A STUDY ON FIBRE REINFORCED BENDABLE CONCRETE

Dr. S. Lavanya Prabha [1], Rebecca Lalremruati[2]

[1]Professor and Head of Department, Department of Civil Engineering, Easwari Engineering College, Ramapuram, Chennai, India

[2]P.G Student of Department of Civil Engineering, Easwari Engineering College, Ramapuram, Chennai, India

ABSTRACT: Concrete which can withstand high bending pressures is known as bendable concrete.Engineered Cementitious Composite (ECC) is another term for it because as concrete bends, fiber moves inside of it to provide it with enough strength to prevent breaking. Engineered cementitious composite, a performance-enhancing substance having a volume percentage of 2% discontinuous fiber, cement, fine aggregate, fly ash and chemical admixture.To make the concrete more flexible, cementitious materials and hybrid fibers such as steel-PVA (Polyvinyl Alcohol) fiber, steel-carbon fiber, and carbon-PVA fiber are used in place of coarse aggregate. A review paper is done based on the mechanical properties, Micro-structure properties and ECC's durability properties. Nearly 50 papers are reviewed and presented in this paper.

Keywords: *Engineered Cementitious Composite (ECC), Mechanical properties, SEM (Scanning Electron Microscopy), PVA, Steel and Carbon Fiber.*

INTRODUCTION

Engineered cementitious composite (ECC), a performance-enhancing substance having a volume percentage of 2% discontinuous fiber, cement, fine aggregate, fly ash and chemical admixture. Due to its superior mechanical properties, ECC stands for high performance fiber reinforced cementitious composites (HPFRCCs), includes considerably increase tensile strain hardening capacity, enhanced ultimate strain potential and better tensile strength inspected by Victor Li [45].The ECC material has been recognized as a highly useful material for barrier protection construction and structures that provide safety due to its excellent mechanical properties and the presence of numerous micro-cracking, which give it a high ability ofshutters that absorb energy and are impact resistant which was explored by Victor Li, Kong H.J[46].

The form, structure, and volume ratio of the mixture components control the mechanical properties of ECC; in addition, the characteristics of the fiber have a great impact on the material’s mechanical features. In the ECC material, combination of fiber, matrices, and contact result in high ductility, and immediate collapse is deferred by the formation of many cracks. ECC mixtures have included fiber such as steel fiber, carbon fiber, basalt fiber, polypropylene fiber, coir fiber, polyethene fiber, jute fiber, polyvinyl alcohol fibers etc. The fiber inclusion boosts the concrete’s strength, capacity for strain, and energy absorption, reducing the harm that a concrete element might experience during the impact carried out by Kawamata et al [42]. Wang et al [50] found out that ECC has the unique property that, after the initial crack, the carrying capacity under tensile pressure keeps increasing so as a response of strain hardening and subsequently repeated cracking. As a result, ECC is susceptible to a 3-5% tensile strain, with cracksof 60µm broad and placed 3 to 6 mm apart. Even while the microscopic cracks may keep on developing the entrance of the moisture or other chemical substance, these small minor cracks might have a lower amount influence based on the material's permeability of water. Steel, glass, and carbon fibers that exhibit a high modulus, improve the material's bulk strength and toughness.

Fiber with a low-modulus like PP, PVA, and PE fiber have been discovered to considerably increase the ductility of the concrete mix and decrease cracks. High strain capacity and tensile strength are required for high resistance to impact as tensile strength is essential for penetration resistance as well as for impact energy, pressure endurance is needed. It has a high potential to resist impact since the hybrid fiber-reinforced ECC material, which combines low and high modulus fiber, is expected to simultaneously enhance in tensile strength and strain capacity. As a result, a maximum strength cementitious composite is employed, a hybrid fiber might be needed for composite with a strong material composition that also retain the same strain-hardening properties.

Thus, the survey obtained from the above paper has indicated that Bendable concrete can be used as an alternative to conventional material for further construction.

2. REVIEW BASED ON SELF HEALING ECC

Throughout the lifespan of concrete construction, cracks are unavoidable. Structures that are directly in contact with the environment are vulnerable to cracking due to harsh weather conditions as well as factors including high loads and restrained shrinkage.

Granger et al carried out that concrete when exposed to water, cracks concrete can heal over time according to studies. It was shown that as water is permitted to seep through damaged concrete cracks, there is a gradual decrease in its permeability. This decrease in permeability is caused by the shrinking fracture widths induced by healing. There is information that a variety of chemical and physical systems are involved in the complex process of healing.Previous research has proposed the following mechanisms for healing: un-reacted hydration of cement, C-S-H expansion, calcium carbonate crystallization, water impurities close crack and spalling particles of concrete on the crack faces to seal cracks. It has been clear that the calcium carbonate precipitation is the primary process for the self-healing of concrete cracks, even though all of these methods contribute to healing explored by Wang et al [39].

Micromechanics has been used to improve the ECC, a fiber-reinforced cementitious composite, to create high tensile strength and small fracture widths. ECC can maintain tight fracture widths of less than 60μm while producing a 3% to 5% tensile strain limit when applied (as opposed to 0.01-0.02% for standard concrete. According to numerous experiments research and direct experience, it is considered that a complex chemical and inside the self-healing of cracks through cementitious materials, physical combination mechanisms are involved. The majority of the literature studied suggested that there are many potential causes for self-healing behaviour. (as in figure) [20]:

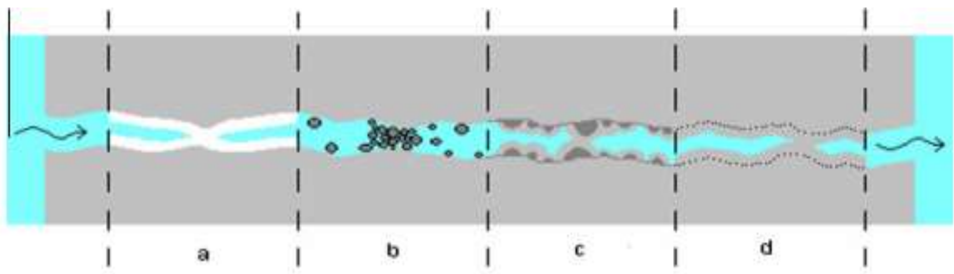


Fig.1 self-healing process in cementitious material [20]

a. Preparing calcium carbonate or calcium hydroxide.
b. Lock crack and loose concrete pieces caused by cracking.
c. Unreacted cementitious material or hydrated cement.
d. Hydrated cementitious gets expand in the fracture flank.

Finally, the small cracks which are an inherent material quality of ECC, induce strong self-healing behaviour, which is hard to accomplish in brittle concrete with wide cracks. No matter how much steel reinforcement is present, ECC's small crack width is independent of both the specimen's and the structure's size.When specimens are healed in a controlled lab setting, self-healing in ECC is extensive and reliable.

3. REVIEW BASED ON VARIOUS MIXED COMPOSITION

3.1 CEMENTITIOUS COMPOSITION

Victor Li [45] researched that cement-based substance is also called as ECC consisting of cement, sand, fly-ash, cooper slag and adhesive supplemented with 2% of volume percentage of short discontinuous fiber that is randomly distributed.

Emily N. Herbert et al [24] found the width of the crack in the material has a substantial influence on an ECC mix's self-healing capabilities. Because of this, it was decided to employ ECC blend with narrower cracks than the combination used in the earlier study of the natural environment.Fly ash of Class F, silica sand with a typical size of particles of 110µm, a high range water reduction mixture based on polycarboxylates (HRWRA), and polyvinyl alcohol fiber were the basic component utilised to make the ECC mix.

Victor Li and T Kanda [45] learned that even though fiber has strength, diameter, and elastic modulus, adjustable elastic modulus and controlled toughness are feature of material's composite.Chemical and frictional bonds contribute to the interfacial zone's slip-hardening properties. Theoretical analyses of micromechanics thatallow interactions between the interface abruptly, matrix, and fiber.

Zhang et al [37]studied that very little fine aggregate and a comparatively weak matrix can be used to manage the fracture resistance of the matrixto produce the numerous cracking behaviours and strain-hardening.

Bypaneni Krishna Chaitanya [3] studies found that replacement of Portland cement with copper slag up to 15% by weight increased stress because of reduced capillary porosity connected to hydrated lime while substituting fine aggregates and coarse mixture concrete with copper slag 40-50% and 40-60% (by weight of sand) improved strength.

Under AS 3972, the ECC mixes' binder component was Portland cement, which had a specific gravity of 3.15.For ECC future of micro-mechanical systems,the fine river sand was selected as the fine aggregate with a maximum size of aggregate of 0.5 mm.Fine sand's fineness modulus, specific gravity and unit weight were comparable at 2.21, 2.61 and 1502 kg/m3. In addition to increasing the flow of the mixture,to keep the matrix stable, the fly ash used had a specific gravity of 2.35–2.40. To obtained desire workability, a range of carboxylic ether superplasticizers with a specific gravity of 1.085 were evaluated [26].

It is concluded from the above paper that water binder has a substantial impact on how well bendable concrete performs. Concrete strength and workability are both influenced by the water-binder ratio. Due to the fly ash's ball effect, a specific amount of fly ash that can be used instead of cement in concrete improves the fluidity of the mixture and aid in the even dispersion of fiber.To achieve the high strength and durability demands in concrete,it is advised that copper slag be used as a fine particle alternative up to 40-50% (by weighing the sand). The water-binder is usually of the matrix at the range of 0.3

3.2 FIBER CONTENT AND SELECTION

Fibers in concrete make the concrete more ductile, so fiber is very important for making ductile concrete and hence reduces the crack growth and increases impact strength. There are many papers using different type of fiber such as aramid, polyethene, polyvinyl alcohol, jute, coir polypropylene, basalt, carbon and steel fiber.

Zhang et al [22] found that high-modulus nanofibers like steel and carbon fiber, which is characterised by limited strain capacity and high tensile strength, are employed in composite made of fiber reinforced cementitious, whereas low-modulus fibers like polyvinyl alcohol show the reverse behaviour.

Yifeng Ling et al [32] discovered that the inclusion of PVA fiber considerably increases ECC’s tensile strain, strength of flexural and tensile. The maximum possible development of flexural strength by 1.5% PVA fiber content was 116.4% and PVA fiber of 1.2% content was almost 100%. Also, the ultimate strain of ECC’s significantly increased as increase in PVA fiber.

S. Wang and Victor Li [44]found that combining 1.5% PVA and 0.5% SF is highly effective in improving strength, ideal strain, and molecular bonding in the process of dehydration of the binder mixture which has resulted in a significant improvement in ECC's ductility and shutter resistor with small damage of area, fragmentation and spalling of concrete.

YifanZheng and FarhadAslani [14] studied the impact of various PVA fibers and ACP (Activated Carbon Powder) contents on the mechanical and fresh characteristics of an ECC mixture, as well as the anisotropy of the 3D composite structure concrete printing. Results show that PVA of 1.5% and ACP of 0.5% provide flexural strength of 8.16 N/mm² and compressive strength was found to be 54.6 N/mm² at 28 days. The density of the specimen was adversely affected by increasing the fiber content to a certain limit.Since ACP granules clog the mixture's pores, the addition of ACP produced denser composites.

Wang S, and Victor Li (2005) learned that in order to strengthen the matrix for outstanding impact resistance, new fiber reinforced ECC hybrid material having PVA fiber of 1.75% and steel fiber of 0.58% is employed. Research discovered on impact strength of concrete with steel fiber that the best steel fiber variation for impact strength should be 0.5% to 0.75%, and when volume of fiber lower than 0.5% of steel fiber will result in rupture failure and when its volume is more than 0.75% may result in tensile failure.

Physical properties of fiber [22 & 5]

fiber	shape	length mm	dia (mm)	length /dia	density kg/m³	young's modulus	tensile's strength
1.PVA	straight	13mm	0.045	288.8	1290	42 MPa	1600 MPa
2.steel	hooked end	35 mm	0.52	67.30	7850	211 MPa	1100 MPa
3.Carbon	straight	12.7mm	0.0072	1666	1810	242 GPa	4137 MPa

Hence, it showed that carbon fiber normally has good thermal and electrical conductivities, low densities, high thermal and chemical stability in the absence of oxidising agents, and good creep resistance. Steel fiber improves cracks, shrinkage reduction and toughness by delaying crack propagation from micro-crack to macro-cracks and PVA fibers offer the advantages of being nontoxic, very elastic, high tensile strength, great hydrophilicity, good dispersibility, and excellent hydrophilicity.

4. REVIEW BASED ON THE TESTING METHOD

The specimens were tested for compressive strength, flexural strength and tensile strength to evaluate the performance of ECC's at various proportion in mixes.

4.1Compressive strength Testing

RadhikaSrikhar and Ravi Prasad [16] investigated that the three cubes measuring 70.6mmx70.6mmx70.6mmwas used to study the performance of bendable concrete. During a 28-day curing period,each combination was formed and tested on a 3000kN universal compression testing machine with a load controller at an applied load of 6kN/min under the Bureau of Indian Standard Code IS:4031 (Part 6) to find the compressive strength.

Fig2. typical test setup for compressive strength [16]

4.2 Flexural strength testing

After 28 days of curing, testing for four-point bending has been performed. In this study, a beam of 305mmx76mmx38mm was used.The support range was 25 mm, the loading length of the third point was 85mm, and beam effective length was set at 255 mm. The ASTM standard code's specified test procedure was followed for all prismatic specimens.

Fig 3.flexural strength testing set-up [16]

4.3 Tensile strength testing

Lianghui et al [24] analyzed theECC specimen’s tensile behaviour with and without hybrid fibers, and formed uniaxial testing. For each mixture, the specimen of uniaxial tensile coupon (shaped like a dog bone) with 80mm gauge lengths and (30x13) mm cross section was moulded and inspected. Three specimens in the form of dog bone of the specified size were cast and examined in UTM throughout 28 days curing period.The specimen contains an 80mm gauge length that is unconnected to investigate the fracture pattern when the early crack load is applied. Every sample were evaluated at a rate of loading of 0.15mm per min with displacement control.

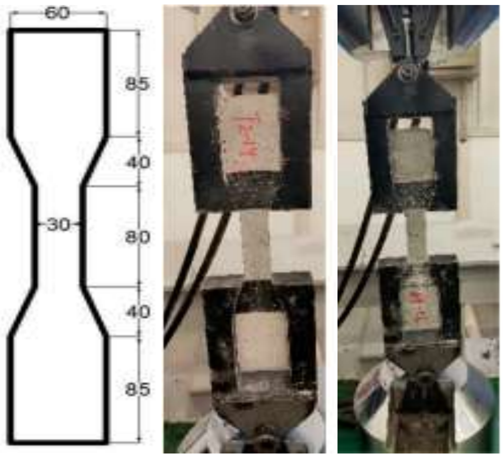


Fig 4. Specimen for the tensile test [1]

5. REVIEW BASED ON MECHANICAL PROPERTIES

Bendable concrete's mechanical properties involving compressive strength, tensile strength, and bending strength are as below:

Khin T. Soe et al [23] carried out the mechanical qualities of newly hybrid fiber made of polyvinyl alcohol and steel fiber reinforced with cement component. Improved impact resistance is the main goal of the development of this new ECC. In comparison to the ECC M1 (PVA 1.5:SE 0.5) material, it has been discovered that new ECC M2 (PVA 1.75:SE 0.58) mix has better mechanical characteristics. These studies show that increasing the volume fraction of steel fiberleads in fiber reinforced hybrid ECC strength, whereas increasing the volume fraction of PVA fiber has negligible effects on deformation. The material’s tensile strength obtained from ECC M1 is 11.7MPa and ECC M2 is 13.4MPa.

Jun Zhang et al [22] found out that adding of steel fiber enhances the composite tensile strength and breaking strength. The composite’s ability to withstand tensile strain can also be increased by steel fiber addition. The composite maximum tensile strain can be positively affected by adding a moderate number of steel fibersThe incorporation of steel fiber causes a decrease in the specific crack width in several crack phases. The smallest fracture size at the achieved tensile strength is around 25µm.PVA 0.37:SE 0.82 and PVA-0.5:SE-

1 composites have compressive, bending, and tensile strengths of 99.4 MPa, 13-17 MPa, 5.04-8.10 MPa, and 83.75 MPa, 9.81-15.95 MPa, and 4.83-7.32 MPa at 28 days.

Lianghui et al [1]found that the addition of steel fibers elevated the flexibility of the HDCC. A higher compressive strength of 31.3MPa was found by the adding steel fiber of 0.5% and PVA fiber content of 1.5%. The incorporation of the steel fiber improves the tensile properties of the admixture. At first, the cracking strength was initially around 2.32 MPa and thus 25.4% higher than in comparison group. However, reducing the PVA fiber content affects the flexural rigidity of the matrix. The HDCC (high ductility cementitious composite) slurry and steel fiber has good binding effect, and the insertion of steel fiber has no influence on the microstructure or dispersibility.

A.R.Krishnaraja, DrS.Kandasamyn [21] studied a new developed Engineer Cementitious Composite (ECC) hybrid bonded with randomly short steel fiber and its performance are evaluated. Fiber hybridization has greatly enhanced the mechanical properties of concrete beams. Based on the outcome, the mixture of steel fiber at 1.35% and PVA fiber at 0.65% show improvement in tensile, flexural, and energy absorption.

From the above papers, it is clear that with less area damage, spalling and fragmentation, the combination of (PVA-1.5: SF-0.5) and PVA-1: SF-0.5 has shown good results for getting better strength, better deformation and molecular bonding during dehydration occurs in cement paste. Such performance is crucial in structure subjected to dynamic load.

6. REVIEW BASED ON DURABILITY

6.1 High-temperature resistance

M. Sahmaran et al [27] Based on this principle, it has been reported that ECC performs better than other materials under high temperatures because its ductility is preserved by internal fiber that are randomly scattered. ECC can also be prevented from spalling, providing durability in high-temperature environments.

Jun Zhang et al. [22] investigated the mechanical parameters of ECC with PVA fiber at semi temperatures (20ºC, 50ºC, 100ºC and 200ºC). Under 200ºC exposure, ECC tensile characteristics decreased as PVA fiber strength decreased and ECC matrix toughness increased on a micro-scale. However, the negative impact of tensile characteristics was reduced because the fiber-matrix interface bonding was reduced.

6.2. Frost Resistance

Hezhi Liu et al [20] discovered that concrete's ability to withstand frost is evaluated using freeze-thaw tests, which are closely related to internal pore distributions. In general, the concrete's ability to resist freezing is worse the more porous it is. According to reports, the ECC pore fraction increases as fiber volume fraction increases, providing it more porous than plain concrete.

Yu Zhu, Yingzi Yang, and Yan Yao [28] examinedECC's self-healing capacity in a condition of water freezing and salt water freezing and thawing. They found that with a pre-load, a tensile stress of 0.5% to 1%, the specimen has best self-healing recovery almost 100% of the time. But when the level of tensile stress pre-loaded is between 1.5% and 2%, the rate of self-healing absorption was limited, and it was difficult to determine when tensile stress under pre-load over 2.5%. In other terms, the ECC’s tensile strength reduces during freezing and thawing cycle as pre-loading rises.

6.3. Shrinkage resistance

ShulingGao et al [18] experiment a lot and noticed that ECC shrinkage grew with a rising water to binder ratio and lowered with an increase in binder of sand ratio, and was affected by the volume of fly ash in fiber. A large portion of ECC's overall shrinking is due to chemical shrinkage. With an increase in sand to binder ratio as well as the binder of water ratio, ECC’s overall shrinkage rate decreases as well as the composite, drying and shrinkage appear to be the same.

M. Sahmaran et al [27] discovered that ECC's concerns with long-term durability are caused by excessive shrinking. ECC's drying shrinkage is influenced by a number of variables including water binder proportion and the sand binder proportion, cement percent, fiber volume, as well as admixture are all factors to consider.

Thus, the ECC's long-term performance in the environment is determined by its durability. This paper reviews recent developments in research on ECC durability, including resistance to high temperatures, permeability, frost, shrinkage, etc. ECC's durability is improved by its tensile flexibility, properties of self-healing and microcracking tendency.

7. REVIEW BASED ON SEM (Scanning Electron Microscopy)

Maryam Monazami and Rishi Gupta [12] studied two different fiber coating techniques-one using adhesive and the other using a paste made of cement and water used to coat polypropylene and carbon fibers. In the samples of mortar, fiberin both single and hybrid forms were employed. The figure displays SEM image of carbon fiber in the mortar that is not coated and is covered with glue. The fiber appears to have a consistent FA (fly ash) coating throughout, covering the fiber with fly ash has roughened the fiber's surface and increases the fiber adhesion to paste. The placement of silicon (a key factor of FA) plus calcium (a main ingredient in cement) was revealed by the elemental mapping, which essentially show the detection of (C-S-H) on the surface.

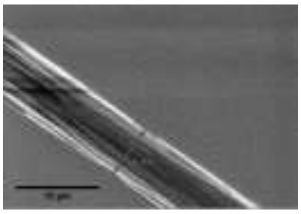
a.  b. 

Fig 5.SEM image of (a) uncoated fiber CF (b) coated in adhesive CF [12]

Lianghui Li et al [1] conducted an SEM examination and found that the S2 (PVA-1: Steel-1) test group showed good mechanical properties. The steel and PVA fibers effective bonding properties can be attributed to the improvement in mechanical properties. The figure depicts S2 group's microscopic structure of tensile cracks. It shows that a small fraction of steel fiber has no noticeable impact on how the PVA fiber distribute. The steel fiber is increased by 0.2 mm, which was further greater increase than the PVA fiber diameter. Large amounts of slurry were attached to the steel fiber surface, indicating strong connections between the HDCC (high-ductility cementitious composite) slurry and steel fibers.

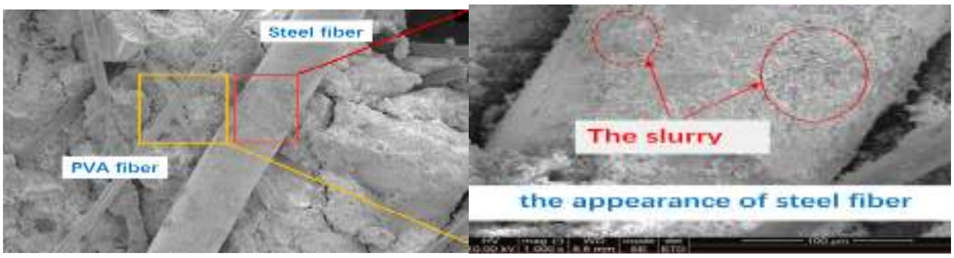


Fig 6. SEM appearance of S2 (PVA-1: Steel-1)

[1] finalized that the PVA fiber at randomised in the slurry and the absence of any agglomeration phenomena indicate that mixing PVA and steel fiber has no

influence on PVA fiber diffusion and consistency. Moreover, dispersed pulp was connected to the PVA fiber end as well as hydration gel product showing that the mixing of steel fiber did not result in PVA structures like scratches or other adverse effects. As a result, steel fiber and HDCC slurry have a strong connection and the steel fiber admixture had no impact on the microstructure or miscibility of the PVA fiber.

[12] conclude that fly ash is found all over the surface of the fiber as evidence by image of SEM, or scanning electron microscopy and X-ray energy dispersive analysis. Peaks of silicon, oxygen, and calcium were observed in the spectroscopy on the fiber's surface. The location of silicon (a key element of fly ash) plus calcium (a major element of cement) was discovered by the elemental mapping, which clearly indicates the existence of product of hydration on the fiber surface.

CONCLUSION

[1] Bendable concrete has key features such as durability, ductility, compressive strength as well as self-consolidation.Although the production rate of ECC is sometimes higher than that of the plain concrete, it offers a wide range of uses.

[2] Deflection, toughness index, and fracture energy all has an negative influence on ECC's compressive strength. However, at this point, the compressive strength has been directly correlated with the flexural strength, initial breaking strength, and peaking load. Also, by planning the mixed proportion of ECC, the optimum value of associated factors in the load-deflection curve may be achieved when the compressive strength is kept within specific limits.

[3] Balancing the mixing order improves the fiber spreads while improving the tensile strain potential and maximum tensile strain ECC in comparison to the normal mixing sequence. Stiffness and compressive strength are decreases as temperature of exposure and size of specimen increases.

[4] The usage of steel fiber rises the composite tensile and cracking strength. Steel fiber can also improve the composite's ability to withstand the tensile strain. In order to get a good response to the composite's tensile load, a modest quantity of steel fiber (1% in the current study) is required.

[5] The hybrid fiber increases the ultimate strength and tensile strength of ECC composite in comparison to the mono-fiber. Higher tensile strain capacity is

achieved in fiber reinforced hybrid cement composite specimen when PVA of 1% and steel fiber of 1% are mixed together.

[6] Increasing fiber content, improves the mechanical properties as well as deformability of cementitious composite mixtures. For a hybrid cementitious composite mixture containing 1.5% of PVA fiber and 0.5% of steel fiber; comparing composite made from fiber to composite made without the usage of fiber, compressive strength is risen by 20%.

[7] In comparison to conventional concrete, composite material gives better mechanical performance and durability. The damage index of several composite specimens shows that the greater quantity of synthetic fiber composite has a superior ability to withstand harm.

[8] In relation to some other hybrid ECC used in this investigation, the specimen with PVA content higher than three times of steel fiber content gives a higher flexural strength. The hybrid ECC fibers with 0.25% PVA and 1.25% steel fiber were observed to have the lowest flexural strength. Hence, such a mixture is not advised in situations when flexural strength is required.

[9] Concrete's microstructure mixes wereinspected with a scanning electron microscopy (SEM). Its aid in detection of the fracture and impurities on the surface. The image which arises show what the concrete is composed of and its physical feature.

[10] According to the damage criterion of several composite specimens, the composite with additional synthetic fiber by volume is more damage-tolerant. The damage resistance of the HPFRCC specimen is around 1.5-2.5 times higher than the conventional in the damaged level.

[11] Conventional concrete beams collapse quickly and frequently with the fewest fracture and wildest cracks. In a while, the connecting of the fiber causes many cracks to form in ECC multilayered beams before failure, and there is no spalling during the cracking load.

[12] Direct shear ductility is dependent on fiber orientation, which is greatly increased when fiber is at right angles to the plane of shear.

[13] The material's composite is mixed with superplasticizer to provide higher compressive strength and more workability at all ages compared with sulfonated melamine formaldehyde-based superplasticizer.

[14]Temperature changes in cement matrix porosity leads to decreased fiber performance. More freeze-thaw cycles result in expansion pressure and osmosis pressure, which weaken the cement matrix and produce microcracks, lowering the cement's resistance to fracture.

REFERENCE

[1] Li, L.; Li, B.; Wang, Z.; Zhang, Z.; Alselwi, O. Effects of Hybrid PVA–Steel Fibers on the Mechanical Performance of High-Ductility Cementitious Composites. Buildings 2022, 12

[2] AyoubDehghani, FarhadAslani, The effect of a shape memory alloy, steel, and carbon fibres on fresh, mechanical, and electrical properties of self-compacting cementitious composites, Cement and Concrete Composites, Volume 112,2020,103659, ISSN 0958-9465

[3] Mohan, A , Vijayan, D.S. , Revathy, J., Parthiban, D., Varatharajan, R. :Evaluation of the impact of thermal performance on various building bricks and blocks: A review, Environmental Technology and Innovation, 23, 101577 (2021).

[4] E.R.K. Chandrathilaka, ShanakaKristombuBaduge, PriyanMendis, P.S.M. Thilakarathna, Structural applications of synthetic fibre reinforced cementitious composites: A review on material properties, fire behaviour, durability and structural performance, Structures, Volume 34, 2021, Pages 550-574, ISSN 2352-0124,

[5] S. LavanayaPrabha, A. Mohan, G. Velrajkumar, A. Mohammedharoonzubair., Study On Structural Behaviour Of Ductile High-Performance Concrete Under Impact And Penetration Loads ., Journal of Environmental Protection and Ecology 23, No 6, 2380–2388 (2022).

[6] ŞükrüÖzkan, FuatDemir, The hybrid effects of PVA fiber and basalt fiber on the mechanical performance of cost-effective hybrid cementitious composites, Construction and Building Materials, Volume 263,2020,120564, ISSN 0950-0618

[7] Gopalakrishnan, R., Mohan, A., Sankar, L. P., &Vijayan, D. S. : Characterisation On Toughness Property Of Self-Compacting Fibre Reinforced Concrete. In Journal of Environmental Protection and Ecology , 21(6), 2153–2163.

[8] Mohan, A., Tabish Hayat, M. :Characterization of mechanical properties by preferential supplant of cement with GGBS and silica fume in concrete, Materials Today: Proceedings, 43, 1179–1189 (2020).

[9] ChaopengXie, Mingli Cao, Mehran Khan, Hong Yin, Junfeng Guan, Review on different testing methods and factors affecting fracture properties of fiber-reinforced cementitious composites, Construction and Building Materials, Volume 273, 2021, 121766, ISSN 0950-0618

[10] Mohan, A., Prabha, G., Balapriya, B., Deepika, M., Hemanthimekala, B.Tribological Investigations on the Properties of Concrete Containing Recycled Plastic Aggregate, Journal of Balkan Tribological Association, 27(6), pp. 1010–1020 (2021).

[11] Yifan Zhang, FarhadAslani, Development of fibre-reinforced engineered cementitious composite using polyvinyl alcohol fibre and activated carbon powder for 3D concrete printing, Construction and Building Materials, Volume 303,2021,124453

[12] Dr.G.Velrajkumar, R.Muralikrishnan, A.Mohan, R.BalaThirumal, P.Naveen John: Performance of GGBFS and silica fume on self compactinggeopolymer concrete using partial replacements of R-Sand, materials today : proceedings, Volume 59, Part 1, Pages 909-917 (2022).

[13] Ali N. Al-Gemeel, Yan Zhuge, Osama Youssef, Use of hollow glass microspheres and hybrid fibres to improve the mechanical properties of the engineered cementitious composite, Construction and Building Materials, Volume 171, 2018

[14] Mohan, A., Saravanan, J.., Characterization Of Geopolymer Concrete By Partial Replacement Of Construction And Demolition Waste – A Review., Journal of the Balkan Tribological Association, 2022, 28(4), pp. 550–558.

[15] GürkanYıldırım, ArashHamidzadehKhiavi, SedaYeşilmen, Mustafa Şahmaran, Self-healing performance of aged cementitious composites, Cement and Concrete Composites, Volume 87, 2018, Pages 172-186, ISSN 0958-9465,

[16] Radhika Prasad, Ravi Prasad, “Study on mechanical properties of hybrid fiber reinforced engineered cementitious composite”, 2019.49(3)

[17] Karthika, V.S. , Mohan, A. , Kumar, R.D. , James, Sustainable consideration by characterization of concrete through partial replacement of fine aggregate using granite powder and iron powder, Journal of Green Engineering,

9 (4), 514-525, 2020.

[18] ShulingGao, Zhe Wang, Wenchang Wang, HuafangQiu, Effect of shrinkage-reducing admixture and expansive agent on mechanical properties and drying shrinkage of Engineered Cementitious Composite (ECC), Construction and Building Materials, Volume 179, 2018, Pages 172-185, ISSN 0950-0618.

[19] Dan Meng, Ting Huang, Y.X. Zhang, C.K. Lee, Mechanical behaviour of a polyvinyl alcohol fibre reinforced engineered cementitious composite (PVA-ECC) using local ingredients, Construction and Building Materials, Volume 141, 2017

[20] Hezhi Liu, Qian Zhang, ChongshiGu, Huaizhi Su, Victor Li, Influence of microcrack self-healing behavior on the permeability of Engineered Cementitious Composites, Cement and Concrete Composites, Volume 82,2017, Pages 14-22, ISSN 0958-9465

[21] A.R.Khrishnaraja, Dr.S.Kandasamy, Flexural Performance of engineered Cementitious Composite layered Reinforced Concrete Beams, 2017,22

[22] Jun Zhang; Qing Wang[2]; and Zhenbo Wang[3], ‘Properties of Polyvinyl Alcohol- Steel Hybrid Fiber-Reinforced composite with High- Strength cement matrix’ ASCE-2017

[23] Khin T. Soe, Y.X. Zhang, L.C. Zhang, 'Material properties of a new hybrid fibre-reinforced engineered cementitious composite' Construction and Building Materials, Volume 43 (2013)

[24] Herbert EN, Li VC. Self-Healing of Microcracks in Engineered Cementitious Composites (ECC) Under a Natural Environment.Materials (Basel). 2013 Jul 15

[25] Tahir Kemal Erdem, Specimen size effect on the residual properties of engineered cementitious composites subjected to high temperatures, Cement and Concrete Composites, Volume 45,2014

[26] Standards Australia, General purpose and blended cement, AS 3972, 2010

[27] Mustafa Şahmaran, ErdoğanÖzbay, Hasan E. Yücel, Mohamed Lachemi, Victor C. Li, Frost resistance and microstructure of Engineered Cementitious Composites: Influence of fly ash and micro poly-vinyl-alcohol fiber, Cement

and Concrete Composites, Volume 34, Issue 2,2012, Pages 156-165, ISSN 0958-9465

[28] Yu Zhu, Yingzi Yang, Yan Yao, Use of slag to improve mechanical properties of engineered cementitious composites (ECCs) with high volumes of fly ash, Construction and Building Materials, Volume 36, 2012

[29] Mustafa Şahmaran, ZaferBilici, ErdoganOzbay, Tahir K. Erdem, Hasan E. Yucel, MohamedLachemi, Improving the workability and rheological properties of Engineered Cementitious Composites using factorial experimental design, Composites Part B: Engineering, Volume 45, Issue 1, 2013, Pages 356-368, ISSN 1359-8368

[30] Qian S Z, Zhou J, and Schlangen E, 'Influence of curing condition and cracking time on the self-healing behavior of Engineered Cementitious Composites', Journal of Cement & Concrete Composites, 2010

[31] Jian Zhou, ShunzhiQian, Guang Ye, OguzhanCopuroglu, Klaas van Breugel, Victor C. Li, Improved fiber distribution and mechanical properties of engineered cementitious composites by adjusting the mixing sequence, Cement and Concrete Composites, Volume 34, Issue 3,2012, Pages 342-348,

[32] Tso-Liang Teng, Yi-An Chu, Fwu-An Chang, Bor-CherngShen, Ding-Shing Cheng, Development and validation of a numerical model of steel fibre reinforced concrete for high-velocity impact, Computational Materials Science, Volume 42, Issue 1,2008,

[33] Schlangen E. Fracture mechanics. CT5146 Lecture Notes. In: Hua X. Self-healing of Engineered Cementitious Composites (ECC) in concrete repair system. Master thesis, Delft University of Technology; 2010.

[34] IS:10080-2004. Indian standard specification for vibration machine for standard cement mortar cubes.

[35] IS:4031(Part 6)-2005. Indian standard methods for determination of compressive strength of hydraulic cement

[36] ASTM C78-94. Standard test method for flexural strength of concrete (Using simple beam with third-point load)

[37] Zhang J, Maalej M, Quek S. Performance of hybrid-fibre ECC blast/shelter panels subjected to drop weight impact. J Mater CivEng ASCE 2007; 19(10):855–63.

[38] Ahmed SFU, Maalej M. Tensile strain hardening behaviour of hybrid steel polyethene fibre reinforced cementitious composites. Construction Build Material 2009

[39] Wang, Z., Zhang, J., Wang, J., and Shi, Z. (2015). "Tensile performance of polyvinyl alcohol-steel hybrid fibre reinforced cementitious composite with the impact of water to binder ratio." J. Compos., 49(18), 2169–2186.

[40] Zhang MH, Sharif MSH, Lu G. Impact resistance of high-strength fibre-reinforced concrete. Mag Concr Res 2007;59(3):199–210.

[41] Granger, S.; Loukili, A.; Pijaudier-Cabot, G.; Chanvillard, G. Experimental Characterization of the Self-Healing of Cracks in an Ultra High Performance Cementitious Material: Mechanical Tests and Acoustic Emission Analysis. Cem.Concr. Res. 2007, 37, 519–527

[42] Kawamata A, Mihashi H, Fukuyama H. Properties of hybrid fibre reinforced cement-based composites. J Adv Concrete Technology 2003

[43] Wang S, Li VC. Polyvinyl alcohol fibre reinforced engineered cementitious composites: material design and performances. In: International RILEM workshop on high-performance fibre reinforced cementitious composites (HPFRCC); 2005.

[44] Li VC, Wang S, Wu C. Tensile strain-hardening behaviour of polyvinyl alcohol engineered cementitious composite (PVA_ECC). ACI Mater J 2001;98:483–92.

[45] Li VC. Engineered cementitious composites (ECC) material, structural, and durability performance. In: Nawy E, editor. Concrete construction engineering handbook; 2007. p. 24-1–24-45.

[46] Li VC, Kong H-J, Kike SG. Fiber reinforced high performance concrete material. Ann Arbor, MI: University of Michigan; 2000.

[47] V.C. Li, Engineered cementitious composites-tailored composites through micromechanical modelling, in: N. Banthia, A. Bentur, A. Mufri, eds. (Eds.), Fiber-Reinforced Concrete: Present and the Future, Canadian Society for Civil Engineering, Montreal, Canada, 1998, pp. 64–97

[48] Edvardsen, C. Water Permeability and Autogenous Healing of Cracks in Concrete. ACI Mater. J. 1999, 96, 448–455.

[49] Wang, K. J., Jansen, D. C., Shah, S. P., and Karr, A. F. (1997). "Permeability study of cracked concrete."Cem. Concrete

[50] Wang, K.; Jansen, D.; Shah, S.; Karr, A. Permeability Study of Cracked Concrete. Cem.Concr. Res. 1997, 27, 381–393