FLEXURAL STRENGTH ANALYSIS OF FIBRE REINFORCED ENGINEERED CEMENTITIOUS COMPOSITES USING MICROSILICA

[1]K.B. Shoba

Associate Professor, Department of Civil Engineering
St. Peter's Institute of Higher Education & Research, Chennai, Tamilnadu, India
Email:haridrab002@gmail.com

[2]V.B.M.Sayana
Professor and Head, Department of Civil Engineering
St. Peter's Institute of Higher Education & Research, Chennai, Tamilnadu, India
Email: vbms19@hotmail.com
[3]P.Partheeban.
[3]Professor and Dean, Department of Civil Engineering,
Chennai Institute of Technology, Chennai, Tamilnadu, India.
Email: dean.pd@citchennai.net

ABSTRACT

This article aims to evaluate the flexural strength of Engineered Cementitious Composites (ECC) incorporatingmicrosilica (at 5% to 25%) as a replacement for cement and polypropylene fibre (at 0.5% to 2.0%) added to serve as micro reinforcements in the cementitious composites. The ECC mixes were grouped based on the percentage replacement of microsilica for cement and percentage addition of fibers. Standard prism specimens conforming to BIS were cast to test the flexural capacity of these ECC mixes with that of control specimen. The test specimens were produced with a constant w/c ratio of 0.30 and exposed to water curing for 28 days strength. All the prism specimens were subjected to flexure test to determine its flexural capacity.The specimen achieving the maximum flexural strength was considered to be the optimum mix among all the ECC mixes. From the test results, it was found that the ECC mix with 20% microsilica replacement and 2.0% fibre addition produced the maximum flexural strength. This optimized mix specimen was considered for finite element modeling and analysis in the ANSYS software. The FEM analysis showed a reasonable agreement with the experimental test results in terms of stresses and deformations.

Keywords: ECC,Finite Element Analysis, Microsilica, Polypropylene Fibre, Flexural Strength

1. INTRODUCTION

Supplementary cementitious materials (SCMs) are used to mitigate the alkaline reactivity and to improve overall hardness through hydraulic or pozzolanic activity, including improved durability, reduced permeability, improved permeability, and reduced enduring capacity. In addition to or partially replacing Portland cement or mixed cement, SCMs are additionally applied to concrete and are usually considered to form part of the total cementing systems. The most common SCMs used in the construction industry include, Fly ash, Ground Granulated Blast Furnace Slag, Silica fume or micro silica, Rice Husk Ash, Metakaolin Clay and more.Fiber-reinforced cement composites have steadily increased over the last 40 years. The fibers are added to control the cracking of fiber-reinforced cemented composites and alter the material's behavior after the cracked matrix, bridging the splits and improving ductility post-cracking. The structure depends upon the characteristics of fiber-reinforced cemented materials. Made of high-performance fiber-reinforced cement composites (ECCs), the producer ensures high flexibility and fiber content optimization.

The development of green-engineered cement composites in which the high cement levels are the result of the rheological control of fiber dispersion has been advanced to encourage the conservation of natural resources and to reduce the environmental impact of building materials in the construction industry. Restrictions on the toughness of the matrix fracture are essential, as multiple cracks occur before the bridging stress of the fiber is maximized. Among them, high tensile ductility is several hundred times that of concrete while maintaining the compressive strength of that high-strength concrete.

ECC's metal-like characteristics can be achieved without depending on the high fiber content. A moderate addition of 2% or lower volume fibers makes the ECC easy to adapt to the construction project in the field or to prevent the production of plant structural elements. ECC has shown flexibility in processing paths, including casting and spraying on site and precasting extrusion. ECC's large tensile ductility makes it compatible with deformations and provides the structural components with a synergistic capacity of load sharing with steel reinforcement. As a result, steel strengthening is better used in enhancing structural performance in strengthened ECC members. At the same time, the lower crack width of the ECC protects the reinforcing steel against typical corrosive processes, which increases the structural durability.Fibres play a pivotal role in adhering external forces. Applying fibre reinforced materials as external load carrying agents received good attention from structural validation and in concrete industry where the dependency factor for engineered cementitious composites are the physical parameters of cementitious materials and fibres.

The material was successfully used for retrofitting dams, skyscrapers, bridge decks, and other structural components and systems. Several full-scale ECC applications have been implemented in different countries in recent years. ECC in precast strengthened ECC beams in the core of two higher-surface buildings in Japan is one of the most important. This application exploits the reinforced ECC's high energy absorption capability to help these large buildings with seismic resistance.

The percentage of mineral additive rice husk ash when higher than thecalciumhydroxidelevelthen it leads to increase in compressive strength of composites, **Feng Qing-geet et. al., (2004).**Polyvinylalcohol fiberenhanced engineered cementitious composites(PVA-ECC) is highly efficient inproviding long-term benefits to repaired structures due to its energyabsorption, strain-hardeningperformance, strong crack width regulations and delamination resistance, **Kim et. al., (2004).**High earlystrength blend ECCmaterialshavebeendevelopedbasedondifferentbindingsystems(using rapid hardeningcement, standard Portland cement and Portland cement type III) undermicromechanicalmodels'guidance, **Shuxin Wang et. al., (2006).**The carbon content of fibers in the green sand ECCinstantly rises substantially compared to thatof ECC M45 which is an implication of carbon particle concentration at the PVA fiber and matrixinteraction, **Michael Lepech et. al.,(2007).** ECC'sintrinsicallytightcrackwidthhasprovedinfluential for long-life oftheinfrastructure due to extraordinary impairment restraints and high toughness atstandard service and severe loading conditions, **MustafaSahmaranet.al.,(2008).**Modification in the blending sequence or mixing seriesby the process of trial outcomes of uniaxialtensileassessmentandfiberdiffusioninvestigationenhances the fiber propagationand distribution thereby raising the ECC's tensile strain potential and ultimate tensilestrength, **Zhou et. al., (2012).**Super-hydrophobicengineeredconcretecomposite (SECC), is a current advanced concrete composition incorporatingpolyvinylalcoholicandhydrophobicchemicals.Thematerial'shighermechanicalperformance, dependability, reliabilityandlongevitystands as an excellent alternativetostandard concrete, **Sobolevet.al.,(2013).**The bending strength increases marginallywith 10% to 25% replacementof cement by rice husk ashand appearsto be effective in structuralconcretereplacement, **GodwinAkekeet.al.,(2013).**Manufacturingof PolyvinylAlcohol(PVA)engineered cement composites usingamicromechanicalmodelwithstresspotentialsof3%to5%and compared with a standard concrete of 0.1% showsthatthecompositeshaveahighlevelofstresshardship, **Srinivasa et. al., (2014).** Integration ofsilica fume into fiber-reinforcedcementitiouscompositesimprovesmatrixbondsbypore-refinedproducts and betterhydrationproduct distribution and also achieves 0.2% higherstrengthatalowervolume comparedtocement mortar, **Ramya et. al., (2014).**Application offiber, iflessthan2% thenextensivestrainhardeningbehaviorofthecompositeis noticed, **Chethanet.al.,(2015).** Higher flexural strengthcharacteristics in variousbendable concreteis possible by the addition of extra cementitious materials such asflyash and reconfigured fibers, **Madhaviet. al., (2016).**

Combination of microsilica and reinforcing polypropylene fibres in composites will enhance the mechanical properties of ECC such as hardness, impact, potential and tensile strength holding better reliability. To identify the suitability of the stated materials influencing theflexural strength under the impact of different forces in various conditions is of utmost importancethat needs to be investigated. The main objective of this experimental study is to develop a new engineered cementitious composite (ECC) material using microsilica, manufactured sand and polyproline fibre and determine the optimum percentage among the various ECC mixtures that achieves the significant performance in the flexural property.

2. EXPERIMENTAL INVESTIGATION

2.1 Materials and Properties

Micro silica is one of the mineral compounds known to have been very fine, composed of solid, glassy silicon dioxide spheres, known as a condensed silicon fume. Microsilica, an inherent silicone and ferrosilicon product, is generally made from silicon dioxide and carbon by adding quartz to the smelting furnace, with excellent chloride and sulphate-resistant qualities at a production time of more than 2000°C and may be considered one of the structural parameters, which improves strength and micromechanical parameters. It must be procured as a byproduct of industrial manufacturing in a high-temperature electric arc furnace of metallic silicon and ferrosilicon.It is essentially in powdered, condensed, slurry shape. The grey appears to be of less than1mm diameter of spherical particles. Multiple densities up to 600 kg/cum.

It decreases chloride permeability and depth of carbonation about its microstructural properties so that it prevents corrosion of strengthening and limits the entry of aggressive agents. When used in engineered cement composites, it reduces separation to the extent that it can be used as a pumpable concrete mode and reduces segregation and hemorrhage with time reduction in workability and consistency. Given hardened properties, it improves bond strength, compressive, split tensile, bending strength, abrasion resistance, sulphates, and cavitation.Table 1 provides the physical properties test results of microsilica.

Table 1.Physical Properties of Micro Silica

S. No.	Physical Properties	Values
1	Specific gravity	2.9
2	Fineness	17.5%
3	Normal consistency	24 to 30%
4	Initial setting time	90 to 140 mints
5	Final setting time	160 to 200 mints
6	Soundness	0.009 to 0.0013%
7	Compressive strength	47.7 to 51.6 MPa

Table 2 provides the chemical composition test results of microsilica conforming to IS 12803: 1989.

Table 2.Chemical Composition of Micro Silica

S. No.	Oxide	Values
1	Silicondioxide(SiO2)	97.36%
2	MagnesiumOxide(MgO)	0.79%
3	Aluminiumoxide (Al2O3)	0.53%
4	SculptureTrioxide(SO3)	0.51%
5	PotassiumOxide(K2O)	0.29%
6	Ferricoxide(Fe2O3)	0.15%
7	CalciumOxide (CaO)	0.14%
8	Proporouoxide(P2O5)	0.09%
9	SodiumOxide(Na2O)	0.06%
10	Chlorine(Cl)	0.02%
11	ManganeseOxide(MnO)	0.01%
12	Lead Oxide(PbO)	0.01%
13	TitaniumOxide (TiO2)	0.01%
14	ChromiumOxide(Cr2O3)	100 ppm
15	Zinc Oxide(ZnO)	70 ppm
16	CopperOxide(CuO)	51 ppm
17	Ru	47 ppm

Polypropylene is one of the cheapest & abundantly available polymers.In situations where thevulnerable cementitious matrix which would deteriorate first under aggressive chemical attack, polypropylene fibers come into rescue as they are resistant to most chemicals. As its melting point is high about 165°C, a working temperature of 100°C may be sustained for short periods without detriment to fiber properties. Polypropylene fibers being hydrophobic in nature can be easily mixed as they do not need lengthy contact during mixing and only need to be evenly dispersed in the mix. Polypropylene short fibers in small volume fractions between 0.5% to 2%are commercially used in concrete.Composite materials containing polypropylene fibres has ductile property combined with resinous matrix. Table 3 provides the properties of polypropylene fibre.

Table 3.Properties of Polypropylene Fibre

S. No	Description	Results	Unit
1	Length of fibre	3.50	mm
2	Density	0.91	g/cc
3	Colour	White	--
4	Diameter of fibre	38	µm
5	Tensile strength	>500	MPa
6	Elongation rate	>15	%
7	Melting & Burning point	180°&>360°	Celsius

2.2 Flexure Test Methodology

The tensile strength of concrete is indirectly assessed using the flexural test. It determines if an unreinforced concrete beam or slab can survive bending failure. The modulus of rupture is another term for flexural strength. Apart from the aforementioned factors, flexural strength is affected by formwork, ambient and mixing temperatures, humidity and curing. Flexural strength analysis is performed to determine deflections and stresses induced by cracks in the concrete under examination. Cracks have a direct impact on the concrete, exposing steel reinforcements to corrosion over time and are also affected by the water/cement ratio.With respect to the flexural property of engineered cementitious composites, flexural strength denotes the ability to resist the forces adhered in static as well as in dynamic environments trying to pull out the component thereby being fractured at elastic phase.

Prism specimens were tested for flexure inaccordancewithIndianStandardsIS516:1959(Reaffirmed2004)–Methodsof tests for strength of concrete under section 7.3.The standard size of the test specimens as per the Code requirementswas 7.5 cm × 5 cm × 35 cm.In overall, a total of 78 sampleswere testedand among that 3 samples from each identity were considered for evaluating the flexural strength of M45 grade of fibre reinforced ECC specimens. Figure 1, shows the casting and testing of fibre reinforced ECC prism specimens made with Micro Silica (MS) as cementitious material.

a. Casting

b. Testing

Figure 1. Fibre Reinforced ECC-MSPrism Specimens

In view towards the flexural property of engineered cementitious composites, the coupon specimen undergoes compressive stress at its surface in concave manner and tensile stress in convex manner. Flexural strength shall be calculated using the following formula:

$$\text{Stress} = 3PA/2bd^2$$

Where,

Stress = Flexural strength (N/mm^2)

P = Maximum Load (N)

A = Distance between the line of fracture and nearer support (mm)

b and d = Width and failure point depth of the specimen (mm)

2.3 Test Results and Discussion

2.3.1Effect of Flexural Strength on ECC-MS Specimens

Flexural Strength, also known as modulus of rupture, bend strength, or transverse rupture strength, is a material property defined as the stress in a material just before it yields in a flexure test, Michael Ashby (2011). It determines whether if an unreinforced concrete beam or slab can survive bending failure. Apart from the factors above, flexural Strength is affected by formwork, ambient and mixing temperatures, humidity and curing. Flexural strength analysis is performed to determine deflections and stresses induced by cracks in the concrete under examination. Trials directly impact the concrete, exposing steel reinforcements to corrosion over time and are also affected by the water/cement ratio.

The flexural strength was tested for the w/c ratio of 0.30 with varying microsilica replacement percentages of 5%, 10%, 15%, 20% and 25% and addition of polypropylene fiber percentages in 0.5 %, 1.0%, 1.5% and 2.0%. Figure2, shows the flexural strength of ECC control specimen and Figure3, showsthe flexural strength of ECC-MS specimens at various percentages of microsilica and polypropylene fibersrespectively.

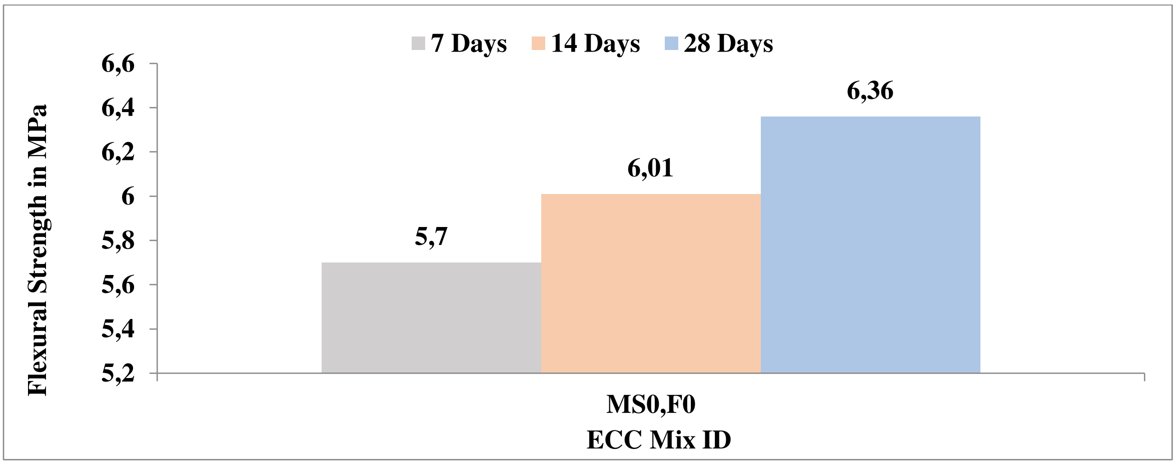


Figure 2. Flexural Strength of ECC Control Specimen

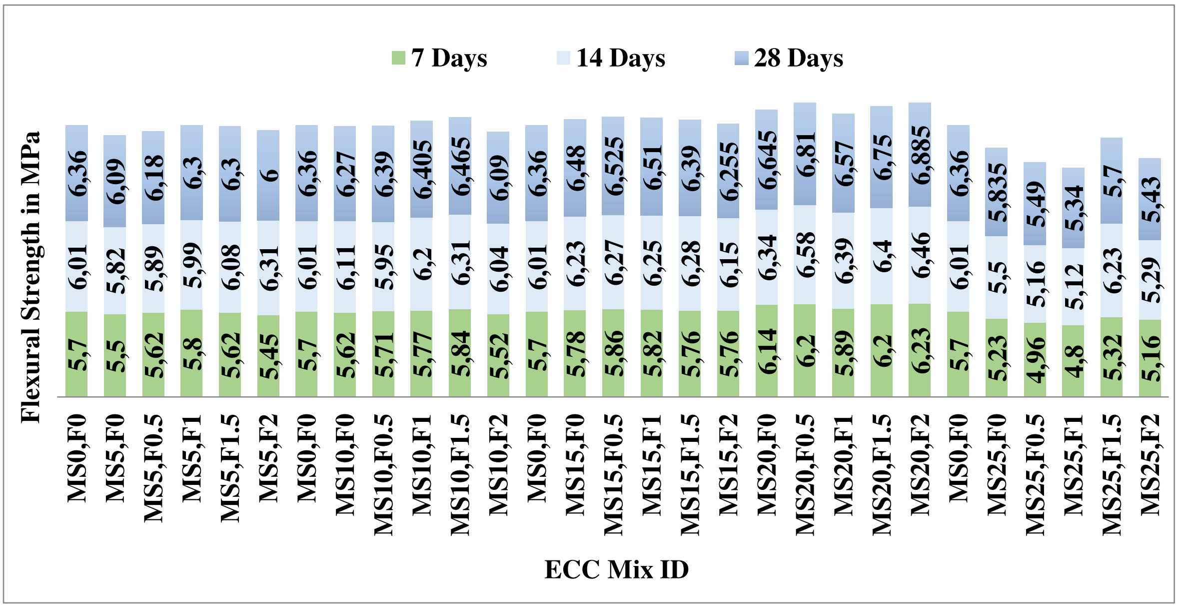
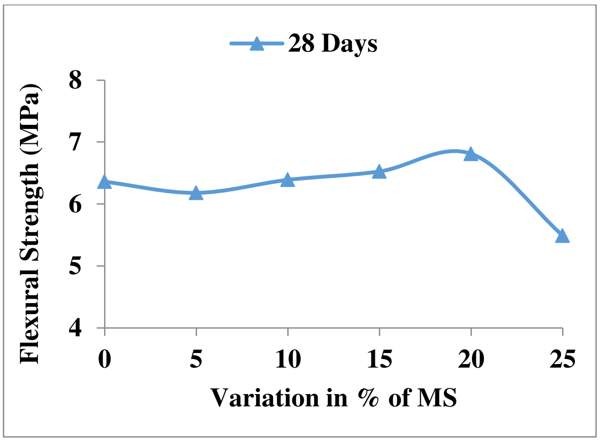


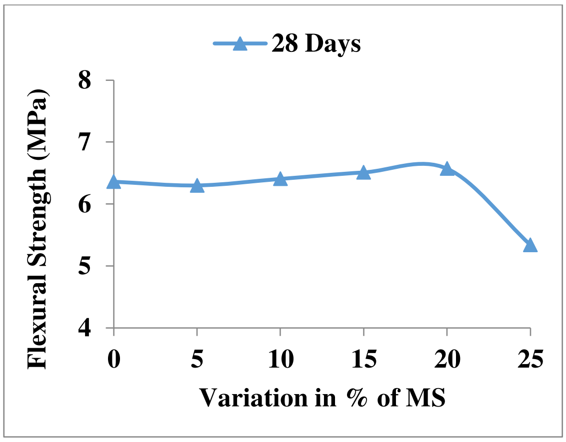
Figure3. Flexural Strength of ECC-MS Specimens

From Figure 2, it was observed that the flexural strength of ECCcontrol mix was 5.7MPa, 6.01 MPa and 6.36MPa at 7, 14 and 28 days of curing respectively. From the inferences of the experimental results shown in Figure 3, it was quite evident that all the mix types showedequally near values of flexure with replacement of MS from 5% to 20%,whereas with 25% replacement of MS the strength value decreased compared to all other mixes including control mix. Highest range of split tensile strength werenoticed in MS20 with addition of various percentage of fiber. The MS20-F2 mix specimen resulted in high flexural strength value of 6.88 MPa.The percentage increase in flexural strength when compared to the control mix with 20% replacement of Microsilica and addition of fiber from 0.5 % to 2% was 4.48% in MS20F0 ,7% in MS20F0.5, 3.30%in MS20F1, 6.13% in MS20F1.5, 8.05% in MS20F2. Thus finally, it was found that MS20-F2 was found to have higher flexural strength than other mixes due to its chemical properties.

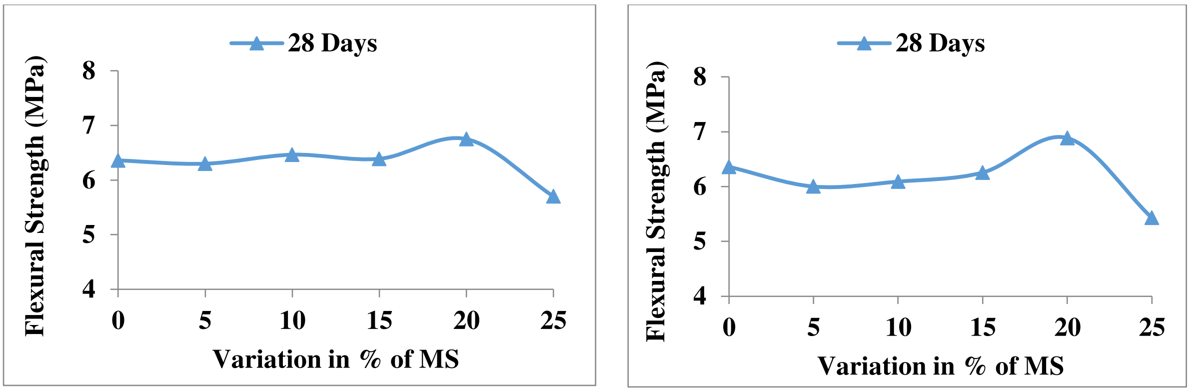
Figure 4, shows the effect of 28 days flexural strength of ECC-MS mixes corresponding to each percentage addition of polypropylene fibers.



a. 0.5% PolypropyleneFiber



b. 1.0% PolypropyleneFiber



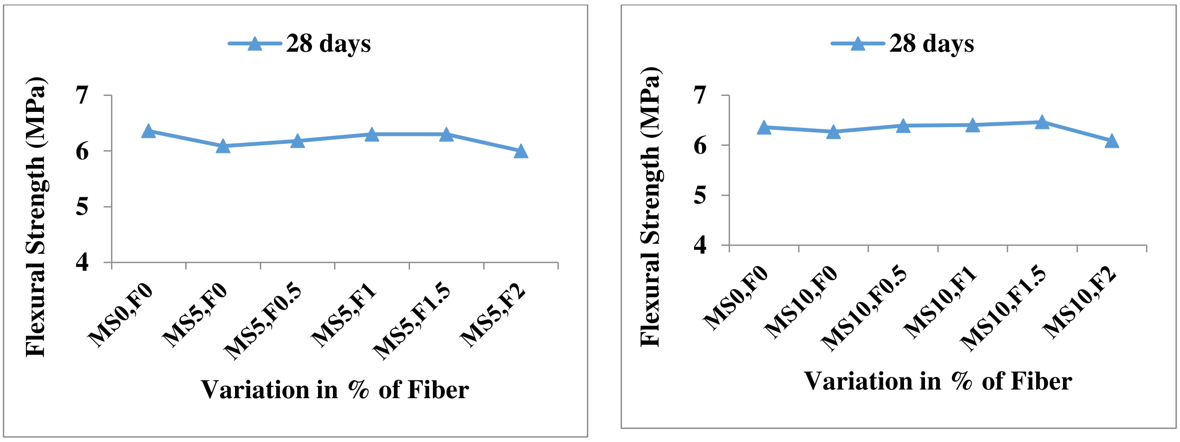
c. 1.5% PolypropyleneFiber

d. 2.0% PolypropyleneFiber

Figure 4. Variation in Flexural Strength of ECC-MS Mixes w.r.t Fiber Addition

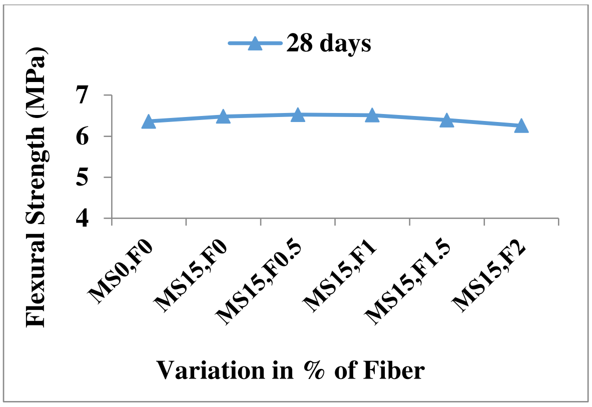
It can be inferred from Figure 4, that the flexural strength of ECC-MS mixes was increasing upto 20% replacement of microsilica beyond which it started decliningin each percentage addition of polypropylene fibre. From these observations, it evinced that 20% replacement of microsilica was found to be optimum providing strength and good control over the mix.

Figure 5, shows the effect of 28 days flexural strength of ECC-MS mixes corresponding to each percentage replacement of microsilica cementitious mineral.

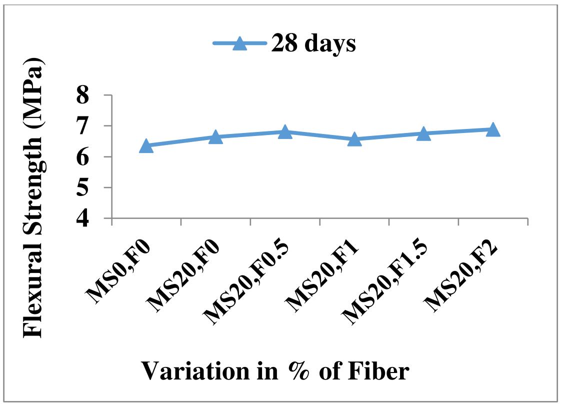


a. 5% MS Replacement

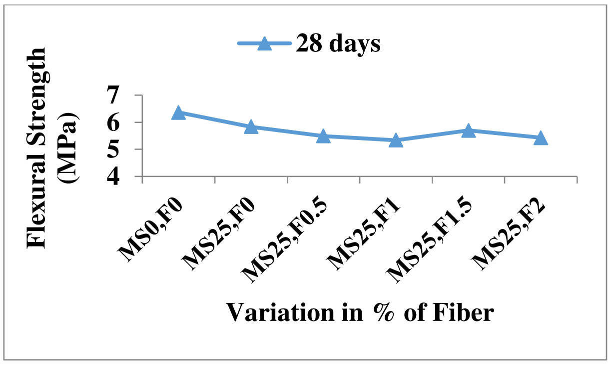
b. 10% MS Replacement



c. 15% MS Replacement



d. 20% MS Replacement



e. 25% MS Replacement

Figure 5. Variation in Flexural Strength of ECC Mixes w.r.t MS Replacement

It can be inferred from Figure 5, that the flexural strength of ECC-MS mixes was increasing upto 2.0% addition of polypropylene fiber beyond which it started declining in each percentage replacement of microsilica cementitious mineral.

2.3.2 Load-Deflection Relationship

Figure 6, demonstrates the load-deflection pattern of the of the optimized fibre reinforced ECC mix, MS20-F2.

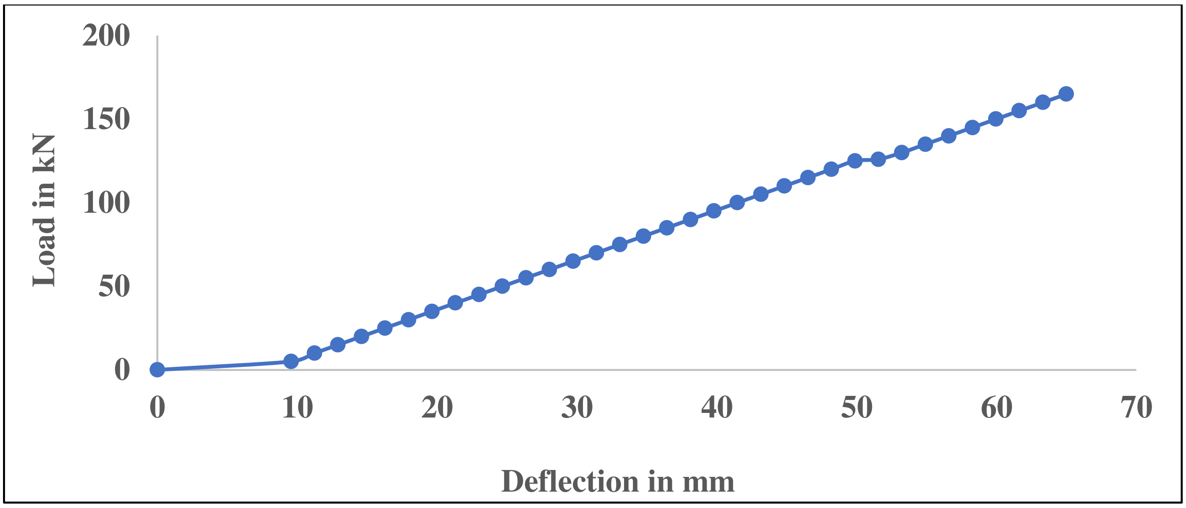


Figure 6. Load-Deflection Profile of Fibre Reinforced ECC-MS Specimen

The load-deflection profile of the fibre reinforced ECC-MS specimen of the MS20-F2 mix showed a linear variation until its failure. At this instance, when the specimen was subjected to initial load, the composites tend to get elongated as a response in multi-direction. As a result, the specimen continued to acquire increase in load until yield point where the polypropylene fibres will resist and elongate until failure. The flexural failure occurred at a peak load of 165 kN corresponding to a maximum deflection of 65mm. The mode of failure of the prism was brittle due to the action of splitting tensile force and the line of fracture occurred at a distance 1/3rd from thesupporttowards the loading point.

3. FINITE ELEMENT ANALYSIS USING ANSYS

3.1 Simulation of the 3D Finite Element Model

Analysis systems (ANSYS) V-14.5 was used to estimate the tensile and flexural strength for the optimized engineered cementitious composites containing 20% microsilica and 2% polypropylene fibres. The sequence of activities carried out in finite element modelling are creating a separate database for the proposed coupon specimen, designing its geometry section in three-dimensional mode and modelling it with required specifications thereafter applying the boundary conditions confining to the degree of freedom such that the software will be able to extract the required parameters say damage, tensile and flexural properties.

Solid-65 element was used to model the coupon specimen describing that as engineered cementitious composite as it has the potential to undergo cracking in terms of crushing in compression and cracking in tension. The solid has 380 elements and 5460 nodes having multiple degrees of freedom in all the three directions say x, y and z. Analysis systems requires engineering data for the proposed model which is then fed into the software to carry out its assessment. At first, the cross section say 75mm and 50mm for the model has been created and extruded to the desired span length say 360mm considering it as a three dimensional model. Another solid element having surface area of 15000 mm^2 had been created and assigned as Impactor in which pressure at the rate of 5E^7 will be applied so that the impactor will transfer the pressure to the entire model. Prior to analysis the entire model had been meshed for 50mm (Figure 7). As the supports are assigned as fixed on either side of the model, the model will undergo deformation when the pressure is applied (Figure 8). In the post processing wing, true scale result outcomes (Table 4) in terms of von mises stress, equivalent elastic strain, maximum shear stress and total deformation will be obtained.

Table4.Input Specifications for the Proposed FE Model

S.	Description	Values	Unit
	Young's Modulus	33462	MPa
	Bulk Modulus	18590	MPa
	Shear Modulus	13943	MPa
	Poisson Ratio	0.3	--
	Ultimate Compressive strength	45	MPa
	Ultimate Tensile strength	460	MPa

The meshing and application of pressure on the 3D simulated finite element model of the optimized ECC specimen MS20-F2, is shown in Figures 7 & 8 respectively.

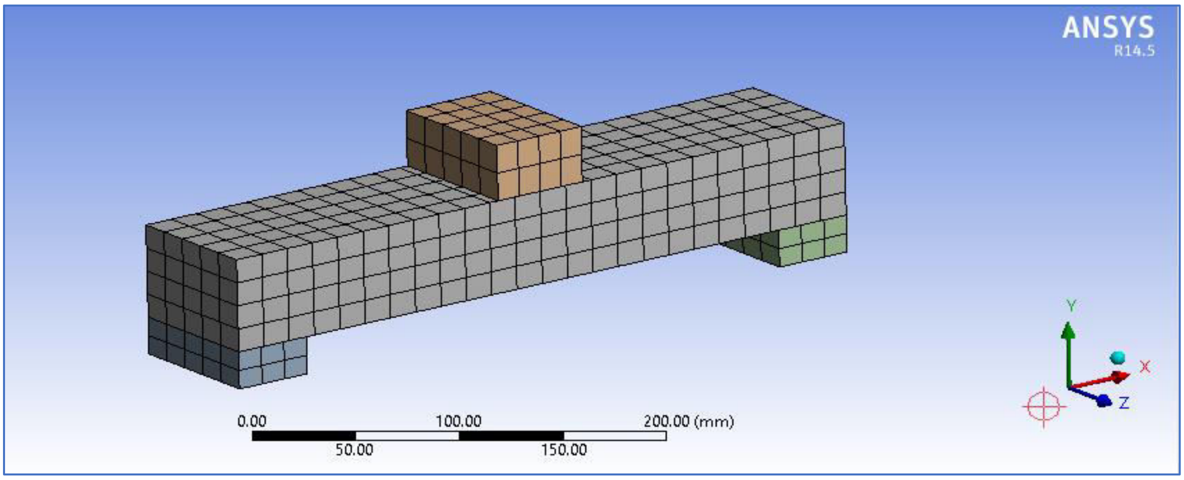


Figure 7. 3D-Meshing of the Optimized ECC Model MS20-F2

ISSN: 2366-1313

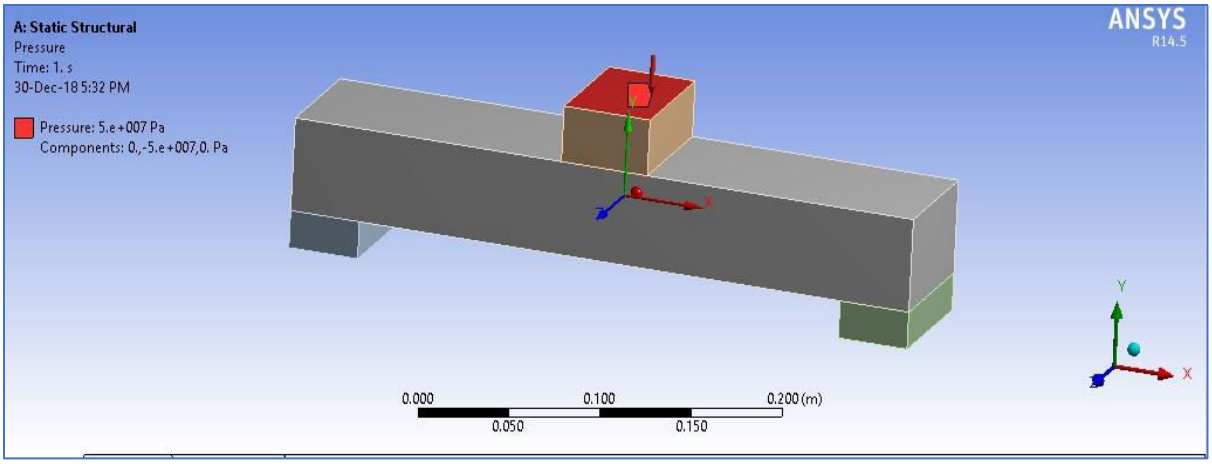


Figure 8.Applying Pressure on the OptimizedECC Model MS20-F2

3.2 Post Processing Outcomes of the Finite Element Simulated Model

Figures 9 to 12 demonstrate the post-processing outcomes of the finite element analyses of the optimized ECC model MS20-F2in terms of equivalent or Von-Mises stress, equivalent elastic strain, fracture at UY direction and total deformation.

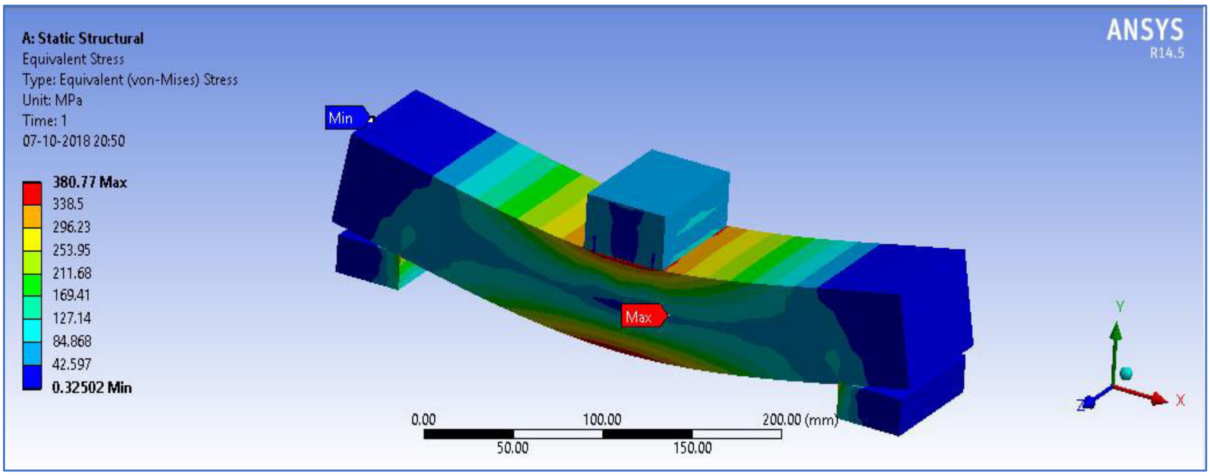


Figure 9.Equivalent (Von-Mises) Stress of the Optimized ECC Model MS20-F2

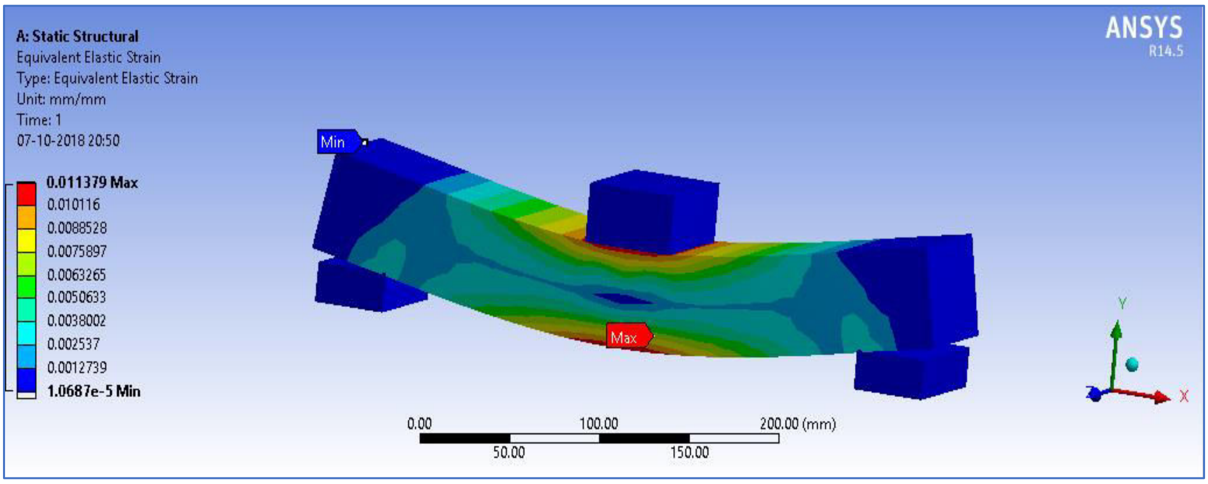


Figure 10.Equivalent Elastic Strain of the Optimized ECC Model MS20-F2

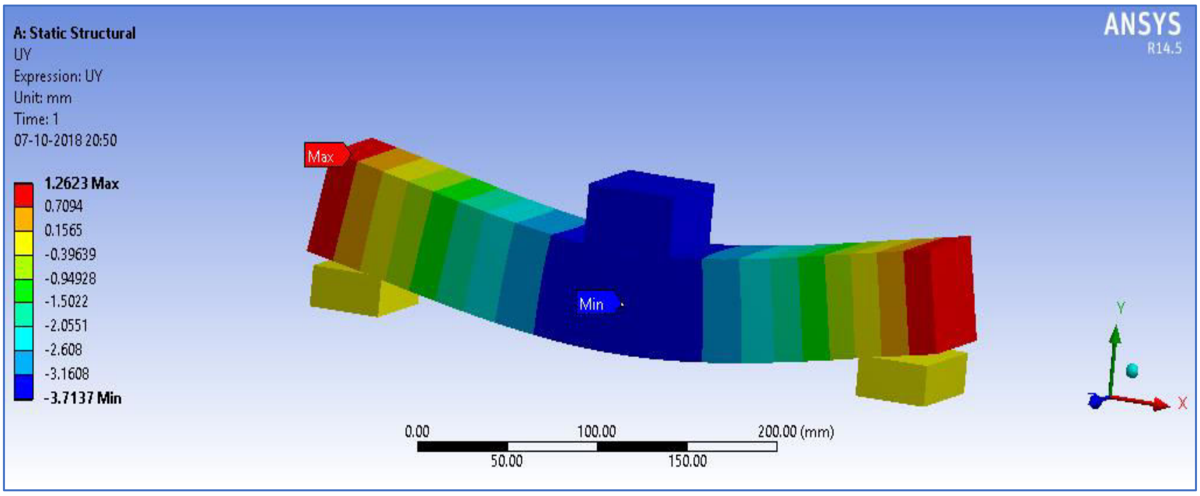


Figure 11.Fracture at UY Direction of the Optimized ECC Model MS20-F2

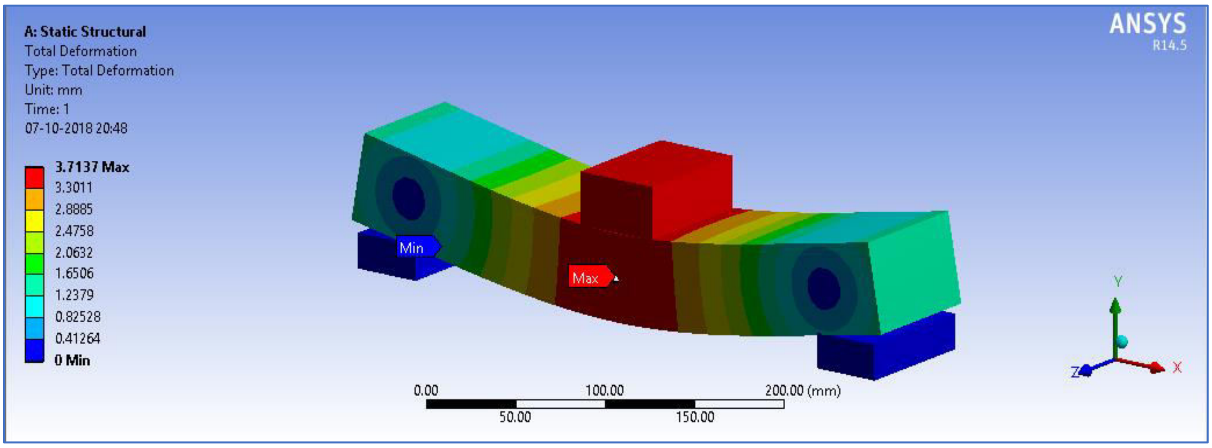


Figure 12. Total Deformation of the Optimized ECC Model MS20-F2

The outcome of the flexural analysis of the finite element simulated ECC model MS20-F2 was obtained through the post processing analysis unit of the ANSYS software.From the FEM analysis, it was observed that the simulated ECC model MS20-F2developed an equivalent stress (Von-Mises stress)to a minimum of 0.32502 MPa and maximum of 380.77 MPa, equivalent elastic strain to a minimum of 1.0687xE^-5 and maximum of 0.011379, displacement in U-Y direction to a minimum of -3.1737mm and maximum of 1.2623mm and total deformation to a maximum of 3.7137mm.

4. CONCLUSIONS

In this study, a detailed experimental investigation was carried out on the engineered cementitious composite mixesby varying the percentage replacement ofmicrosilicaand percentage addition of polypropylene fibres. In addition, a finite element model was simulated on the optimized prism specimen to study its bending behaviour. Based on these investigations, the following conclusions on the flexural aspects of the fibre reinforced ECC specimens are drawn.

1. Among all the ECC-MS mixes the optimum mix was found to be MS20-F2.

2. The maximum 28 days flexural strength produced by this optimum ECC mix specimen MS20-F2 was 6.89MPa.

3. The percentage variation of 28 days flexural strength of the optimum ECC mix specimen MS20-F2 with that of control specimen MS0-F0 was 8.05%.

4. The load-deflection relationship of the optimum ECC mix specimen MS20-F2 was linear until its failure.

5. The failure mode of the optimum ECC mix specimen MS20-F2 was purely a splitting tensile failure.

6. The simulated model of optimum ECC mix specimen MS20-F2 using ANSYS software showed a good coherence with the experimental results.

References

1. B.S. Mohammed et al., Evaluation of nano-silica modified ECC based on ultrasonic pulse velocity and rebound hammer, Open Civ. Eng. J. 11 (1) (2017).
2. C. Srinivasa, D. Venkatesh, A literature review on engineered cementitious composites for structural applications, Int. J. Eng. Res. Technol. 3 (2014) 2278–10181.
3. E.-H. Yang et al., Rheological control in production of engineered cementitious composites, ACI Mater. J. 106 (4) (2009) 357.
4. E.H. Yang, S.Wang, Y. Yang, V.C. Li, Fiber-bridging constitutive law of engineered cementitious composites, J. Adv. Concr. Technol. 6 (2008) 1–13.
5. E.H. Yang, Y. Yang, V.C. Li, Use of high volumes of fly ash to improve ECC mechanical properties and material greenness, ACI Mater. J. 104 (2007) 620–628.
6. Hyun-Joon Kong, Stacy G Bike and Victor Li, Constitutive Rheological Control to Develop a Self-Consolidating Engineered Cementitious Composite Reinforced with Hydrophilic Polyvinyl alcohol Fibers, Cem. Concr. Compos. 25 (3) (2003) 333–341.
7. Fischer, G., Stang, H., and Dick-Nielsen, L. (2004). Initiation and Development of Cracking in ECC Materials: Experimental Observations and Modeling. Technical University Denmark, Lyngby, Denmark.

ISSN: 2366-1313

8. Fischer, G.; Wang, S.; and Li, V. C., "Design of Engineered Cementitious Composites for Processing and Workability Requirements," *Seventh International Symposium on Brittle Matrix Composites*, Warsaw, Poland, 2003, pp. 29-36.

9. Fukuyama, H., Sato, Y., Li, V.C., Matsuzaki, Y., and Mihashi, H. (2000). Ductile Engineered Cementitious Composite Elements for Seismic Structural Application. 12th World Conferences on Earthquake Engineering (WCEE).

10. H. Siad et al., Advanced engineered cementitious composites with combined self-sensing and self-healing functionalities, Constr. Build. Mater. 176 (2018) 313–322.

11. Kanda, T., Tomoe, S., Nagai, S., Maruta, M., Kanakubo, T., and Shimizu, K. (2006). Full Scale Processing Investigation for ECC Pre-Cast Structural Element. Journal of Asian Architecture and Building Engineering, Vol. 5, No. 2: 333-340

12. Kendall, A.; Keoleian, G. A.; and Lepech, M., "Material Design for Sustainability through Life Cycle Modeling of Engineered Cementitious Composites," *Materials and Structures*, V. 41, No. 6, July 2008, pp. 1117-1131.

13. Kong, J. H.; Bike, S.; and Li, V. C., "Development of a Self-Consolidating Engineered Cementitious Composite Employing Electrostatic Dispersion/Stabilization," *Journal of Cement and Concrete Composites*, V. 25, No. 3, 2003, pp. 301-309.

14. Lepech, M. D., and Li, V. C., "Large-Scale Processing of Engineered Cementitious Composites," *ACI Materials Journal*, V. 105, No. 4, July-Aug. 2008, pp. 358-366.

15. Lepech, M. D., and Li, V. C., "Long-Term Durability Performance of Engineered Cementitious Composites," *Journal of Restoration of Buildings and Monuments*, V. 12, No. 2, 2006, pp. 119-132.

16. Li, V. C., "Engineered Cementitious Composites—Tailored Composites Through Micromechanical Modeling," *Fiber Reinforced Concrete: Present and the Future*, N. Banthia, A. A. Bentur, and A. Mufti, eds., Canadian Society for Civil Engineering, Montreal, Quebec, Canada, 1998, pp. 64-97.

17. Li, V. C., "Reflections on the Research and Development of Engineered Cementitious Composites (ECC)," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC)—Application and Evaluation*, Takayama, Japan, Oct. 2002, pp. 1-21.

18. Li, V. C.; Wang, S.; and Wu, C., "Tensile Strain-Hardening Behaviour of PVA-ECC," *ACI Materials Journal*, V. 98, No. 6, Nov.-Dec. 2001, pp. 483-492.

19. Li, V. C.; Wu, C.; Wang, S.; Ogawa, A.; and Saito, T., "Interface Tailoring for Strain-Hardening Polyvinyl Alcohol-Engineered Cementitious Composite (PVA-ECC)," *ACI Materials Journal*, V. 99, No. 5, Sept.-Oct. 2002, pp. 463-472.

20. Li, V.C. and Kanda, T. (1998). Engineered Cementitious Composites for Structural Applications. ASCE Journal Materials in Civil Engineering, Vol. 10, No. 2: 66-69

21. Li, V.C., "From micromechanics to structural engineering--the design of cementitious Composites for civil engineering applications", *JSCE J. of Struc. Mechanics and Earthquake Engineering*, **10** (2) (1993) 37-48.

22. M. Li, V.C. Li, Behaviour of ECC/concrete layered repair system under drying shrinkage conditions, Journal of Restoration of Buildings and Monuments, Vol.12, No.2, 2006, 143-160.

23. Sahmaran, M. Li, V.C. Li, Transport properties of engineered cementitious composites under chloride exposure, ACI Mater. J. 104 (2007) 604–611.

24. Peled, A.; Cyr, M. F.; and Shah, S. P., “High Content of Fly Ash (Class F) in Extruded Cementitious Composites,” *ACI Materials Journal*, V. 97, No. 5, Sept.-Oct. 2000, pp. 509-517.

25. Redon, C.; Li, V. C.; Wu, C.; Hoshiro, H.; Saito, T.; and Ogawa, A., “Measuring and Modifying Interface Properties of PVA Fibers in ECC Matrix,” *Journal of Materials in Civil Engineering*, ASCE, V. 13, No. 6, Nov.-Dec. 2001, pp. 399-406.

26. Sahmaran, M., and Li, V.C. (2008). Durability of Mechanically Loaded Engineered Cementitious Composites under Highly Alkaline Environments. Cement and Based Composites, Vol. 30, No. 2. 72-81

27. Sobolev, K., Tabatabai, H., Zhao, J. Flores-Vivian, I., Rivero, R., and Muzenski, S. (2013). Superhydrophobic Engineered Cementitious Composites for Highways Applications: Phase I, Final Report of University of Wisconsin-Madison

28. T.C. Hou, J.P. Lynch, Monitoring strain in engineered cementitious composites using wireless sensors, International Conference on Fracture XI, Turin, Italy, 2005.

29. Li, V. C., “Reflections on the Research and Development of Engineered Cementitious Composites (ECC),” Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC)— Application and Evaluation, Takayama, Japan, Oct. 2002, pp. 1-21.

30. V.C. Khed, B.S. Mohammed, M.F. Nuruddin. Effects of different crumb rubber sizes on the flowability and compressive strength of hybrid fibre reinforced ECC. in IOP Conference Series: Earth and Environmental Science. 2018. IOP Publishing.

31. Wang, S., “Micromechanics Based Matrix Design for Engineered Cementitious Composites,” PhD thesis, University of Michigan, Ann Arbor, Mich., Apr. 2005, 222 pp.

32. Wang, S., and Li, V. C., “Engineered Cementitious Composites with High-Volume Fly Ash,” *ACI Materials Journal*, V. 104, No. 3, May-June 2007, pp. 233-241.

33. Weimann, M. B. and Li, V. C., "Hygral behavior of engineered cementitious composites (ECC)," *International Journal for Restoration of Buildings and Monuments*, **9** (5) (2003) 513-534.

34. X. Huang, R. Ranade, V.C. Li, Feasibility study of developing green ECC using iron ore tailings powder as cement replacement, J. Mater. Civ. Eng. 25 (7) (2012) 923–931.

35. Yang, E.H., Wang, S., Yang, Y., and Li, V.C. (2008). Fiber-Bridging Constitutive Law of Engineered Cementitious Composites. Journal of Advanced Concrete Technology, Vol. 6, No. 1: 181-193

36. Z. Lin, T. Kanda, V.C. Li, On interface property characterization and performance of fiber reinforced cementitious composites, Concr. Sci. Eng. J. 1 (1999) 173–184.

37. Z. Pan et al., Study on mechanical properties of cost-effective polyvinyl alcohol engineered cementitious composites (PVA-ECC), Constr. Build. Mater. 78 (2015) 397–404.