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ENGINEERED CEMENTITIOUS COMPOSITES - A REVIEW

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ABSTRACT

This study presents a short summary on the recent progress within the analysis, growth and specific use of Engineered Cementitious Composites (ECC). The use of ECC as a replacement to conventional concrete will contribute to safer, more durable and sustainable concrete infrastructure. The material properties such as tensile and flexural characteristics, compressive strength, durability, permeability, self-healing capacity and seismic performance have been reviewed here. The material constituents and mix design used to achieve the unique properties of ECC concrete have been listed out and discussed. The potential structural applications such as Earthquake Resistant Structures (ERS), Bridge deck and link slabs, Pavements, Repair and Retrofitting works, which utilize the special qualities of ECC are included in this paper. A comparison between ECC and conventional concrete in terms of feasibility and cost efficiency has been made. The concept of green ECC for sustainable infrastructure and the scope for future research work has been addressed.

INTRODUCTION

In civil engineering applications like buildings, bridges, pavements, retaining wall structures, tunnel linear, etc are developed by the use of cement concrete. In recent decades, high compressive strength concrete is being used in various applications. Concrete is brittle in nature and as the compressive strength increases its brittleness increases. Higher brittleness can increase the chance of sudden failure/collapse during earthquake and impact loading [1]. If by some method the ductility is introduced into the concrete, it can reduce the sudden collapse or failure. In such cases concrete material is needed to improve its power and tensile capacity. To make the concrete ductile concept of Engineered Cementitious Composites (ECC) is introduced. ECC has ultra-fibres mixed with concrete. The ultra-fibres having reinforcement and ductile properties and it makes the mix ductile and more workable. The first use of ECC was found at the University of Michigan by Victor C Li. ECC is strong resistance against impact and earthquake loading [2]; also it reduces the total amount of reinforcement used in concrete. Ultra-fibres present in the ECC makes the flexible bond with cement-sand and aggregates which makes it more deformable against external forces [3]. It has higher resistance against vibration and heat. It is bendable with respective forces (moving loads, wind load, earthquake forces etc.) and absorbs the shocks. It can sustain higher loads with small amount of deformation; in other words, stiffness of ECC is huge as compared to conventional concrete. Further, ECC has, self-healing properties and improved durability. Apart from its use in structural elements, ECC is finding its way into repair and retrofitting of structures. In the present paper a deep review of various properties of ECC and its applications is presented.

CHARACTERISTICS OF ECC

The application of precast building material composite as a construction material is different from standard concrete being used now- a- days thanks to better properties of the former. Level of excellence is based upon its mineral composition to produce a new effect with the surrounding environment shown by it. ECC has self-healing property when it gets damaged from physical and chemical reactions. Tensile strength and ductility gets improved due to its improved physical characteristics. The tensile strength within a very low degree of permeability considerably decreases the micro cracking. This low permeability degrades the trend related to the assimilation of chemicals that include the corrosion of steel reinforcement and erosion of the concrete itself. These above characteristics are used to increase the lifespan and repair cycle of the concrete and the structure as a whole, whereas also making the requirements that permit certain chemical reactions to occur which will help bring about healing of the cracks of the concrete [4].

Tensile and flexural characteristics

ECC has the tensile strain capacity up to 3-5% (300-500 times varies from normal concrete) because the conventional concrete has tensile strain capacity up to 0.01% only. ECC can attain high ductility with comparatively low fibre content (2%) through methodical modification of the fibres, matrix, interface characteristics and guided by micromechanics properties. Micromechanics is the study of heterogeneous or composite materials on the extent of the individual constituents that represent the materials. Micromechanics theory affords a systematic approach in selecting the type, size and amount of the constituents and their combinations [5]. The principle of micro cracking is responsible for the distinctive tensile properties of ECC when compared with conventional concrete. ECC flexes without fracturing, due to the interaction between fibres, sand, and cement working in a matrix that binds everything together within the material. Where ordinary concrete and fibre-reinforced concrete (FRC) are designed to resist cracking, ECC is designed to develop cracks only in a controlled manner. The cracks that appear in ordinary concrete

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and FRC increase in width as they grow longer, these are termed Griffith-type cracks. Whereas the width of cracks that are designed into ECC remains constant regardless of the length, these are known as steady state (or flat) cracks [6]. A direct application of pure tensile stress is difficult and hence an indirect way is adopted by measuring the flexural strength of beam. The flexural reaction of ECC reacts with its tensile ductility. Underneath flexure, at the bottom of the beam multiple micro-cracks are formed, consequently it leads to tolerate a remarkably massive curvature growth, an occurrence that has provided it the name of bendable concrete. A flexural strength of regarding 10 to 15 MPa may be achieved. Deflection hardening is an essential property of ECC based on geometry. ECC has notable enhancements in fatigue strength compare to standard concrete and FRC. ECC was developed based on flexural fatigue tests where it shows high fatigue durability and ductility when compared with standard cement mortars widely utilized in repair and retrofitting applications [7].

Permeability and freeze-thaw durability

The Permeability Crack provides an easier access for the water, oxygen and other aggressive agents to pass through the concrete cover and come in direct contact with the steel reinforcement, therefore resulting in the beginning and proliferation of steel corrosion. Since cracks inevitably exist in concrete elements, the influence of crack width on the water permeability is of great interest from academic and practical point of view. Therefore, the micro-cracked ECC should definitely have better corrosion resistance in comparison with the normal concrete. Accelerated corrosion test has been conducted on steel-reinforced ECC beams, where mortar specimens of an equal compressive strength were used as reference. The results showed that due to its micro-cracking behavior and high ductility, ECC prolonged the corrosion propagation stage and retained much higher level of the loading capacity. These results are expected to contribute substantially in increasing concrete structures durability and sustainability by minimizing the needs of maintenance during the life span of ECC structures [5].

Self-healing capacity

Formations of cracks are inevitable during the lifetime of concrete infrastructure. Cracks are often shaped thanks to progressively high loading, volumetric modification thanks to temperature changes, plastic settlement, restrained shrinkage, creep, chemical actions like alkali-silicate reaction and freeze/thaw cycles. Cracks on concrete structures will have undesirable effects in various ways. It should cut back the sturdiness by making sequence for corrosive sources to perceive the concrete cover and affect the inside steel reinforcement. It can cause a rise in the maintenance cost and reduce the service life. Thus it's extremely desirable to develop concrete which will automatically recapture this loss of capability due to cracking. Theoretical and experimental results have exhibited that once cracked concrete is exposed to water, the un-hydrated cement gets hydrated thereby having the potential to cure itself over time by decreasing the crack width and this development is referred to as self-curing of cracks. The range of self-curing of cracks is especially based on the crack size. Compare to larger width cracks the smaller width cracks cure fully and at a quicker rate [10]. Thereby, the event of a cementitious composite that may autogenously counter the results of cracking by self-healing is extremely desirable. Self-healing results in crack-closing, therefore improving sturdiness, permeability, mechanical properties and therefore prolonging the service lifetime of infrastructure [11]. The long lifespan of ECC is not only attributed to its low permeability, high tensile and compressive strength, but also to the chemical action of self-curing that happens within the small size cracks formed. Thus it's needed to see up to what extent an ECC specimen will cure itself fully when susceptible for daily environmental situations. ECC specimens were observed up to one-year for mistreatment mechanical and resonant frequency (RF) loading for study the speed and range of self-curing within the inherent atmosphere. It was discovered based on the resonant frequency (RF) range, initial cracking influence improvement and stiffness enhanced with the rise in period of exposure to natural environment. Experimental results have shown that ECC samples kept under tensile strain and subjected to damp dry cycles, successfully healing the 100 micrometer cracks. Further testing during this study has exhibited that the addition of fly ash can reduce the average crack dimension up to 10 micrometers, therefore providing a faster and completely filled self-healing specimen.

MATERIAL CONSTITUENTS AND MIX DESIGN

ECC concrete constitutes of cement, sand, fly ash, water, admixtures and an optimum amount of fibers. Coarse aggregates aren't employed in the mix as they have an inclination to adversely have an effect on the distinctive ductile behavior of the composite. Ordinary Portland cement of desired grade can be used. Blast furnace slag can be used as adhesive if required. The fine aggregate to be used can be river sand or manufactured sand based on availability. To improve the fresh concrete workability without increasing the water cement ratio by adding super plasticizer is possible. The use of super plasticizers will avoid the need for compaction as they add on to the self-consolidating property of ECC concrete. Fly ash is a pozzolanic material which will be used as a partial replacement for cementitious material. The use of fly ash can reduce heat generation without considerable loss in strength. Unlike some High Performance Fiber Reinforced Concrete (HPFRC), ECC doesn't utilize great quantity of fiber. usually 2% or less by volume of intermittent fiber is sufficient, albeit the combined is meant to significant structural benefits. Based on the comparatively less quantity of fibers used, the mixing method of ECC concrete is kind of the same as that used for mixing standard concrete. The most common type of fiber used in ECC is Poly Vinyl Alcohol (PVA) fiber. High Young's modulus, bonding strength, durability and tensile strength are some of the properties that make it suitable for reinforcing cementitious composites. Water free from alkalis, oils, acids or any

other organic Impurities should be used for mixing concrete. In short water used for making concrete should be of consumable standards. The main purpose of adding water to concrete is for it to react with cement to form a cement paste adhesive until it hardens. Water cement ratio engages a critical part for determining the potential of hardened concrete. Optimum water cement ratio has to be used to maintain perfect balance between workability and strength of concrete [8].

STRUCTURAL APPLICATIONS

The special characteristics of Engineered Cementitious Composites that have been repeatedly tested in laboratories, pose several benefits to the construction industry through application. ECC's will make way for several potential enhancements to the present standing of typical concrete, and in some places, they have already been used as a construction material in projects. ECC structures shows more durability and less possibility to damage. Since feasibility is the capability to sustain, the additional study and long-lived structures related to the utilization of ECC's not provide solely for the feasibility of infrastructures in the world, however additionally for conjointly in preservation and renovate prices, as far as good environmental influence, and an overall development for the invulnerability of structures created by concrete [4]. Structural applications where ECC can be used are as impact resistant panels, strengthening of unreinforced masonry walls, repair and corrosion resistance for RCC beams and columns. Due to its ductility and tensile strength, ECC is suitable for members that take high loading and shock absorption like bridge surface decks, link slabs in bridges, pavements and seismic structures.

Bridge deck and link slab

ECC's mechanical properties and durability factors are its tensile behavior, crushing strength (350 times that of concrete and FRC) [12] and tight crack width control. The micro crack width of ECC formed is below 100 μm and can be independent of structural geometry and loading. Since steel reinforcement is not required to control crack width which is a cost effective advantage. Flexural Behavior of ECC helps to absorb shocks during transport and it also possess superb abrasion and wear protection. When the tensile strain is loaded to 15%, it is found that micro-cracked ECC displayed roughly the similar permeability as that of sound concrete. ECC has less water permeability by virtue of controlled formation of cracks, crack width is less. ECC also does not have dependency on the properties steel reinforcement and does not rely on applied strain level when strain capacity of ECC is not exceeded [12]. Rate of Chloride diffusion in ECC is comparatively lower. As a result, corrosion resistance is good. This signifies that the lifetime under service of reinforced ECC will be close to 15 times compared to reinforced mortar. Fatigue loading has no effect on the crack formation and fatigue resistance is fairly high. There is less reflective cracking in repairs due to formation of micro cracks.

Bridge deck patching

In 2004, ECC pavement patching test was done by MDOT in a two-lane bridge overpassing. Patch repair ECC was used in Southern Michigan on the bridge deck of Curtis Road over M-14 in October 2002. The mentioned bridge built in 1976, has simply supported four span along with a nine inches thick reinforced concrete deck and steel girder. Traffic survey conducted by the Washtenaw County Road Commission was measured average daily traffic (ADT) for this bridge around 3000 vehicles per day. In this experiment one part was patched using ECC while other part was patched using OPC for comparative study.

Over a long duration both patches were observed during site visits and pictures were taken to study day by day progress of crack development and patterns. After two days patching in concrete had a distinctly visible crack, around 300mm wide had been formed possibly due to shrinkage deformation whereas there were no visible cracks in ECC. After four months, during winter, small micro cracks, 50mm wide, created in the ECC patch. Concrete crack observed shortly after casting the concrete had widened to 2mm and showed signs of deterioration due to spalling. A crack of 50mm was revealed after 10 months of the patch work, whereas concrete had serious deterioration. Thus ECC survived the best under severe environmental and mechanical factors.

Bridge deck link slab

Between adjacent bridge decks, failure of mechanical expansion joint is a major issue, which could eventually lead to leaks and thermal deformations leading to failure of entire super structure. At the bridge deck water was discharging and fully soaking wet with de-icing salts used through cold weather, finally leaks through the damaged joints is the cause to corroding the steel girders, also penetrating moisture into the precast concrete girders moreover corroding the steel reinforcement [13]. Experiments showed that ECC had 4% strain in uni-axial tension unique capability to buckle close to while preserving small crack widths, this permits the ECC link slab to contain the distortion placed on the adjoining bridge decks during the contraction and thermal expansion, all the period the superstructure is protected from the action of corrosion. ECC had large tensile strain capacity as a link slab and saturated micro cracking (width 60 mm). This is sufficient to take care of all structural applications in link slabs. Also reduction in reinforcement is an added advantage in terms of cost.

Seismic applications

ECC Applications are considered mainly in structures where good energy absorption and high failure tolerance is required during performance. ECC can be opted to reduce seismic action and damage of structural members. Normal concrete simply as a brittle material is susceptible to collapse. Basic concept in earthquake engineering is based on the fact that when a building absorbs seismic waves from the earth it is transferred thorough out the buildings components like beam and columns. The Joints and structural members need to be ductile enough to absorb the vibration created without formation of cracks, which occurs at a faster rate in brittle material due to lack of elasticity. ECC having higher ductility and tensile strength is a suitable material for seismic resistance. Particularly the joints and structural members of the building need to be ductile, since it is the basic skeleton of the building and its failure could lead to complete collapse. To find out the seismic resistance of ECC a cyclic loading alternatively of tension and compression was given to beam members. The test outputs done with PVA-ECC showed that the brittle and shear failure seen in RCC can be prevented using ECC and it gave good ductile capacity. The PVA (polyvinyl-alcohol) fibers also helped confine the concrete after fracture. [14] The beam-column connections were also tested [15] using reverse cyclic load capable of producing seismic action using a 500KN hydraulic actuator. From the corresponding hysteresis loop diagram generated, ECC proved to have higher energy dissipation than other material. Also multiple small cracks were created in the plastic zones and joint cores allowing ECC joint to maintain its structure. As a result of these findings, ECC has massive potential in seismic resistance development of buildings where ductile material that are capable of withstanding seismic shocks are required.

Repair and retrofitting

Retrofitting is the process of modifying a finished structure by changing structural components to improve its performance and amenities. Some structures over time may need extra elements like columns or beams to undertake changes over years due to age and tectonic movement. It is uneconomical to demolish and rebuild old structures from scratch. In such case structural elements can be added using repair and retrofit techniques Properties of material that are particularly required for retrofit techniques are high efficiency, durability, Isotropic properties, easy flexible processing and shorter fibers at moderate volume fractions [16]. Isotropic property helps when the stress field has changing load conditions or the stress is multi-directional. Retrofits are designed by analyzing ECC established on its synergy between the fibers, interface and matrix components under load. To test its capacity as a retrofit material pre-cast ECC and FRC were analyzed under simplified boundary and loading conditions. The observations made were that ECC had three times the shear capacity of FRC. Also the strain distribution method is ease to finding the stress concentration for the ECC specimen. ECC thus has good shear absorbing capacity and tends to be isotropic in nature due to equivalent distribution of micro cracks formed. Repair-where a repair material is laid over a defective material. The repair material is required not to carry the stress from the defective material and develop cracks in itself. Repair factors that need to be taken into consideration is the lifecycle of repair, cost and durability. This durability can be created when the bond between the substrate material and repair material is at its best. Based on the bonding between these two layers, failure can occur in the form of “de-lamination” where weak bonds cause an internal defect. It can also occur if the bonding is too strong and if the repair material is brittle compared to the substrate. This failure is called “spalling”. Bond tests need to be conducted to analyze how the behavior or repair and substrate material is. Sometime difficulty in bond test occurs when there is a change in environmental conditions from the laboratory to the actual field performance. This is caused due to the mechanics of failure and material reaction under different conditions. In case of the mechanics, failure of bond is predominately due to fracture process variation for similar specimen of shape and geometry under different field conditions. ECC thus produces a solution to the bond failure problem. This is proved by a test where a substrate specimen already having a notch is coated with three different repair material-plain concrete, FRC and ECC. For ECC Overlay, a series of minute interface micro cracks occur under increasing applied loading. This makes it suitable as a repair material since there is no sudden failure, thus increasing lifetime of the repair component.

Pavements

Transportation is an important facility which determines the mobility of goods between places thus improving the overall development of a country. As a result, pavements are important transportation components required for a country also cost, durability, life time and maintenance criteria are some factors to be considered for effective and efficient pavement systems. Pavement Overlays- are materials used to rehabilitate and fix surface defects on a pre-existing pavement and to create a durable rigid surface with a long life-time and least maintenance. Types of Pavement Overlay (i) mixed asphalt with high temperature (HMA) (ii) an unconstrained concrete overlay. From these mentioned overlay systems, cause of the ultimate failure system is reflective cracking which decrease the life of surface of the overlay [17]. This reflective cracking is caused when an overlay also tends to develop cracks due to transfer of pre-existing cracks in substrate layer during differential loading caused by moving traffic. Extra Info-Modern methods to minimize reflective cracking contain the implementation of a bond disintegrate layer (i.e. HMA) beneath concrete overlays that reduce stress concentration at the origin of reflective cracking, full rubblization (In situ broken concrete into particles like aggregate) of pair deterioration of remaining

pavement before overlaying or surface of the concrete. Presently, reflective overlaying cracking has not been effectively eliminated in rigid pavement overlays.

Need for ductile rigid pavement overlay

A ductile material would be a solution to the formation of cracks which is due to brittleness of a material. Whereas a tensile material could help overwhelmed the fracture based phenomena caused by reflective cracking. This is where ECC comes into play. Based on mix proportions having 3% to 5% for the ultimate tensile strain capacity. This strain capacity is 300 times normal Ordinary Portland Cement and is created by many closely spaced micro cracks under load. These cracks carry increased load after formation causing materials strain hardening to be similar to ductile material. Inelastic strain is created in material due to distribution of micro-cracks along gauge length instead of single localized crack like in FRC. In FRC cracks are caused due to dislocation slip on crystallographic plane and the cracks open wide due to slow loading showing tension softening behavior by rupture of fibers. Conducting tests on these models overlay thickness were determined and a relationship between the highest stress developed in the appropriate edge loading of a one equivalent single axle load (ESAL) (80kN) dual axle load. Subgrade parameters and existing block were remaining constant ($E_{existing} = 20.7\text{GPa}$, $k_{subgrade} = 27.1\text{MN/m}^3$). For all combine designs in ECC overlay the coefficient of elasticity was additionally kept constant at 20.7GPa . But the coefficient of elasticity was magnified to 34.5GPa for the design of a concrete overlay. Based on the FEM model, subsequent overlay design chart was formed, concerning within the overlay design thickness with the highest stress level.

COST ANALYSIS

Engineered Cementitious Composites are around three times more expensive than conventional concrete, but when comparing costs, it is necessary to take into consideration the cost over the entire life span of the structure rather than taking into account only the initial costs. The financial benefits in the long run favor ECC as it saves up on the service costs. The use of high cement in ECC and expensive Poly Vinyl Alcohol (PVA) Fibers is responsible for the price difference when compared to regular concrete. PVA fibers weigh much less when compared to other fibers and steel used in FRC's and normal concrete. It is to be noted that ECC has a very low fiber volume when compared to other FRC's. The use of cheap pozzolanic alternatives such as fly ash as partial replacement for expensive cement will help in lowering the price of ECC without causing much changes in its properties. Since ECC is less brittle, more ductile and durable and also possesses self-healing property, it can cut down on frequent maintenance costs. In short, ECC is a cost effective construction material alternative to conventional concrete [4].

ENVIRONMENTAL SUSTAINABILITY

ECC by itself is not sustainable without the combination of industrial wastes. Green Engineered Cementitious Composites (ECC) where industrial wastes are used as constituents can be used to give more sustainable, eco-friendly, durable and rigid structure. It reduces pollution due to cement production and can use industrial waste as its constituents thus giving a greener alternative to ordinary cement. Use of industrial waste up to 70% in ECC has no reduction in its mechanical performance and there is 50% reduction in thickness of overlays reducing spacing. Furthermore "Green" ECC has been attempted to be formulated for sustainable development and environmental protection. The development of green ECC material is based on certain indicators called Material Sustainability Indicators (MSI). These indicators include the environmental factors like total production of energy; resulting amount of solid waste, carbon dioxide levels during production, water pollution caused by chemicals in ECC. Comparatively ECC has good mechanical performance but its environmental effects due to its manufacture are adverse in nature because of the proportionately of standard ECC has more cement content, also the addition of polymeric fibers is necessary. In terms of solid waste production, fly ash material usage reduces solid wastage. Fly ash is a waste that is created in from power plants where coal is used. We can infer from the table that by reducing cement and use of PVA fibers without compromising the ductility and other mechanical properties; we can reduce the environmental burden caused by ECC and increase its sustainability in comparison to concrete. The replacement of the components of ECC like cement and fiber with industrial wastes without compromising its mechanical properties is important. Few potential alternatives like fly ash and bottom ash can be used since they affect the environment and this can be reduced by using them to create green ECC. Other different materials need to be tested to find suitable alternatives. Experiments suggest inclusion of fly ash lead to improvement in the materials strain-hardening. When high volumes of fly ash were used. The results of the composites show 3% to 4% of the tensile strain capacity and while the material sustainability ratios significantly improved then the tensile strength becomes more than 4.5 MPa (653 psi) [19], Thus by using the concept of micromechanics, high performance criteria can be achieved using industrial wastes provided that the parameters are carefully designed.

CONCLUSION

ECC shows a number of special characteristics that look appealing to the construction industry and its engineers. Experimental studies show that ECC can perform remarkably better than conventional concrete when subjected to all forms of severe environmental and mechanical conditions. After a long stretch of

research and development of ECC, it is now not just confined to research laboratories but is making its way into real life applications in the construction industry through precast elements, conventional in-situ casting and repair and retrofitting works. ECC also has demonstrated to possess flexibility in the processing route, which include in-situ self-consolidating casting, spraying in form of shotcrete and also in precast and extrusion elements. The application of ECC in the commercial market may benefit many, established consequently on the fact that the life span of the concrete infrastructure gets increased exponentially. The fields of application of ECC are forever expanding. The use of green ECC makes way for significant reduction of energy resource consumption, material consumption and emission of pollutants. Engineered Cementitious Composites anticipated in future become more ubiquitous in all concrete infrastructure construction works worldwide. Despite the advancement in the improvement of ECC and real life use accessible, a large amount of experimentation and more number of research are still needed. On further research, more favorable characteristics of ECC might be discovered that will make way to modern infrastructure applications [20]. As research advances more laboratory work and investigations can be done to determine the shear resistance and Poisson's ratio of ECC. Another space for analysis is an examination of the fiber distribution and orientation within the materials, and also the development of strategies to gauge the orientation and effect of fiber distribution on the tensile response of the materials. Applied mathematics strategies will be used to develop representative samples of the fiber orientation, and surface bond strength of the fibers [21]. Continued research will maintain the materials-structure interaction approach and will focus on filling in knowledge gaps in material properties and design [13]. The use of pozzolanic industrial wastes as partial substituents to cement has to be studied in detail to develop eco efficient green Engineered Cementitious Composites.

CONFLICT OF INTEREST

There is no conflict of interest.

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