An Introduction to Engineered Cementitious Composites: A Review

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***Abstract*—This paper discusses about the research and development in the field of Engineered Cementitious Composites (ECC) in last three decades since its inception in the early 1990's. This paper presents an introduction to the elements that make up the ECC, the various types of ECC etc. The importance of micromechanics in the design of ECC is emphasized. The composite structure can be constructed with the help of a micromechanical model having higher strain capacity in range of 3 to 7% in comparison to standard concrete (0.01%). It has very low fraction of fiber (2%) which indicates the performance of most composite weights. The beneficial use of ECC in certain phases of construction, repair and remodeling processes is reviewed. This paper discusses environmental issues such as greenhouse gases and emissions through the production of cement composites. While considering past developments, future challenges of continuing ECC developments are recognized.**

Keywords: Engineered Cementitious Composites (ECC), Strain Hardening, Bendable or Flexible Concrete, Polyvinyl Alcohol (PVA).

I. Introduction

The construction sector is one of the pillars of the global economy directly accounting for 6% of global GDP. Concrete is the most common building material used worldwide in today's times. It is considered as the greatest engineering milestone in field of construction with global construction of 20 billion tons [2]. Normal concrete has a fragile nature. Therefore it cracks with ease due to natural and mechanical loads that affect its structural strength. Efforts to reverse this harsh state of conventional concrete have led to the development of ECC's supply under a wide range of environmental exposures, and poor carbon footprint resulting in an environmentally sustainable construction [7].

Engineered Cementitious Composites (ECC) is an easily formed compound of mortar reinforced with selected short-stranded fibers. ECC has a strain capacity of 3-7%, which is quite higher in comparison to 0.01% of standard Portland (OPC) adhesive, mud or conventional concrete. These are also known as Strain Hardening Composites or more popularly as flexible concrete. ECC is therefore more effective as ductile metal material than fragile glass material (as does OPC concrete), resulting in more types of performance [1], [3].

Therefore, the ECC can be used in many frameworks to increase their service life, reducing maintenance and repair costs. Recently, the ECC has been used extensively for shelters, on high-rise buildings, to improve their stability under the effect of seismic loads or forces, and for use in repairs [8]. In case of ordinary concrete, aggregates are responsible majorly for the mechanical properties of hard concrete. But they cause the poor distribution of fiber to reinforced fiber concrete. Since distribution of fiber is considered as an effective specification in the study of complex behavior of the ECC, it becomes absolutely necessary to use good combination which will increase the ductility of the ECC. Therefore, the size and number of aggregates are fixed to this content of ECC. The cement content of the ECC makes it easier to control distribution of fiber and helps in achieving better strength characteristics [8].

II. Literature Review

Concrete is one of the most important building materials used by construction industry worldwide. Historically, architects and civil engineers are dependent on concrete to carry all their heavy buildings loads. However, in-situ conditions, concrete experiences stiffness while undergoing these loads. The environmental factors such as shrinkage, chemical attack and heat effects also responsible for certain amount of stiffness in the concrete. In the early studies it has been found out that the tensile strength of concrete is very less (only 10%) when compared to its compressive strength. Significant failure of concrete occurs because it has fragile nature and hence, due to this natural damage occurs and requires repeated care of the members of the structure [10]. High-strength concrete works best under pure compressive pressure loading. However, in –situ conditions many buildings will undergo flexural as well shear loads which will produce tensile stresses in them. In case of heavy loads, compression stresses in the form of pressure waves will travel in the size of a concrete object and try to reach a free surface. These can reflect back as a tensile wave

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leading to the formation of high debris emitted from the rear side of the building. It cannot be prevented by any amount of steel reinforcement. It also causes concrete spalling and splitting because the steel reinforcement always requires a concrete cover [10].

Normal concrete will withstand a great deal of load before it cracks. **Victor Li** was the leader of that team which invented a special type of concrete having flexible or bendable nature. This new concrete has a special property that it can bend under load and can adjust its shape accordingly. Professor Victor Li has named the new flexible concrete as Engineered Cementitious Composites (ECC) [10].

The ECC was originally established at the University of Michigan in the early 1990's. It is a new material with many advantages over conventional concrete such as it has high ductility and durability under tensile loads. It can restore wide cracks occurring inside due to heavy loads or other factors. ECC's are also known as high-performance fiber-reinforced cementitious composites (HPFRCC) due to their higher ductility and intermediate fiber content. The tensile strength in the range of 3 to 7% is shown in the ECC materials. It has fiber content up to 2% which consists of polyethylene fibers and PVA fibers [3].

The self healing behavior of concrete is often considered. Two methods to promote self-sufficiency have proven to be promising. In the first method focus is on the adhesion of concrete-containing compound inside the concrete mix, while in the second method the continuous distribution of self-adhesive compounds within the concrete matrix is at prime focus. It is similar to human bodies self- healing function. When you get a small injury or wound in your hand your body tries to cure it by forming blood clot. But if you have a bigger injury, your body needs medical help like stitches. "We have created something with a small amount of cracking that treat itself successfully. The cracks remain small even if you load it more than its prescribed limits. Flexible concrete bends but does not break." This was found out by Victor Li and Benjamin Wylie [10].

In the construction industry, strong buildings structures have been established in the previous 2-3 decades with the help of special concrete which has very high compressive strength. However, the structural failure in the structure can be controlled by compressive strength only up to a level after which it all depend upon the tensile strength. This understanding has been responsible for the growth of concrete materials with strong durability. The Integrated Structures and Materials Design (ISMD) conceptualization helped in study the benefits of both Materials Engineering and Structural Engineering. It also helped in achieving better efficiency of buildings in terms of well-being and ability to last [12]. The strength of the steel, the width of the small cracks, the self-cure of the cracks are some of the factors that control the operation of a building safely and firmly [10]. The cracking of the concrete occurs under the effect of mechanical loads and its exposure to climatic conditions [14].

In contrast to concrete and standard fiber-reinforced concrete (FRC) that exhibits loading after initial fracture of the matrix, the ECC exhibits the strength of the stiffness obtained by the subsequent development of multiple matrix fractures. The durability of the ECC is a few hundred times more than that of standard concrete and the width of the fracture in the ECC is self-regulating and achieves a permanent rate after an extension of 1%. It has been found that the ECC has low water infiltration and low active chloride depletion in comparison to cracked concrete where the cracks are not self-regulating and have larger size of several millimeters [5].

While giving explanation to the reasons for inventing flexible concrete, Li revealed, it was the answer to some big problems like climate change, extreme weather conditions experienced by building structures during their life period. He tried to make it environmental friendly by reducing problems associated with high energy and carbon dioxide emissions during production of cement. Cement production accounts for 5% of global greenhouse gas emissions. All of these problems prompted the Society to seek some of the best building materials as reported by Victor Li.

III. Methodology

The Engineered Cementitious Composites is known as a family of materials. It consists of new micromechanically materials. All the cement materials which are designed based on micromechanics are called ECC. They are also based on fracture mechanics theory which defines their large tensile ductility characteristic, Therefore, the ECC is not a fixed-structured material, it includes all the materials under different categories of research, development, and implementation phases. Hence, ECC material family is still growing [1].

A. Types: There are several types of ECC, including:

1. The lightweight (low density) ECC was developed in order to decrease the dead load of the buildings structures. It is made with the addition of voids of air, glass bubbles, polymer spheres, and / or lightweight aggregates in pace of ordinary aggregates. Lightweight ECC has higher ductility. It can be used in floating homes, boats and canoes [1].
2. 'Self Compacting concrete' is defined as the concrete that can flow under its own weight. For example, these materials will be able to fill molds that contain steel reinforcement without the use of any vibrator to ensure proper distribution. Self-compacting ECC was developed by using chemical admixtures to reduce

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viscosity and by controlling particle contact with equal mixing [1].

3. Spray able ECC, which can be blown through the pipe, developed using various super plasticizing agents and admixtures that reduce viscosity. Compared to other reinforced fiber-sprayed sprays, the spraying ECC has improved pumping ability over its distinctive mechanical properties. Spray ECC spray used for remodeling / repair work and tunnel / field lights [1].
4. The Extrudable ECC to be pumped out of the pipeline was first introduced in 1998. It was used in extrusion of pipes which will have higher load capacity and higher defects than any other composite pipes with reinforced fiber [1].

B. *Materials:*

1. Ordinary Portland Cement: Ordinary Portland cement (commonly as OPC) is a common type of cement used worldwide. It is the main constituent used to make concrete. It is made from argillaceous and calcareous materials [4, 14].
   a. Physical properties of OPC
      i. *Fineness:* Fineness is defined as quality of any material to have fine size. Smaller the size of particles of material means it will have more surface area-to-volume ratio. So the area for the reaction of water and cement per unit volume is more. Particle fineness of Portland cement affects hydration rate. The rate of strength gain by the concrete mix is dependent on this hydration rate.
      ii. *Soundness:* The quality of a strong cement mortar to maintain its shape after setting is defined as soundness. Cement containing large quantity of free lime is subjected to volumetric change. A test is performed with the help of Le chart liar's apparatus to find the soundness of cement.
      iii. *Consistency:* The quality of cement paste to flow is defined as consistency. It can be found with the help of Vicat apparatus. It has a plunger which penetrates through the cement paste. The penetration value is noted up to 10±1 millimeter and the water-cement ratio at this penetration value is reported as the consistency of cement.
      iv. *Setting Time:* The initial set time is time required by the cement to set after water is added in the mix. After this mortar start behaving like plastic objects. After passage of this time period the cement paste will start providing resistance to penetration. While the final set time is that time required by the cement to reach a certain level of hardness to carry the load. These tests are performed with the help of Vicat apparatus.
2. Sand: Fine sand bank river without any earthy and organic matter. The particles have angular shape. The size of the sand particles does not exceed 250 microns and are retained on a standard sieve having size of 150 micron. The sample prepared after sieving is washed in water to release silty, earthy and other organic matter and then left for 48 hours under the sun for drying [4], [14].
3. Water: Water which fits to the purpose of drinking can be used for mixing of aggregates. The suspended impurities and foreign matter such as acid, alkalis should be absent. Water has two important parts to play in concrete mixing. First, it reacts with the elements of the cement to form a mortar in a chemical reaction. It helps in holding the aggregates of mix in suspension stage till the mortar achieves its hardness. Second, it is used to provide moisture content during mixing of aggregates [4], [14].
4. Fly ash: Fly ash is a coal combustion product produced in the coal power plants when the exhaust gases come out after burning. Then these gases are given treatment in the electrostatic precipitators and the tiny particles are collected in them. These fine particles are known as fly ash. A part of ash does not come out with the exhaust flue gases. This remaining part is known as bottom ash. Fly ash contains large amounts of silicon dioxide (SiO_2), aluminum oxide (AL_2O_3) and calcium oxide (CaO). The silicon dioxide is present in both amorphous and crystalline forms. These compounds are also found from the rocky stratum containing a large amount of coal [9].
5. Super Plasticizer: These are used to improve the physicochemical properties of new concrete. Super plasticizers are added to the concrete. They help in spreading the constituent's materials evenly in the entire mixture of concrete. They remove liquids from cement particles where water is trapped and available for operation. Super plasticizer helps in increasing the slump value from 5 centimeters to 20 centimeters without the adding the water. Thus it reduces the need for water by 15-20 %. When the phases have closer reinforcement, the addition of super-plasticizer in the mix also increases workability. Hence no vibrator is required for compaction purposes. The permeability of concrete is very important property which is used to describe the durability of concrete. By addition of super plasticizer the workability of the concrete mix is increased. Hence, water to cement ratio is maintained in low proportion but the permeability of cement paste is reduced very much with it [4], [14].
6. Fibers: The performance of the ECC under heavy loads is dependent on the availability of fibers. It has

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fibers in small quantities when compared to Fiber Reinforced Concrete. Usually the most commonly used fiber in ECC is Polyvinyl Alcohol which has one notable feature that it makes a very strong bond with the cement matrix. The $Ca(OH)_2$ layer is made up of Polyvinyl Alcohol fiber having circular or round shape . This layer of the fiber is known as interfacial Transition Zone which has a white part. It cannot be seen in the case of poly propylene and glass fibers. It is found that PVA forms a complex bond with the hydroxide metal present in the cement matrix. Cement matrix has one Ca + and two different OH- ions in the which are absorbed by the Polyvinyl Alcohol fiber and used to form a layer of $Ca(OH)_2$. Hence this layer of $Ca(OH)_2$ plays an important role in making a strong bond between fiber and matrix because it is made around the fibers. It helps in increasing overall strength. The Poly propylene fibers and glass fibers have high tensile strength but they does not coated with any epoxy. Hence not preferably used due to their alkali nature [4], [14], [15].

C. *Mixing*

As mentioned above, ECC materials are cement, fly ash, fine sand, water, super plasticizer & 2% PVA fibers per volume. Practically, the dry mixture consist of cement, ash fly, sand and super plasticizer when mixed for the first time using a lab mixer type. This mixing should be done for 1 min. After the dry mixing water was added in the mix and mixed thoroughly for further 4 min. During this time, the prepared mix paste showed sufficient flow capacity and viscosity. It is required for good workability and proper distribution of the fiber in the mix. Finally, the Polyvinyl Alcohol fibers were gradually added and then the mix is mixed for about 3 min [8].

D. *Mechanics*

The tensile strain-hardening characteristic of ECC is because of the complex structure using the micromechanics model considering the interaction between the fiber, matrix and fiber-matrix configuration. Fiber-matrix configuration has characteristics which play a very important role in the strong tensile strain-hardening characteristic of ECC. The most commonly used type of fiber in ECC is a polyvinyl alcohol (PVA). Generally it has a diameter of 39 micrometer and a length of 6-12 millimeter. PVA fiber exhibits a slip hardening characteristic when removing from a matrix based on cement [6], [16]. The fiber-matrix than completes its debonding which is acc-companied by a decrease when the initial load reaches the maximum value in the pullout curve of single fiber. After this the bonding force occurring between both fiber and matrix start increasing till the fiber slips out of the matrix. It has also found out that the fiber gets completely out of the matrix if embedding length is less. In case of large embedding length the fiber will be broken. If the ECC has loading in tension, than the matrix start splitting itself into phase at a weak point in the cross section. The fibers which are able to cross this split are used to take the tensile stress. As the fibers come out of the matrix, the split continues to open. Due slip hardening characteristic the ECC can bear increasing load, creating new cracks at some sites. By repeating this process the ECC demonstrates the effectiveness of multiple fragmentation and, therefore, strain-hardening behavior. Fiber cracks are controlled by solid state waste disposal mode which stops these cracks from further widening [11], [12].

V. Disscussions

The development of environment friendly construction techniques over the past few decades has made it necessary to examine the existing construction practices and building materials. In the whole world, there are many ongoing efforts that have been made focusing on the invention and use of eco-friendly material which requires low-energy construction processes. It reduces the need for energy and also reduction in the waste materials. Another recent test in this area has been the development of Engineered Cementitious Composites (ECC).

In general, fragileness of concrete will increase with increase in compressive strength. This is the limitation of high-strength concrete use in buildings. The basic advantage of ECC material over normal concrete is that it produces cementitious material having very high ductility. It can be used for structural applications. It has characteristics of high strength concrete as well as increased tensile strain capability in comparison to normal or fiber reinforced concrete. Concrete is responsible for creating many significant social, economic and environmental impacts. In today's times, during the production of cement large amount of greenhouse gases (5%) such as essential NOx levels and particles also got released in the atmosphere. It is therefore important that sustainable and durable building materials such as ECC should be used effectively in any given environmental context to integrate eco-friendly communication between nature and construction. ECC's have been identified as part of the green materials for the overall purpose of improving environmental sustainability.

A. *Mechanical Characteristics of ECC*

ECC has a wide range of applications in different areas including structural repairs, earthquake resistance, impact and explosion due to its high-ductility, stiffness, and high strain capacity behavior when loaded. It can be considered as a group of materials having different properties and can be used for different functions. Self consolidating ECC are used for large scale applications for site construction, high-strength ECC are used when it is required to gain high strength quickly for the applications in transport sector, and light weight ECC are used when dead load of building is required to be less or minimum [7], [18].

B. Self-healing Characteristics of ECC

Buildings under the effect of natural environment are at risk of cracks mainly due to overloading, restricted restrictions, and severe weather conditions. ECC's can achieve its original strength which is lost by cracks due to the nature of the automatic healing. But at high temperatures it may be damaged and also the formation of small cracks occurs during self-healing leading to slow-moving treatment within a particular template. At high temperatures there will be an increase in final strength and a slight decrease in the strain hardening of ECC. It is due to the incomplete hydration of unused cement and fly ash. Self-healing can considered be useful in real life structures under certain natural conditions. It does not depend upon the life of the structures [7], [17].

Over the past decade, ECC's have emerged with a comprehensive public infrastructure - transport, construction, water and energy industries. ECC's have been used in the area of new integration property and in precast building structures in both new and existing buildings that need to be repaired or remodeled with the ECC [7].

C. RC Structures Strengthened by ECC

The use of ECC for RC structures, including RC beams, columns, and beam-column members. ECC is often used in conjunction with FRP fabrics or steel bars to maximize the strength of the structure member. When the ECC is introduced into a building member, several small cracks build up on the tensile surfaces or areas under complex stresses, such as under the beam and therefore T and the joint spine, while the load bearing capacity of the building member will not decrease. This rupture process often leads to a mode of ductile failure. FRP fabrics and steel bars can also improve the integrity of the structure to some extent, especially in strengthening the RC columns. However, the main role of FRP fabrics or metal bars is to increase the strength of the structure members [13], [15].

V. Conclusions

Concrete is the most important material used worldwide in all types of buildings. It has many different functions most common being to carry the heavy building loads. Due to the relatively fragile nature of concrete structure, there is nothing much that we can do in case of high tensile stresses and loads carrying capacity of the structure. Unfortunately, during the cement production itself large amounts of carbon dioxide got released into the atmosphere, which has a profound effect on global warming and temperature.

The ECC considers these specific factors and proves to be very beneficial in the use of the structure due to their unique characteristics and variety such as self-healing, low permeability, high ductility and high tensile strength. It is also environment friendly. The invention of the Engineered Cementitious Composite (ECC) has proven to be one of the most eco-friendly construction materials for upcoming generations with recent developments which made its use easy, efficient and economical in the real world. As we study the recent progression made in the field of ECC technology over the past decades, we certainly can expect much more exciting times in this field in the next decade. As work continues in research field, we will surely find some new positive aspects of the ECC that can used in new construction applications. It is envisaged that a new generation of ECC materials will include new designs, new materials etc. These new things will be

1. Designed to meet the performance standards of a building.
2. Friendly in terms of social and environmental standards.
3. Self-healing if damaged.
4. They will work beyond their efficiency to provide financial benefits.
5. Linked to this issue, a new construction techniques or programs with one or more of these features will be invented in near future:
6. Safe from repair requirements at least even after installation in difficult loading circumstances.
7. Intelligent with adaptability.
8. Large scale but without going back in size.
9. Negligible care and low maintenance even if used in a difficult area.
10. It is built with high speed and low waste.

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