Vol. XIII & Issue No.10 October - 2020
INDUSTRIAL ENGINEERING JOURNAL

ENGINEERED CEMENTITIOUS COMPOSITES FOR SUSTAINABLE DEVELOPMENT

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Abstract

Concrete with adequately high compressive strength has been in use for structural purposes. However, the majority of these materials continue to be brittle. It has been observed that sometimes the brittleness is increased as the compressive strength rises. This creates potential restrictions on the use of high strength concrete in structures. When there is a contact between concrete and steel, a high stress concentration is produced that may cause a fracture of the concrete. Therefore, use of high ductile concrete becomes necessary for increasing the durability of the concrete structures. This paper focuses on development of Engineered Cementitious Composites (ECC) with increased tensile strain capacity using high tensile strength Polyvinyl Alcohol fiber up to 2 Percent by volume of Concrete. Environmental Scanning Electronic Microscope (ESEM) images show the development of self healing microcracks which depict ECC are a promise to high resilient structures.

Keywords: ECC, Fly-Ash, Polyvinyl Alcohol (PVA) Fiber, Superplasticizer. Sustainable Development

1.0 INTRODUCTION

In terms of material constituents, ECC utilizes similar ingredients as fiber reinforced concrete (FRC). It contains water, cement, sand, fiber, and some common chemical additives. Coarse aggregates are not used as they tend to adversely affect the unique ductile behavior of the composite. In general 2% or less by volume of discontinuous fiber is adequate, even though the composite is designed for structural applications. Because of the relatively small amount of fibers, and its chopped nature, the mixing process of ECC is similar to those employed in mixing normal concrete. Also by deliberately limiting the amount of fibers, a number of proprietary studies have concluded economic feasibility of ECC in specific structural applications. Various fiber types can be used in ECC, but the detail composition must obey certain rules imposed by micromechanics considerations This means that the fiber, cementitious matrix, and the interface (mechanical and geometric) properties must be of a correct combination in order to attain the unique behavior of ECCs. Thus ECC designs are guided by micromechanical principles. The most fundamental mechanical property difference between ECC and FRC is that ECC strain-hardens rather than tension-softens after first cracking

Concrete is the most accepted construction material in the field of Infrastructural Development on our Mother Earth with more than 11.4 billion tons of Concrete consumed annually worldwide. It was estimated that each ton of cement produced generates an equal amount of Carbon Dioxide, a major contributor for Green House Effect and Global Warming. Ordinary Portland Cement, though costly and energy intensive is the most widely used ingredient in the production of concrete mixes. Unfortunately, production of cement itself involves emission of large amounts of Carbon Dioxide into the atmosphere. Hence, it is inevitable either to search for another material or partly replace it by an alternate material. Any such material which can be used as an alternate or as a supplementary to Portland cement would lead to a sustainable construction.

Civil and Structural Engineers who have developed High-Strength Concrete structures over the last few decades have given hopes for stronger structures. However, there is also increasing recognition that when a certain level of compressive strength is reached, the failure of the structure will be dominated by brittle fracture in tension. This recognition has lead to an expansion of materials property development towards tensile ductility in recent years.

2.0 Literature Survey

Concrete is the most important construction materials used worldwide. Historically, structural designers have primarily relied on concrete to carry compressive loads. However, in real field conditions, concrete is also subjected to tensile stresses due to loading and environmental effects including shrinkage, chemical attacks and thermal effects. The tensile strength of concrete is only 10% of its compressive strength [8]. The main shortcoming of the concrete is its brittle nature and as a result of its brittle nature cracking, damage and deterioration occurs and it requires repeated maintenance of the structural members.

High-strength concrete performs well under pure compression loading. However, many structures experience flexural and shear loading that invariably introduces tensile stresses into the material. In dynamic loading, compressive stress waves travelling through the thickness of a concrete element and approaching a free surface would reflect back as a tensile wave that results in high velocity debris ejected on the back side of the structure. No amount of steel reinforcement can prevent this type of failure mode involving concrete spalling and fragmentation since the reinforcement always require a concrete cover [11].

The conventional concrete will be subjected to a greater pressure before it breaks. A team lead by Victor Li has developed a new type of flexible concrete that bends under such pressure and can repair itself. The self-healing concrete develops many hairline fractures when bent, distributing the pressure over its area. The tiny cracks will seal themselves with calcium carbonate when exposed to rainwater and carbon dioxide. Professor Victor Li named this new flexible concrete as Bendable Concrete or ECC. It is a relatively new material with a number of benefits; including high ductility under Uniaxial tensile loading and improved durability due to intrinsically tight crack width [9], and also finds widespread use across the country since 2005. It is like if you get a small cut on your hand, your body can heal itself. But if you have a large wound, your body needs help and it might need stitches etc. We have created a material with such tiny crack widths that it takes care of the healing by itself. Even if you overload it, the cracks stay small. 'The flexible concrete bends but doesn't break'. This was reported by Victor Li and Benjamin Wylie [14].

ECC represents a special kind of high performance fiber reinforced cementitious composite featuring high tensile ductility. Unlike concrete and conventional fiber-reinforced concrete (FRC) which shows unloading after matrix first cracking, ECC exhibits tensile-strain hardening behaviour achieved by sequential development of matrix multiple cracking. The tensile ductility of ECC is several hundred times that of normal concrete and crack width in ECC is self controlled and reaches a constant value (~60µm) after 1% elongation. It has been reported that ECC has lower water permeability and lower effective chloride diffusivity in the presence of micro-cracks when compared with cracked concrete in which the crack width is not self controlled and is usually in the range of several hundred micrometer to several millimeter [7].

ECCs are a unique class of new generation high performance fiber-reinforced cementitious composites (HPFRCC) featuring high ductility and medium fiber content. Tensile strain capacity at a range of 3 to 5% has been demonstrated in ECC materials using polyethylene fibers and PVA fibers with fiber volume fraction not greater than 2% [3].

The fracture toughness of ECC is similar to that of aluminum alloy and ECC remains ductile even when subjected to high shear stress. High tensile ductility and toughness of ECC material greatly elevates the mechanical performance of reinforced ECC structure by preventing brittle failure and loss of structural integrity which is usually found in traditional reinforced concrete [5].

In concrete repair applications, the immediate shrinkage deformation of the new repair material after placement is restrained by the old concrete substrate which has already undergone shrinkage. Consequently, tensile stress is built-up in the repair layer and a combination of tensile and shear stress is developed along the interface between the repair and the concrete substrata. These stresses may cause repair surface cracking, and/or interface delamination as reported by M. Li. and V.C. Li. [1]. The ECC can be used as a repair material to improve the durability of repaired concrete structures.

Self healing of cracked concrete is an often-studied phenomenon. Two strategies for the promotion of self-healing have proven promising. One approach focuses on the embedment of capsules that contain self-healing compounds within the concrete material, while the other relies on a continuous dispersion of self healing compounds intrinsic to the concrete matrix. The latter often referred to as autogenous healing as reported by Yingzi Yang [10].

The conventional concrete along with steel or fiberglass reinforcing bars, known in industry jargon as rebar is used to increase the tensile strength and to reduce cracking. However, this material is strong in compression but weak in tension or bending. Bendable concrete or ECC resembles regular concrete but can weigh up to 40% less, consisting mostly of the same ingredients except for the coarse aggregates. It has small Polyvinyl Alcohol (PVA) fibers embedded within it, 8-12 mm long and about 40 microns in diameter, about half the thickness of a human hair. They have a nanometer-thick surface coating that allows them to slip rather than break under heavy loads. In place of coarse aggregates, it relies on fine sand as coarse aggregates disturb placement of the fibers and destroy the ductility and in some applications, rebar can be eliminated.

While explaining the motivations for developing bendable concrete, Li reveals, it was a response to many of the major concerns we face every day in the Society. The things like climate change, infrastructure is experiencing more and more loads from extreme weather conditions. The concerns about environmental sustainability relating to the high energy and carbon dioxide emissions of producing cement. The production of cement is responsible for 5% of global greenhouse gas emission [4]. The infrastructure in many of the countries is not being in great shape and of course the economic crisis. All these problems make Society to go for alternate better materials for construction as reported by Victor Li. [12].

The concrete technology communities are always looking for the development of high compressive strength concrete over the last several decades has given hopes for stronger structures. However, there is also an increasing recognition that when a certain level of compressive strength is reached, the failure of the structures will be dominated by brittle fracture in tension. This recognition has lead to an expansion of materials property development towards tensile ductility in recent years as reported by Victor Li. [11]. The analytic tool used in ECC is Micromechanics, which quantifies the mechanical interaction between fiber, matrix and fiber/matrix interface [2].

The Bendable concrete has a compressive strength similar to that of conventional concrete. But while conventional concrete has a strain capacity of 0.01%, ECC has a tensile strength capacity of 3 to 5%, or about 300 to 500 times as much, making it far more ductile. ECC therefore acts more like a ductile metal than a brittle glass, leading to a wide variety of applications.

While long-term studies are still needed, comparison studies by the School of Natural Resources and Environment's Centre for sustainable systems, in conjunction with Li's group, show that over 60 years of service on a bridge deck, the ECC is 37% less expensive, consumes 40% less energy, and produces 39% less carbon dioxide, a major cause of global warming than regular concrete [6].

2.1 Unique Characteristics of ECC

The most important characteristic of ECC is the high tensile ductility represented by a Uniaxial tensile stress-strain curve with strain capacity as high as 5%). This metal like behavior shows a characteristic "yield point" at the end of the elastic stage when the first microcrack appears on the specimen. Subsequent increase in load results in a strain-hardening response,

ECC can be regarded as a family of materials with a range of tensile strengths and ductility that can be adjusted depending on the demands of a particular structure. ECC also represents a family of materials with different functionalities in addition to the common characteristics of high tensile ductility and fine multiple cracking. Self consolidating ECC (e.g. ECC M45 and its variants) is designed for large-scale on-site construction applications (Kong et al, 2003; Lepech and Li, 2007). High early strength ECC (HES-ECC) is designed (Wang and Li, 2006) for applications which require rapid strength gain such as transportation infrastructure that needs fast reopening to the motorist public. Light-weight ECC (LW-ECC) is designed (Wang and Li, 2003) for applications where the dead load of structural members must be minimized. Green ECC (G-ECC) is designed (Li et al, 2004, Lepech et al, 2007) to maximize material greenness and infrastructure sustainability. Self-healing ECC (SH-ECC) emphasizes the functionality of recovering transport and mechanical properties after experiencing damage (Yang et al, 2005; Li and Yang, 2007). [15]

2.2 Applications of ECC

ECC has found use in a number of large-scale applications in Japan, Korea, Switzerland, Australia and the U.S. [13]. Engineered cementitious composites are being used in shear elements that are subjected to a cyclic loading, in the mechanical elements of the beam and column combination, and for general structural repairs. These composites are commonly being used in structures that have high energy absorption, including dampers, steel element joints and for hybrid steel connections. In addition to the structural applications, these composites are being used as a shielding layer for increasing the corrosive resistance of structures. Other potential targets of engineered cementitious composites include underground structures, highway pavements, and bridge decks.

A few important applications are as reported below.

1. Construction of Jointless Bridges
2. Earthquake Resistant Structures
3. ECC Overlays
4. Flexible Roads and Bridges

Some of the fields Applications are as follows:

1. The Mitaka Dam near Hiroshima was repaired using ECC in 2003
2. Glorio Roppongi high-rise apartment building in Tokyo
3. An earth retaining wall in Gifu, Japan,
4. Mihara Bridge in Hokkaido, Japan
5. A 225-mm thick ECC bridge deck on interstate 94 in Michigan

3.0 METHODOLOGY

A most common question asked of ECC is how it achieves its unique ductile properties, but uses ingredients similar to those for FRC or HPFRC, and at the same time contains such small amount (typically less than 2% by volume) of discontinuous fibers. The answer lies in the composite constituent tailoring. A fiber has several attributes - length, diameter, strength, elastic modulus, etc. Interface has chemical and frictional bonds. The tailoring process selects or otherwise modifies these "micromechanical" parameters so that their combination gives rise to the ECC composite with its attendant properties.

The Methodology involves the development of Engineered Cementitious Composites by adopting Micromechanics Model which helps us to use to the different ingredients by knowing their physical and mechanical properties such as Specific Gravity, tensile strength of the PVA fiber, Size of the Sand, amount of Cement and ratio of Cement to Fly ash, water to binder ratio, etc.,

Mix the cement, fly ash and fine aggregate until the mixture is thoroughly blended and is of uniform color. Add 75 percent of water and 75 of percent of Superplasticizer and mix it thoroughly until the concrete appears to be homogeneous. Add slowly the remaining water and Superplasticizer, mix it and then add PVA fibers. All the constituents are meticulously mixed until the desired homogeneity and consistency is achieved.

4.0 INGREDIENTS OF POLYVINYL ALCOHOL FIBER REINFORCED CONCRETE

Bendable concrete or ECC resembles regular concrete but can weigh up to 40% less, consisting mostly of the same ingredients except for the coarse aggregates. It has small Polyvinyl Alcohol (PVA) fibers embedded within it, 8-12 mm long and about 40 microns in diameter, about half the thickness of a human hair. They have a nanometer-thick surface coating that allows them to slip rather than break under heavy loads. In place of coarse aggregates, it relies on fine sand as coarse aggregates disturb placement of the fibers and destroy the ductility.

1. **Cement:** The Cement used was UltraTech 53 Grade Ordinary Portland Cement. The physical properties of the Cement are shown in Table 1.

2. **Fine Aggregates:** Locally available Sand was used. The Particle Size Distribution Curve is shown in Fig 1.

3. **Fly Ash:** Fly Ash used was Class F and brought from Raichur Thermal Power Station (RTPS). Some of the Properties of Fly Ash are shown in the Table 2

4. **Superplasticizer:** High performance MasterGlenium SKY 8233 (Formerly Glenium B233) Superplasticizer based on Polycarboxylic Ether (PCE) was used.

5. **Polyvinyl Alcohol Fibers:** Ultra-High Performance Fibers were used. Performance Test Data is shown in Table 3

6. **Water:** Water which is fit for drinking was used.

Table 1. Physical Properties of Cement (Conforming to IS 12269-1987)

Sl. No.	Description of Test	Results
1	Specific Gravity	3.15
2	Fineness of Cement	0.05%
3	Standard Consistency of Cement	32%
4	Initial Setting Time	55 minutes
5	Final Setting Time	360 minutes

Table 2. Physical Properties of Fly Ash

Sl. No.	Description of Test	Results
1	Loss on Ignition	2.26 %
2	Bulk Density	2.1163 gm/cc
3	Silica Content	66.06 %
4	Alumina Oxide	0.005 %
5	Calcium Oxide	6.29 %

Various Proportions were tried keeping the Water to Binder ratio as Constant and varying the dosages of Superplasticizer for understanding the fresh property of the concrete. The Characteristic Deformability Factor test is used to quantify the effects of particle size distribution of the fine aggregates in ECC along with other ingredients as outlined by Kong et.al. A standard concrete slump cone is filled with fresh ECC and discharged onto a level Plexiglas or glass plate. Following discharge, two orthogonal diameters of the ECC "pancake" are averaged and a Characteristic Deformability Factor, denoted by τ is calculated using; $\tau =$; Where, D_1 is the average of two orthogonal "pancake" diameters, in mm and D_0 is the diameter of bottom of original slump cone, in mm. Fig 2 Shows the Wet Mix of the ECC.

Characteristic Deformability values for a few percentages of PVA fibers are shown in Table 4. Table 5 shows the Typical Mix Proportion of ECC. The mix was homogeneous and there was no segregation and bleeding.

Table 3 Performance Test Data (ASTM confirming to ASTM C1116)

Sl. No.	Parameters	Results
1	Filament Diameter	8 Denier (38 Microns)
2	Fiber length	0.375″ (8 mm)
3	Specific Gravity	1.3
4	Tensile Strength	210 ksi (1400 MPa)
5	Flexural Strength	4200 ksi (30 GPa)
6	Melting point	435ºF (225º C)
7	Color	White
8	Water Absorption	<1% by Weight
9	Alkali Resistance	Excellent
10	Concrete Surface	Not Fuzzy
11	Corrosion Resistance	Excellent

Table 4. Workability Test (Characteristic Deformability Test)

Mix Designation	Cement (kg)	Sand (kg)	Fly Ash (kg)	SP (kg)	Water (kg)	Fiber% by Volume	FA / PC	W / B	T50 cm flow Test (Seconds)	Average Diameter, D_1 (mm)	Bottom Diameter of Slump Cone, D_0 (mm)	$\Gamma = (D_1 - D_0) / D_0$
PVA-0.0	570	456	684	4.013	338.6	0.0	1.2	0.27	0.98	1000	200	4.00
PVA-1.0	570	456	684	4.013	338.6	1.0	1.2	0.27	3.33	950	200	3.75
PVA-1.5	570	456	684	4.013	338.6	1.5	1.2	0.27	4.37	820	200	3.10
PVA-2.0	570	456	684	4.013	338.6	2.0	1.2	0.27	4.37	790	200	2.95

Table 5. PVA Fiber Reinforced Concrete Trial Mix Proportions

Typical Mix	Cement	Sand	Fly Ash	SP	Water	Fiber	FA/PC	W/B
PVA Concrete (Kg / m³)	570	456	684	3.135	338.6	26	1.2	0.27
FA: Fly Ash, W/B: Water to Binder ratio, FA/PC: Fly Ash to Portland Cent								

5.0 EXPERIMENTAL STUDIES ON ECC

This includes Mix Design and various tests on ECC in its fresh and hardened state.

5.1 Material Design Methodology:

In the world of Materials Engineering, raw ingredients are shaped into a composite material through processing. Traditionally, selection of raw ingredients is based on empiricism. In recent years, composite materials are systematically being designed. One such material is "Engineered Cementitious Composite" (ECC). Micromechanics can be a powerful tool to deliberately tailor the composite ingredients, such as fiber dimensions and surface coatings along with sand particle amount and size. In addition, knowledge of material processing and its effect on both fresh and hardened properties aid in composite design.

Ordinary Portland Cement 53 Grade, Natural river sand (IS Zone III), Polycarboxylate Ether (PCE) based Superplasticizer, Fly Ash (Class F) and Polyvinyl Alcohol fibers (diameter 38 microns, length 8mm and the tensile strength 1400 MPa) were used in the design of concrete mix. The specific or recommended guidelines are not available for the Fiber Reinforced Concrete Mix Design. Hence, the Ideal Mix Proportion given in the Literature of ECC was used in this study. Various trial mixes were tried to satisfy the workability property of the PVA concrete. High volume fly ash content, low water to binder ratio of 0.27 with a Superplasticizer dosage of 0.25 percent of cementitious material and an aspect ratio of PVA fiber equal to 210 has passed the requirements of deformability characteristics of ECC. These requirements have established a target for the tailoring process of materials.

5.2 Proportioning of Concrete:

The specific or recommended guidelines are not available for the Fiber Reinforced Concrete Mix Design. Hence, the Ideal Mix Proportion given in the Literature of ECC-Concrete was used in this study.

5.3 Compressive Strength Test:

Compressive strength results are primarily used to determine that the concrete mixture as delivered on site meets the requirements of the specified strength. The specimens were subjected to compressive load in a Compression Testing Machine (CTM) of capacity 2000 kN to know the compressive strength of the PVA fiber concrete for various percentages of PVA fibers.

5.4 Direct and Indirect Tensile Strength Tests:

Tensile strength is a paramount property of concrete. It determines the load-bearing behavior of concrete structures because the compressive strength, which is usually taken as design parameter, depends also on the tensile strength. Unreinforced concrete structures rely completely on the tensile strength. The same is true for durability aspects. Fig 3 shows the dimensions of the Tensile strength test specimen. Fig 4 represents the Bar chart for the values of Split Tensile Strength and Flexural Strength.

Fig 5 shows the Tension Test being conducted in UTM. The Specimens were cured for 28 days and subjected to Uniaxial tensile tests with suitable steel grippers in an UTM (Universal Testing Machine) of capacity 1000 kN and under displacement control of 0.005mm/s to know the strain hardening behaviour of the PVA fiber concrete and consequent development of micro cracks. Fig 6 depicts Stress-Strain curve for 2% of PVA fibers. Fig 7 and Fig 8 represent the ESEM Images of Microcracks propagation of ECC Test Specimens subjected to Uniaxial Tensile Tests.

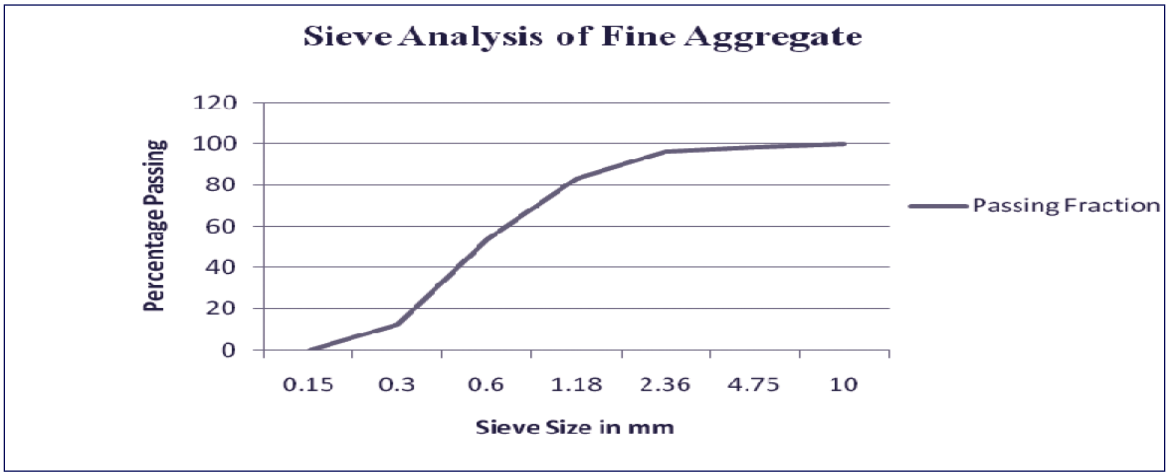

Fig 1. Particle Size Distribution Curve

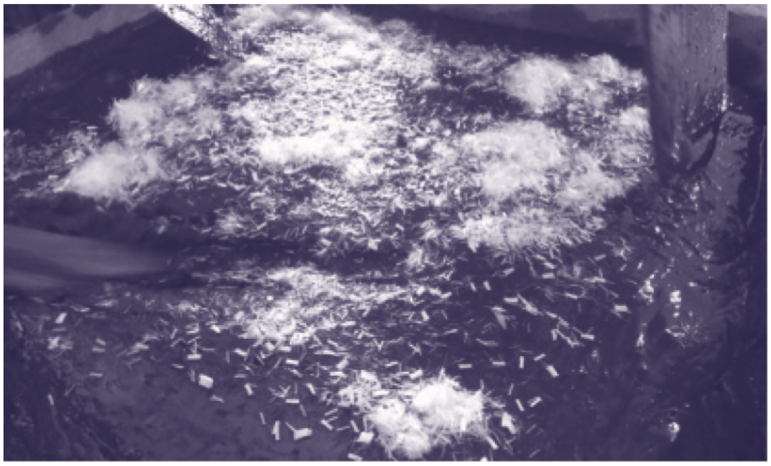

Fig 2 Wet Mix of Bendable Concrete

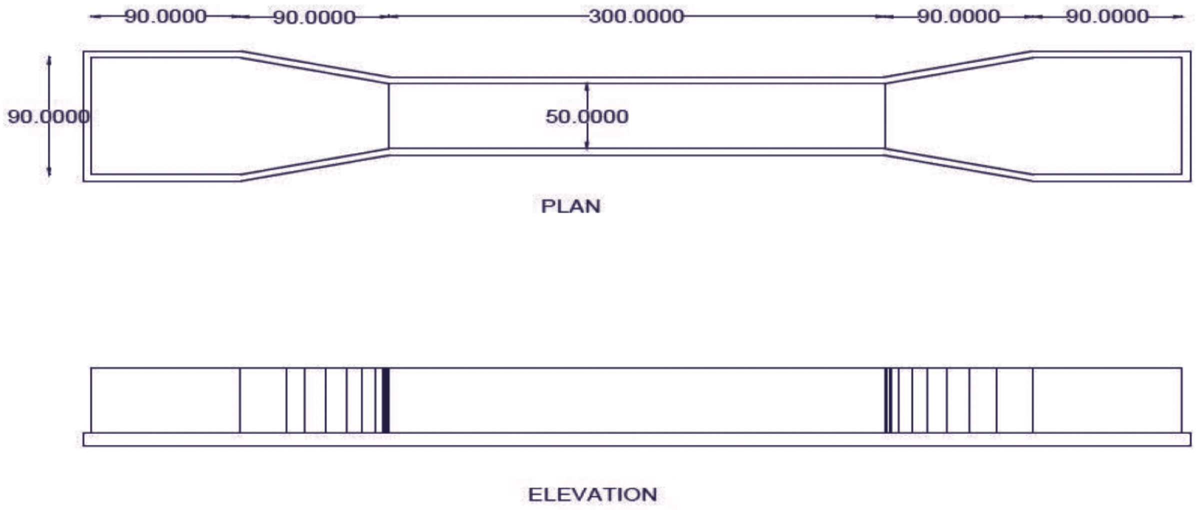

Fig 3. Tensile Test Specimen

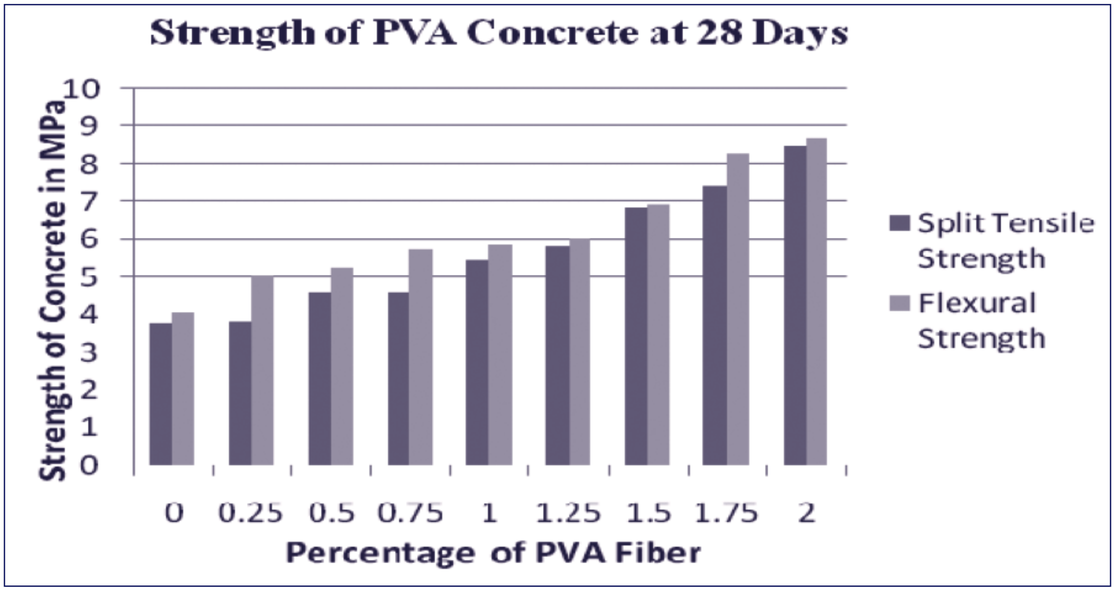

Fig 4. Indirect Tensile Strength of ECC

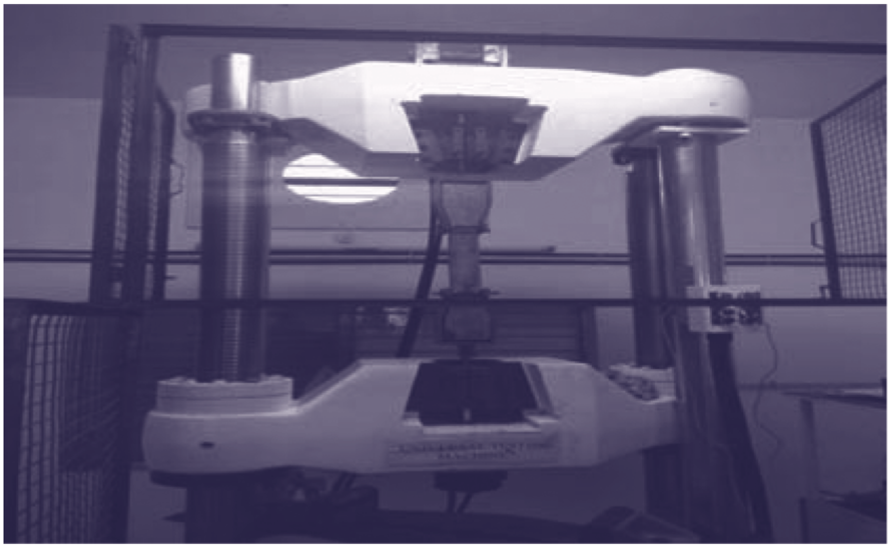

Fig 5. Tensile Strength Test in UTM

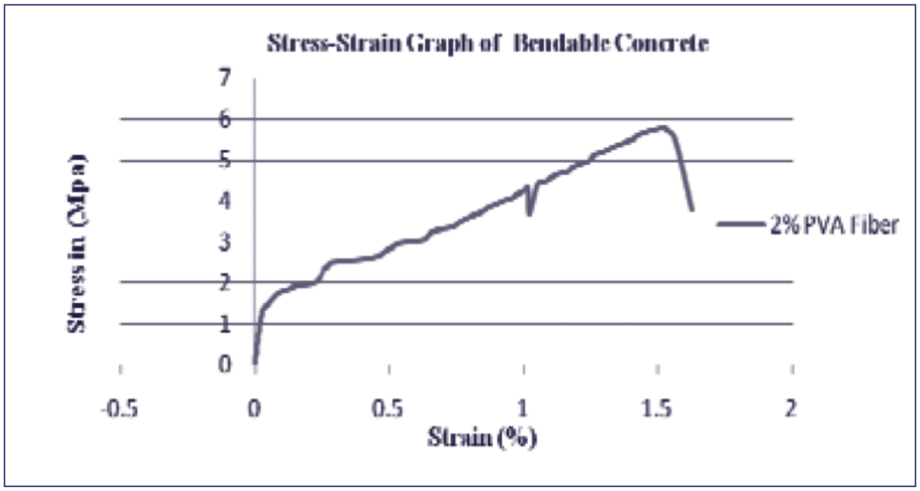

Fig 6. Stress-Strain Curve of ECC

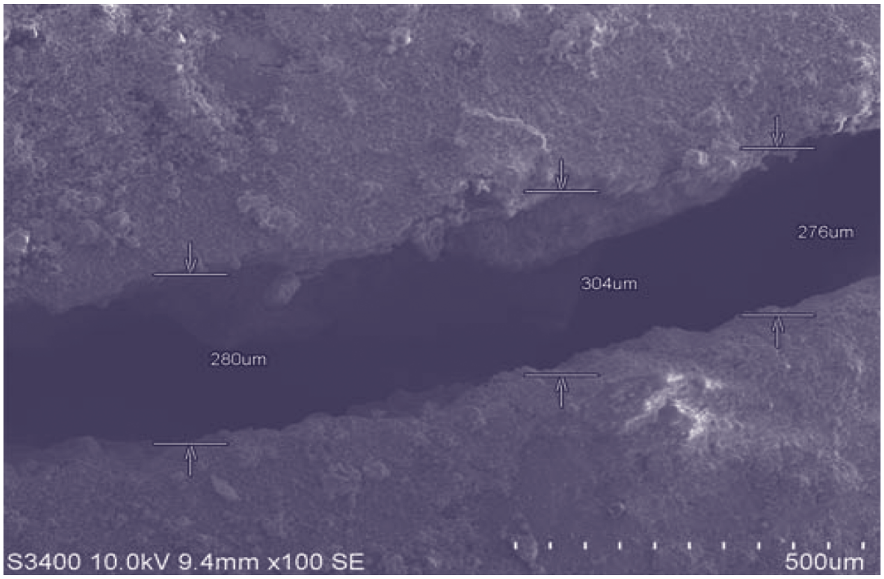

Fig 7. ESEM Image of Microcracks in ECC for 1% PVA fiber

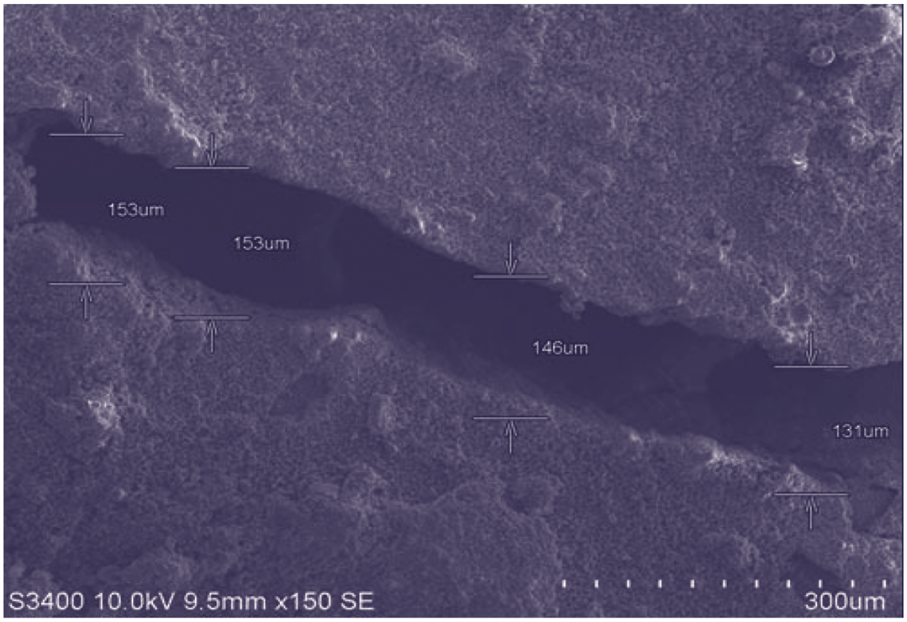

Fig 8. ESEM Image of Microcracks in ECC for 2% PVA fiber

6.0 RESULTS AND CONCLUSION

The deterioration process of concrete can be considered in two different stages. During the first stage, on account of weathering effects and loading, the voids and microcracks developed in the interfacial zone will be gradually interlinked. Later on these interlinked networks of microcracks will get connected to cracks present at the concrete surface. This is how fluid transport mechanism takes place into the interior of the concrete. This is the stage where there will not be any noticeable change in the strength but some protective barrier is being broken down such as depassivation of steel by Carbon Dioxide or Chloride penetration. Further, permeability increases greatly and marks the second stage of deterioration in which, Water, Oxygen, Carbon Dioxide and Acidic ions are able to penetrate easily into the concrete. The concrete eventually undergoes increased cracking, spalling and loss of mass and ultimately reduces the strength as well as the durability of the concrete.

The ECC has a very high tensile ductility and a very tight crack width. ECC can be accepted as a virtually crack-free concrete and is expected to aid in extending the service life of concrete structures. Our civil infrastructure can be much smarter and ECC opens the door to potential applications where conventional concrete currently cannot be used.

A Compressive Strength of 52.71 MPa (MegaPascal) has been attained for a fiber volume of 2 % at 28 days. A Flexural Strength and a Split Tensile Strength were found to be 8.72 Mpa & 8.48 Mpa respectively.

A Direct Tensile Strength of 5.84 MPa and a corresponding Strain of 1.55% have been achieved for a fiber volume of 2% at 28 days of age. Average microcrack widths observed through Environmental Scanning Electronic Microscope (ESEM) were 145 mm and 287 mm for 2% & 1% PVA fibers.

This shows that the PVA Concrete has a very good strain hardening behaviour when compared to Conventional Concrete which has a strain capacity of only 0.01%.

The depth of water permeated through 2 % PVA Concrete at the age of 28 days and was only 11.51mm which is less than the minimum cover to be provided in concrete elements. This shows the sign of durable concrete. The charge passed during RCPT test was 1458

The Research work suggests the importance of ECC as an alternative material as far as Strength and Durability are concerned.

7.0 ACKNOWLEDGEMENT

The Authors would like to graciously thank Mr. Shatrughna Thimmappa, Columbus, Indiana, USA who has helped us in procuring the indispensable PVA fibers for the Research Work. The Research work was carried out with the assistance from Raichur Thermal Power Station (RTPS), Raichur, India. The authors sincerely extend gratitude to RTPS, Karnataka, India.

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