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A Review on Different Materials Composition of Engineered Cementious Composites, Micromechanics and Structural Applications

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Abstract

Concrete, a commonly used material in construction, has limitations such as brittleness, low tensile strength, and shrinkage cracks, which impact its sustainability. These limitations result in a brittle failure mechanism under load, highlighting the need for alternative solutions to enhance durability and address these challenges. Engineered Cementious Composite (ECC) is a fiber-reinforced concrete with high ductility, strain-hardening behavior, and multiple fine fractures. It offers improved impact strength and self-healing properties, making it a valuable material for enhancing structural performance. This study explores the application of bendable composite or engineered cementious composite (ECC) in building, transportation, and water resources infrastructure. Different researches from the developed countries has been studied and the parameters for the bendable composite are identified. It aims to provide insights for developing countries to produce and use ECC with local materials effectively in their infrastructure projects.

1. Introduction

Sustainability in construction is requirement of this modern time. Concrete being a material used widely in development has some flaws which puts a limit on its utilization and durability. Concrete used in construction has certain flaws like brittleness, weakness in tension and shrinkage cracks formation. Concrete exhibits brittle failure mechanism under load due to low tensile strength [1]. Concrete can have synthetic and polymer fibres added to it at specific ratios to increase the vital ductility behavior. Bendable composite also called ECC engineered cementious composite are fiber-reinforced composites with strain hardening behavior and multiple fractures development [1-2]. ECC may reach a strain capability of 3% and a fracture width under 100 micrometer in tension stress with correct micromechanics-based design, which gives structures remarkable ductility and robustness [1]. Many nations, including those in North America, Asia, Australia, Europe, South America, and South Africa, have created, developed, and deployed a variety of ECC mix designs in different structural elements [3].

Bendable composite or ECC consists in a classification of fiber reinforced composites that has high tensile strength and resilient tensile properties with many fine fractures of width less than 100 micrometer, then concrete having one large crack. Due to its outstanding strain-hardening capabilities and high mechanical performance, fibre reinforced cementious composites are frequently used to prevent the spread of fractures and reduce the brittle fracture of traditional cementious composites [2]. ECC has ability to heal these small cracks, when it comes in contact with water and air [3] [4]. Subjected to tensile and bending loads, typical ECC displayed good energy dissipation capability and formed a considerable number of fine fractures [5]. ECC, a specific class of fiber reinforced cementious composites, have been developed to increase the impact strength of structural materials [6]. The number and breadth of the crack, which distinguish the various cracking procedures of ECCs, are highly correlated with the higher flexibility and durability of ECC.

Local materials are favored for BC or ECC in large scale applications for both structure performance and economic reasons. In Germany and Brazil, ECCs made from regional raw materials and PVA fibres have been created successfully. ECCs made using local PVA fibers were also studied in China. Mechanical qualities and cost management, however, are still unacceptable. Hence, a better alternative fibre option has to be created. BC or ECC has been prepared with different material composition and fiber types. There have been several attempts to replace all or a portion of PVA fibres with less expensive synthetic fibres like polyethylene (PE), polypropylene (PP) and polycrylonitrile (PAN) fibres. Finding substitute fibers is crucial since the widespread use of ECC has been greatly constrained by the material performance and high cost of PVA fibers [11].

ECC application has been reported in three different types of infrastructure i.e Building infrastructure, Transportation and Water Resources infrastructure. Issues in Building, Transportation and water resources infrastructure are resolved using different qualities of ECC material [21]. This study is focused on the emerging new material that is bendable composite or engineered cementious composite with in the developed countries and how the developing countries can produce this material. Different papers have been studied in which ECC has been reported. BC or ECCs behavior, micromechanics design and its criteria's, along with the material used by the developed countries and followed by the practical applications in different infrastructure. The knowledge can be utilized by the developing countries for producing the bendable composite and utilizing it for solving various issues in different infrastructure projects.

2. Nature of BC and NC

Concrete has traditionally been used by structural engineers to support compressive loads. However in actual field circumstances, loads and environmental factors like shrinkage, chemical deterioration, and heat impacts can predispose concrete to tensile stresses. Concrete's tensile strength is only 10% as strong as its compressive strength. The fundamental drawback of concrete is that it is brittle, which leads to damage, degradation, and cracking, and necessitates frequent repair of the structural parts [7]. A composite known as bendable concrete or engineered cementious composite, which has properties with strain hardening effect of the reinforced fibre, is developed when synthetic polymer fibre from the textile industry of high tensile strength is combined with concrete ingredients less coarse aggregates, along with fly ash and super plasticizer. The composite is exceptionally durable, capable of self-healing, and highly resistant to shrinking, impact, and fire resistant [6]. Traditional concrete is limited in its ability to withstand tensile stresses due to its brittleness, leading to damage and frequent repairs. A composite material called bendable concrete or engineered cementitious composite, combining high-tensile-strength synthetic polymer fibers with concrete ingredients, offers improved durability, self-healing properties, and resistance to shrinking, impact, and fire.

Bendable composite or (ECC) are fiber-reinforced materials with strain hardening behavior and multiple fracture development [8].ECC may reach a strain capacity of above 3\% and a fracture width under 100 um in tension with suitable micro mechanics-based design criteria. Due to their outstanding strain-hardening capabilities and high mechanical performance, fibre reinforced cementious composites have been widely used to stop the spread of fractures and reduce the brittle fracture of conventional cement-based materials [9]. Fibres are placed into concrete, which has great impact and abrasion resistance, to reduce cracking caused by dryness and plastic shrinkage [10]. The tensile strength of ECCs is approximately (4:12) MPa, and the range of the midpoint beam deflection is (4:7) mm. When compared to a regular concrete mix, it has a higher resistance to freeze-thaw [12]. Bendable composite materials, such as fiber-reinforced ECC, offer high strain capacity and narrow fracture widths, making them effective in preventing crack propagation and reducing brittleness in cement-based materials. By incorporating fibers, they improve impact resistance, reduce cracking, and exhibit enhanced freeze-thaw resistance compared to regular concrete mixes. Fig 1 shows the brittle nature of normal concrete, tension softening of FRC and strain hardening nature of ECC.

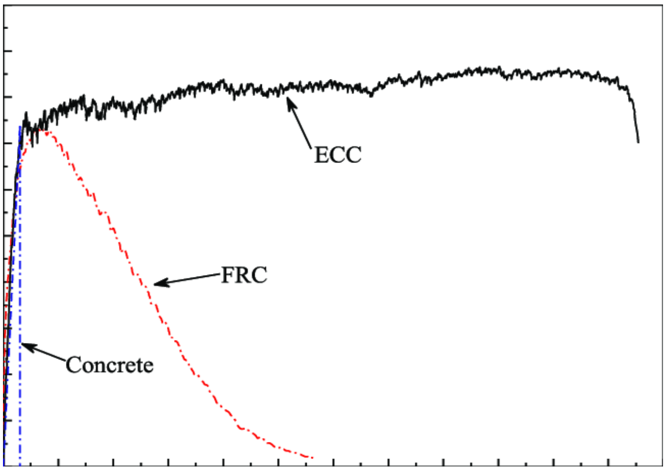

Figure 1. Tensile stress-strain curves of strain-hardening ECC, tension-softening FRC, and quasi-brittle concrete [11].

2.1. Bendable Composite Micro-Mechanics

To ensure crack initiation at multiple locations, the maximum fiber-bridging strength must be greater than the matrix rupture strength, while the complementary energy of the bridging fiber must surpass the peak of the crack toughness to ensure steady-state condition multiple cracking. These requirements are outlined in the ECC pseudo strain hardening criteria [3-12, 16-20]. According to the strength requirement, the ultimate crack-bridge stress must be greater than the matrix initial cracking strength. The energy criteria states that the fracture tip toughness of the matrix should be outperformed by the fibre bridging complementary energy. Fig 2 represents load crack opening relation of fiber reinforced ECC The likelihood of creating new fractures in an ECC specimen is more favorable with a higher bridging energy value [20-22]. Micro-crack initiation from flaw happens at cracking strength, and steady-state flat crack growth happens at steady-state stress. Multiple cracking occurs when both the strength conditions are satisfied, as seen by the ECC's tensile strain hardening effect presented in Fig 2. The ECC pseudo strain hardening characteristic state that maximum fiber bridging capacity strength must surpass the matrix rupture strength while the complementary energy of bridging fiber should surpass the peak of the crack toughness. ECC materials demonstrate a tensile strain hardening effect through multiple cracking when these strength conditions are met.

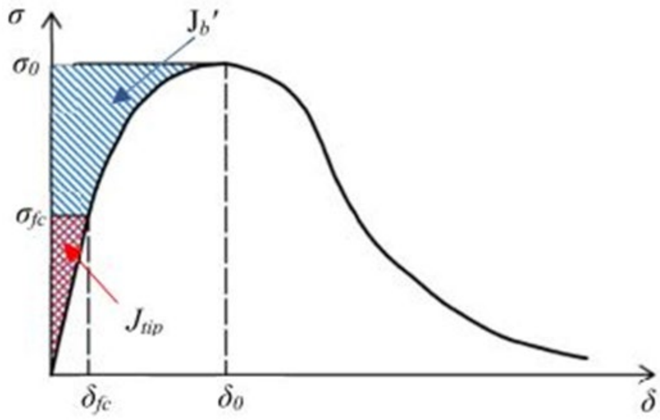

Figure 2. Represents the Stress vs crack opening relationship of bridging fibers in ECC [3]

2.2. Cracking Phenomena

Multiple cracks in steady state condition that develop after starting within fault locations and extending in the matrix under continuous ambient load—are reasoned for the ECC tensile behavior of strain-hardening [2-3]. The energy added from external effort less the energy of the fiber-bridging, which is referred to as the complementary energy of fiber-bridging. The need for steady-state cracking, according to physical interpretation, is that the system's net available energy be adequate to overcome the fracture tip toughness for indefinite crack expansion at an uninterrupted ambient load [5-7]. Another crucial requirement for the development of numerous steady state fractures in ECC is that the composites tensile fracturing strength must be larger than the fiber-bridging strength [18]. A strength-based crack formation criterion makes sure that fractures can start from a variety of rupture locations whereas the steady-state condition fracturing specifies the mechanism of crack propagation [9-10].

The addition of various fibre kinds and sizes can have various inhibitory impacts on the spread of fractures in concrete. When steel and polymer fibres were combined to create ECC, some researchers discovered that the hybrid fibres' synergistic impact allowed ECC to achieve substantially smaller fracture widths and less drying shrinkage [11]. Inner pores and the interaction among sand and cement mix in ECC are the main contributors to crack start and growth [14]. As the mid-crack gap expands endlessly with crack length in this crack development mode, fibres farther from the fracture tip can be dragged out or shatter. This phenomenon has the immediate effect of requiring an ambient load drop to maintain balance as the fracture widens, causing the material's sensitivity to strain to soften. The depletion of bridging fibres caused by the whole path of the propagating fracture will reduce the composite's ability to support loads. This crack propagation method, also known as Griffith form crack propagation, is undesirable for repeated cracking because it causes the specimen to continuously unload (soften) after a matrix first crack appears [15].

For cemetitious composites reinforced with fibres, a different flat crack growth pattern is proposed. In this pattern, the fracture is largely flat with a constant opening for cracks under a stable ambient load, with the exception of a tiny area around tip of the crack. This flat cracks mode beats the Griffith fracture propagation mode, if the following condition is satisfied: When a crack starts at a defect site, the maximal complimentary energy is necessary to surpass the matrix toughness for the flat crack development mode to must win over the Griffith crack development mode. This may be accomplished by restricting the matrix toughness, which is controlled by the matrix's material composition. For the ECC matrix, these considerations offer design recommendations. Alternately, raising will also encourage the spread of flat cracks and consequent multiple cracking. Standards of design for the fibre and ECC interface are provided by this factor. For this, a deeper comprehension of the stress crack opening connection is required [18-22].

3. Materials used in ECC and Normal Concrete

For producing plain cement composite (PC), OPC cement along with sand locally available and portable tape water are used. While making bendable composite OPC cement, Fly ash, Sand, Super plasticizer and portable water are used along with synthetic polymer fibers. When cracking begins in the matrix (post-cracking area), fibre crack bridging, which includes crack limiting and crack stabilization, becomes the principal role of the fibres in the matrix [12].ECC reinforced with PVA fibres having a tensile strength 1,600 MPa produced a tensile value of 4.5 MPa and tensile strain value of more than 4%. In contrast to PE fibres, which have a tensile strength in the range of 2500–3800 MPa, PVA fibres have a comparatively low tensile strength of 800-1600 MPa. Due to the high tensile strength, elastic modulus, and hydrophobic properties of PE fibers—all of which are crucial for the structural reliability performance—PE-ECC produces more robust tensile ductility than PVA-ECC, with a tensile strain capacity of over 4% [16-18]. The different material combinations which are used in different studies for making of ECC are represented in table 1.

The performance of the fibre and matrix interfaces determines the characteristics of ECC composites. The fibre component of ECC serves as coarse aggregate in part and boosts ductility by bridging crack forms. Recron 3s, a polyester fibre, was utilized in ECC, and it was discovered that it eliminates shrinkage cracks, hence reducing moisture infiltration. It produces homogeneous concrete, enhancing its capacity to absorb more energy while also improving its mechanical characteristics, ductility, and flexural strength. Further research revealed that the steel, carbon, glass, and polyethylene (PE) fibres are also used in ECC as represented in Table 1. Because coarse aggregate is totally neglected in this composition, the part of powdered content is considerably larger than that of typical concrete. In order to make the paste for creating ECC concrete, several pozzolanic ingredients were added to cement in order to enhance powder content. Numerous studies were done to assess how well ECC combined with various mineral admixtures performed. Table 2 lists the different mineral admixture types and their impact on ECC.

Table 1. Different material composition used for ECC

Ref	Fiber/Length	Fiber Tensile Strength	Cement	Fly ash	Sand	Superplasticizer	W/B Ratio
[1]	PVA/ 12mm PET/ 12mm	950 MPa 900 MPa	OPC	Class F	Silica Sand	Polycarboxlate SP	0.30
[2]	Steel/30mm	1570 MPa	OPC	-	Normal Sand	Polycarboxlate SP	0.35
[5]	PE/ 12mm	3000 MPa	OPC	Class F	Silica Sand	Polycarboxlate SP	0.30
[6]	PVA/ 12mm	1560 MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.28
[7]	PVA/ -	-	OPC	Class F	Silica sand	Polycarboxlate SP	0.30
[9]	PE/ 18mm	2400 MPa	OPC	-	Silica sand	Polycarboxlate SP	0.30
[11]	PE/ 12 mm Steel/ 13mm	3000 MPa 2850 MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.24
[13]	PE/ 18mm	2900 MPa	OPC	Class F	Silica Sand	Polycarboxlate SP	0.32
[14]	PE/ 6mm	3000 MPa	OPC	Class F	Silica Sand	Polycarboxlate SP	0.26
[15]	PE/ 13mm	3200 MPa	OPC	-	Silica Sand	Polycarboxlate SP	0.38
[16]	PE/ 6mm	3000 MPa	OPC	Class F	Quartz sand	Polycarboxlate SP	0.26
[17]	PE/ 18mm	3000 MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.20
[18]	PVA/ 12mm	1631 MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.42
[22]	PVA/ 8mm	1620 MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.27
[23]	Basalt/ 9mm	2230 MPa	OPC	Class F	-	Polycarboxlate SP	0.20
[24]	PVA/ 8mm	1600 MPa	OPC	Class C	Silica sand	Polycarboxlate SP	0.25
[25]	PE/ 12mm	3000 MPa	OPC	-	Silica sand	Polycarboxlate SP	0.35
[26]	PE/ -	3000 MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.32
[27]	PVA/ 8mm	1600 MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.11
[28]	PVA/ 8mm	1600 MPa	OPC	Class F	River sand	Polycarboxlate SP	0.32

Table 2. Mineral admixtures types used in ECC

Reference	Mineral admixture type	Observation
[1,5,6,7,11,13,14,16,17 18,18,22,23,26,27,28]	Fly Ash Class F	increases the toughness, ductility, and workability
[9,15,25]	Silica Fume (SF)	Improve mechanical properties and Durability
[9]	(GGBS) Slag	Reduced permeability, increased toughness, Long term strength and reduced hydration Heat.

4. Application of ECC in Structural Elements

Without practical uses for the material, the making of Engineered Cementious Composites (ECC) would fall short. Applications for the field have several uses. First, it offers the chance to link fundamental material properties—in particular, the high tensile strain ductility of ECC—to improved structural performance. Second, field applications demonstrate the value of ECC's special qualities, which are not possible with regular concrete. Third, practical experience with ECC in structures offers a feedback channel for further material development and improvement. Several large-scale applications in Japan, China Korea and the US in structural elements and problem solving. Some of the applications are listed in Table 3 below.

Table 3. ECC applications in infrastructures, [21].

Infrastructure	Application	Issue Solved	Property Utilized	Process Method
Building	Building Core Coupling Beams	ECC's damage tolerance enables rapid recovery from seismic occurrences while also	Damage tolerance, tensile ductility, energy absorption	manufactured precast

		reducing the need for repairs and replacements, cutting down on installation costs and time, and increasing useable floor space.	under stress, and fire resistance	
	External walls insulation	comply with governmental energy regulations; Reduce the cost, time, and labor of building Reduce the possibility of uneven building quality on the job site.	Resistance to drying and heat cycles	manufactured precast
	Retrofit of External walls to prevent concrete spalling	Reduce the likelihood of falling debris and the associated responsibility; accelerate retrofit; and increase reliability.	durability in tropical climates and along coasts; capacity to hold spalling	Hand troweling at the spot
	Modular housing	Decrease installation time, weight, labor, and installation equipment.	Crack resistance without steel reinforcement	manufactured precast
Transportation	Retrofits to the bridge deck and the link slabs on the roads	Reduce the frequency and expense of maintaining the bridge deck; quiet down the traffic	Narrow crack width, tensile ductility to accommodate heat deformation, fatigue resistance, and wear resistance.	Precasting or casting in situ
	Composite bridge deck	Reduce the possibility of steel deck fatigue failure. Reduce the price and weight.	Tensile strength and fatigue resistance	casting in situ
	Tunnel linings repair and retrofit	Reduce costs and labor. Reduce maintenance needs	Water tightness, carbonation resistance, freeze-thaw resistance, and tensile ductility	Spraying
Water Resources	Retrofit of Mitakadam	Extended service life and less chance of dam leaking	Water tightness; resistance to cracking and spalling	Spraying
	Repair of dam of hydraulic power plant	Reduced chance of reflective cracking; lessening of water leakage	Tensile ductility Water tightness	Spraying
	Irrigation channel repair	Prevent water loss; Reduce Maintenance frequency and cost	Water tightness; resistance to cracking and spalling	Hand troweling; spraying

5. Conclusions

Bendable Composite or ECC exhibits superior pseudo ductile behavior compared to normal concrete due to multiple cracking phenomena and resilient strain hardening nature. Single brittle crack in concrete is replaced my multiple small cracks which dissipates the energy in steady condition. ECC provides crack-resistant concrete for use in structural applications. Bendable composite is a fantastic material to employ in the construction sector due to enhanced mechanical qualities of concrete, which the normal concrete can doesn't have. The following findings are drawn in light of the assessment of the ECC concrete study:

- Utilization of ECC in flexural elements of all categories improved the load taking capacity and fracture performance. Flexural members composed of ECC exhibited enhanced ductility and dissipation of energy which were exceptionally excellent then conventional concrete.
- Bendable composite materials, like fiber-reinforced ECC, are effective in preventing crack propagation and reducing brittleness in cement-based materials.
  - The ECC tensile behavior of strain hardening is achieved through the development of multiple steady-state cracks.
  - The energy input exceeds the stored energy in fiber-bridging, and the composite's tensile fracturing strength must be greater than the fiber-bridging strength.

- For ECC concrete, PVA fibre is typically chosen. But the outcomes of other fibres, such those made of steel, glass, and (PE), are equivalent to those of PVA fibres. Because of strain hardening tendency of beams upon loading, fibre dosages within 1.5% and 2.0% had demonstrated greater flexural strength performance and ductility.
- ECC exhibits superior performance in buildings, transportation and water resources infrastructures. Various problems are solved through utilization of ECC qualities in terms of ductility, toughness, strain hardening behavior and durability.

The developing countries can utilize this emerging material properties to solve different issues. From materials prospective ECC made from local material is encouraged if the matrix exhibits behavior of similar nature. The tensile properties enhancement of concrete is mostly preferred. ECC application has predominantly been studied in large-scale infrastructures, while its presence in small-scale projects remains limited.

Nomenclature

BC: Bendable Composite
ECC: Engineered Cementious Composite
PVA: Poly vinyl alcohol
PE: Poly Ethylene

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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