing purposes. The final height of the cores consisted of approximately 30 mm of the substrate and 10 mm of overlay material.

According to Table-2, it is displayed that plain mortar had a greater tensile bond strength than ECC. This result is opposite to the research outcome of Sahmaran *et al*.[41], whereby the tensile bond strength of ECC overlay was higher than a micro-silica concrete (MSC) overlay. The near explanation for the reviewed result is that various workability of the two mortars affected the tensile bond strength. Predominant, good workability correlates to a better flow of fresh mortar and allows the latter to form an effective bond with the substrate through a mechanical interlock. Moreover, it will enable better capillary absorption on the substratethat further improves the anchorage effect within the substrate surface, thusly leading to a better bond strength[42].

3.9 Flexural

The third point loading test was pefromed on several specimens 100 x 100 x 500 mm mortar beams in order to determine the flexural strength. Theanalysiswas performedin accordance with the South African Nation Standard (SANS) [43]. All varieties were cured in a water basin for the same amount of time (14 days) beforeexamining. The average load at failure was used to determine the analytical maximum tensile strength on the assumption that stress varies linearly with distance from the neutral axis.

$$f = \left(\frac{Pl}{bd^2}\right) \quad (7)$$

where,
f – flexural strength (MPa)
P – load at failure (N)
l – the distance between axes of supporting rollers (mm)
b – width of the specimen (mm)
d – depth of the specimen (mm)

The flexural strength of ECC analogous to a conventional mortar was assessed by comparing the results. It is reviewedthat ECC reached 6.6 MPa shows outstanding flexural strength while plain mortar got 3.5 MPa for the given water to binder ratio and fly-ash content. This result can be associated to the high ductility (multiple cracking and strain hardening properties) of ECC and suggestsexceptional performance of ECC for repair utilizations where the overlay is inclined to be subject to large imposed loads and deflections. These results agree with [17, 44], whereby similar observations were made.

4. CONCLUDING REMARKS

Concrete is one whichremarkably accepted as a fundamental component nowdays and is being used in various and different infrastructures that are very critical for the flawless and comfortable function of the world. Due to the property of very strong in compression yet comparatively weak in tensile nature of cement concrete resulted in the development of ECC with distinctive properties of self-healing, high, tensile strength and ductility where tensile strength is approximately 500 times that of standard concretes.

The numerious investigations accomplished by several authors related to the development ofECC and its functions in the real world proves to be one of the best viable concrete materials of the future generations.However, degradation initiates at a very begining stage and thus maintenance and repair are aconsiderable concern to our society. ECC is givenvery promising alternative materials with beneficial properties in the field of application.

The normal (plain) mortar had different properties to ECC. ECC recorded undoublty higher ultimate tensile strain capacity and tensile strength as to compare to the plain mortar. The strain hardening property was maintained with age and accordingly, a tensile strain capacity of about 2.5 % was obtained in more longterm. The plain mortar showed an inferior level of tensile relaxation, higher elastic modulus and lower drying shrinkage strain compared to ECC for the same water to binder ratio and fly-ash content. In spite of the smaller shrinkage strain of the plain mortar, it appears that the combined influence of lower tensile strength and relaxation and higher elastic modulus had more effect on its age at cracking. Furthermore, ECC displayed naturally lower crack width both in the short and long term and thissuggestssuperior resistance to the ingress of corrosion producing substances. Higher flexural strength was obtained for ECC, indicating better resistance to imposed loads.

Consider the information mentioned above; it can be concluded that, overall, ECC displays better material properties than plain mortar. The inclusion of fibers in the mortar matrix significantly improves performance regarding the potential for cracking and crack width. Fair bond strength and durability were obtained. Therefore, the results of this study indicate that ECC can be effectively used as a repair mortar or even to improve capacity by combined with RC for depressed concrete structures, assuming proper surface preparation, workmanshipand design.

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