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EXPERIMENTAL STUDY ON ECC STRENGTH WITH HYBRID FIBRES AND MINERAL ADMIXTURES

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Abstract: The advent of Engineered Cementitious Composites (ECC) has resulted in a high-performance material exhibiting high ductility, crack resistance and durability as compared to normal concrete. This is an experimental study on the strength behaviour of ECC made with hybrid fibres and mineral admixtures. The hybrid fibres made up of steel and polypropylene were used to replace the supplementary mineral admixtures, fly ash and silica fume, in different ratios. The compressive strength, split tensile strength and flexural strength were evaluated at various ages of curing. The observed results suggest that the use of hybrid fibres can be used to enhance the tensile and flexural strengths, with the help of effective crack-bridging mechanisms, and that the mineral admixtures can be used to enhance compressive strength by improved microstructure and secondary hydration. The control mix was found to have approximately 20 percent increase in compressive strength, 45 percent growth in tensile strength and 26 percent growth in flexural strength. The ECC specimens also showed the strain-hardening behavior with multiple micro-cracks, and hence increased ductility and the structural reliability. The findings demonstrate that the hybrid fibre-reinforced ECC with mineral admixtures is a promising approach in the creation of sustainable and high-performance material that can be used in innovative structural applications.

Keywords: Engineered Cementitious Composites (ECC), Hybrid Fibres, Mineral Admixtures, Fly Ash, Silica Fume, Compressive Strength, Tensile Strength, Flexural Strength, Sustainable Concrete, High-Performance Materials

I. INTRODUCTION

Engineered Cementitious Composites (ECC) is a type of fiber-reinforced cementitious composite, which is created to overcome the brittle nature of conventional concrete. ECC exhibits strain-hardening behaviour, and multiple micro-cracking as opposed to conventional concrete that cannot tolerate tensile stress over tensile stress and therefore has much greater ductility and toughness. Such features of ECC make it very suitable in applications where durability, crack resistance and extreme loading such as earthquake are required.

In recent times the use of fibre has proved to be crucial for improving mechanical properties of ECC. Although single fibre systems are effective, they may not optimise the strength and ductility. In order to address this issue hybrid fibre systems, which are produced by blending different types of fibres such as steel and polypropylene fibres have been developed. The steel fibres will increase the load carrying capacity and the stiffness of ECC while the polypropylene fibres will enhance the crack resistance and energy absorbtion which results in a synergistically improved performance of the composites.

Apart from fibres, mineral admixtures such as fly ash and silica fume are widely used in ECC to improve its micro structural properties. The pozzolanic activity improves the workability and long term strength of fly ash and silica fume improves the pore size distribution and bonding at the interface between the fibres and matrix. The hybrid fibres and mineral admixtures are used together to improve the strength but they are also beneficial for sustainability as they reduce the cement content in ECC and its carbon footprint.

Despite the significant advances in research efforts on ECC, it is essential that a systematic experimental approach is made to understand the combined effects of hybrid fibres and mineral admixtures on strength behaviour. The literature is fairly split between those investigating the effects of fibre reinforcement or mineral admixtures separately and little has been undertaken to explore the effects of both.

Hence, the current research project will be an experimental study of the strength properties of ECC with hybrid fibres and mineral admixtures. The focus of the research is to understand the strength properties in compression, tension and flexure under various mix proportions. It is expected that the findings of this study will assist in developing high-performance and sustainable ECC to be used in modern buildings.

II. LITERATURE SURVEY

The popularity of Engineered Cementitious Composites (ECC) has increased due to its superior mechanical properties and durability compared to the conventional concrete. A great deal of research has been done to enhance the ECC properties through fibre reinforcement and admixture.

Fibres are used to increase strength and ductility of ECC. It has been found that fibre-reinforced composites are strain-hardening and controlled crack micro-cracking, which results in high structural performance [1]. Hybrid fibre systems, which are a combination of different fibres, have been found to be more effective than single fibre system because of better toughness and strength [2]. Synthetic fibres (e.g. polyethylene) contribute to greater flexural and crack resistance while steel fibres contribute to higher load-bearing capacities [3].

The most popular mineral admixtures to improve the microstructure and properties of ECC are fly ash and silica fume. Fly ash increases the workability and strength gain of concrete with time through pozzolanic reactions, and reduces the heat of hydration [4]. Silica fume is a very fine particle that improves the cement microstructure and interfacial bonding properties [5]. It is reported that using mineral admixtures together has a great reduction in porosity and improvement in compressive strength [6].

A number of studies have focused on the mechanical behaviour of ECC under different stress conditions. ECC has been observed to have a higher tensile strain capacity and crack control as compared to concrete [7]. Stress transfer and crack bridging by fibres result in better flexural behaviour [8]. Hybrid fibres also improve dynamic and impact performance [9].

The research has shown the importance of fibre dispersion and fibre orientation in ECC. If the fibres are uniformly dispersed it will lead to better mechanical properties and if they are not, it will lead to poor strength and durability [10]. Improved mixing techniques have been proposed to ensure the best fibre dispersion in the matrix [11].

The other key driver for ECC research is sustainability. The use of industrial byproducts such as fly ash reduces the environmental impact and leads to sustainable development [12]. Fly ash rich mixes have been reported to be more durable and have lesser carbon emissions than ECCs [13].

Recently, the use of hybrid fibres and mineral admixtures to achieve overall performance has been investigated. The synergy of fibre and pozzolanic materials have been shown to lead to higher strength and durability [14]. However, there is no systematic experimental study that examines the combined effect of hybrid fibres and mineral admixtures on the mechanical properties of ECC yet [15].

III. METHODOLOGY

This section reports the experimental approach used for assessing the strength properties of Engineered Cementitious Composites (ECC) with hybrid fibres and mineral admixtures. This approach involves material selection, mix design, sample preparation, testing and formulae shown in figure 1.

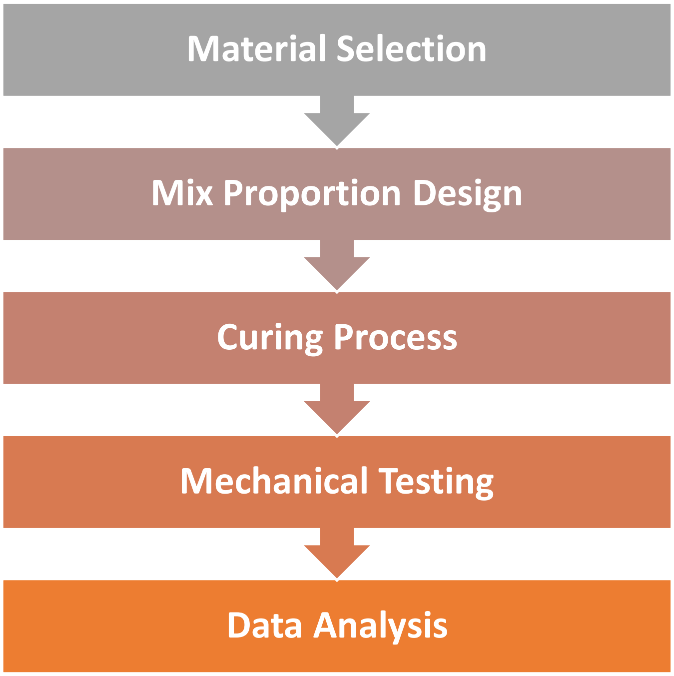

Figure 1: Proposed Work flow

A. Material Selection

The choice of materials is essential to achieve the desired strength, durability and sustainability in Engineered Cementitious Composites (ECC). This research used high-quality materials to achieve optimal performance.

Ordinary Portland Cement (OPC 53 Grade) was selected as the binding agent because of its high early strength and good quality. The cement is in accordance with IS 12269. It has the required hydration characteristics to achieve the desired strength.

The fine aggregate was river sand through a sieve of 4.75 mm. It was free from organic impurities and well-graded. Fine aggregate enhances workability and strength of the ECC composite.

Mineral Admixtures

(a) Fly Ash

Class F fly ash was incorporated as a partial replacement for cement. It improves:

- Workability of the mix
- Long-term strength
- Durability through pozzolanic reactions

Additionally, fly ash reduces heat of hydration and contributes to sustainable construction.

(b) Silica Fume

Silica fume, an ultrafine pozzolanic material, was used to enhance:

- Microstructural density
- Interfacial bonding between fibres and matrix
- Compressive and tensile strength

Its high surface area helps in reducing porosity and improving durability.

Fibres

(a) Steel Fibres

Hooked-end steel fibres were used to enhance:

- Load-carrying capacity
- Crack bridging ability
- Flexural strength

They significantly improve the toughness and stiffness of ECC.

(b) Polypropylene Fibres

Polypropylene (PP) fibres were incorporated to improve:

- Crack resistance
- Ductility
- Impact resistance

These fibres limit the propagation of micro-cracks and increase strain capacity. Impure water was not used for mixing and curing. The water meets IS 456:2000 standard, promoting hydration and strength gain.

B. Mix Proportion Design

The mix design of Engineered Cementitious Composites (ECC) is essential to ensure the right balance of strength, ductility and workability. In this research, the mix design was based on the theory of cementitious composites reinforced with fibres, and partial substitution of cement with mineral admixtures.

The initial ECC mix without fibres was designed according to the guidelines. The mix proportions were chosen to achieve satisfactory workability and strength.

Table 1: Base Mix Composition

Material	Proportion (by weight)
Cement	1.0
Fly Ash	0.25 – 0.30
Silica Fume	0.05 – 0.07
Fine Aggregate	1.2 – 1.5
Water	0.30 – 0.35 (w/cm)
Superplasticizer	0.8 – 1.2%

Hybrid fibres were incorporated to enhance mechanical properties.

Table 2: Fibre Reinforcement Proportion

Mix ID	Steel Fibre (%)	PP Fibre (%)
M1	0	0
M2	1.0	0.5
M3	1.5	0.5

- Steel fibres improve strength and stiffness
- Polypropylene fibres improve ductility and crack resistance

Table 3: Final Mix Proportions

Mix ID	Cement	Fly Ash	Silica Fume	Sand	Water	Steel Fibre	PP Fibre
M1	1.0	0.25	0.05	1.3	0.32	0	0
M2	1.0	0.25	0.05	1.3	0.32	1.0%	0.5%
M3	1.0	0.30	0.07	1.4	0.30	1.5%	0.5%

Water–Cementitious Ratio

$$w/cm = \frac{W}{C+FA+SF} \text{----1}$$

Where:

- W = Weight of water
- C = Cement

- FA = Fly Ash
- SF = Silica Fume

A lower w/cm ratio improves strength and durability.

Fibre Volume Fraction

$$V_f = \frac{V_{steel}+V_{pp}}{V_{total}} \text{-----2}$$

Where:

- Vf = Fibre volume fraction
- Vsteel, Vpp = Volume of steel and polypropylene fibres

C. Curing Process

Curing is an important phase in the fabrication of Engineered Cementitious Composites (ECC) as it controls the hydration process of the cementitious materials and affects the strength and durability of the composites. Curing plays a vital role in retaining moisture and regulating temperature, which ultimately contribute towards desirable microstructural development and bonding between the fibres and matrix.

Following casting, the specimens were left undisturbed in laboratory environment at ambient temperature for 24 ± 2 hours for initial setting. Afterwards, the specimens were demoulded without damaging the surface or causing micro-cracking. Then, the specimens were cured in water.

For the present study, water curing was employed as it ensures a continuous supply of water for full hydration of cement. The specimens were stored in a curing tank containing fresh potable water at a temperature of 27 ± 2°C, as per IS 456: 2000. This curing method ensures continuous moisture supply and avoids premature drying, which might lead to strength loss.

The curing process was carried out for 7, 14 and 28 days to assess the early and long-term strengths. The curing process can be modelled as:

$$\text{Cement Compounds} + H_2O \rightarrow \text{C-S-H Gel} + Ca(OH)_2 + \text{Heat-----3}$$

The formation of calcium silicate hydrate (C-S-H) gel is primarily responsible for strength development in ECC. The degree of hydration significantly influences the compressive strength and durability of the material.

The strength gain of ECC with curing time can be approximated using empirical relationships such as:

$$f_t = f_{28}\left(\frac{t}{28}\right)^n \text{-----4}$$

where ft is the compressive strength at time t (days), f28 is the 28-day strength, and n is a coefficient dependent on material composition.

Additionally, the moisture content during curing plays a critical role in strength development. The degree of hydration (α) can be expressed as:

$$\alpha = \frac{W_h}{W_c} \text{-----} 5$$

where Wh is the amount of water consumed during hydration and Wc is the total cement content.

Curing is further improved by mineral admixtures. Fly ash engages in secondary pozzolanic reactions, reacting with calcium hydroxide to produce more C-S-H gel, thus enhancing the long-term strength. Silica fume, with its high surface area, promotes early hydration and pore refinement, resulting in lower permeability and better durability.

Curing also enhances the interfacial transition zone (ITZ) between the fibres and cement matrix, essential for efficient stress transfer and crack bridging in ECC. Poor curing can lead to poor bonding, higher porosity and lower strength.

During the curing process, quality control was upheld. Water level in the curing tank was maintained above the specimens, and temperature was carefully checked. Care was taken during removal to prevent mechanical damage.

D. Mechanical Testing

The strength properties of the Engineered Cementitious Composite (ECC) mixes were tested in the laboratory using standard tests such as compressive strength, split tensile strength and flexural strength tests. These tests were performed in accordance with Indian Standards (IS) and ASTM standards to ensure reliable, repeatable and comparable test results. The tests were conducted on specimens cured for 7 days, 14 days and 28 days to assess the rate of strength gain.

The compressive strength was tested on cube specimens of 150 × 150 × 150 mm in accordance with IS 516. The cube was placed in the centre of a calibrated compression testing machine and the load was steadily applied at a constant rate until failure. The compressive strength was calculated as the maximum load divided by the area of the specimen. This test is mainly related to the load-bearing capacity of ECC matrix and the role of mineral admixtures in matrix densification.

The split tensile strength of ECC cylinders was determined using 150 mm diameter and 300 mm long cylindrical specimens, as per IS 5816. The samples were placed on a horizontal loading platen of a testing machine and a compressive force was applied along the diameter of the specimen. The indirect tensile strength was determined using the load at failure, accounting for the specimen's dimensions. This test is crucial for evaluating the crack resistance and tensile properties of ECC, which are greatly affected by the hybrid fibres.

Flexural strength was measured from prism beam specimens (500 × 100 × 100 mm) as per IS 516. These were loaded in two-point bending until failure, with the load at failure being noted. Flexural strength was calculated using beam theory, considering the span and cross-sectional area of the specimens. This method offers a measure of flexural strength and toughness of ECC, which is increased by fibre bridging.

Besides assessing the strength, load-deformation response was recorded during testing to assess the ductility of ECC. Unlike conventional concrete, which fails in a brittle manner, ECC specimens showed strain-hardening characteristics with the formation of multiple fine cracks along the loading axis. This suggests redistribution of stress due to fibre reinforcement.

In addition, crack pattern analysis was conducted to understand the failure mechanisms. The results showed that ECC mixes with hybrid fibre reinforcement had a large number of micro-cracks and controlled crack widths, while conventional mixes had large cracks and a sudden failure. The enhanced crack control is due to the combined effect of steel fibres, imparting strength, and polypropylene fibres, imparting ductility and resistance to cracking.

Tests were performed on a Universal Testing Machine (UTM) with load and displacement transducers. The specimens were carefully aligned and loaded to avoid errors in testing. The results yield valuable insights into the mechanical properties of ECC mixes with hybrid fibres and mineral admixtures, which serve as a foundation for further comparison and analysis.

Compressive Strength Equation

$$f_c = \frac{P}{A} \text{----6}$$

Where:
fc = Compressive strength (MPa)

P = Ultimate load (N)

A = Cross-sectional area (mm²)

E. Data Analysis

The experimental results of the mechanical testing of Engineered Cementitious Composites (ECC) were analysed to determine the effect of hybrid fibres and mineral admixtures on the strength properties. The compressive strength, split tensile strength, and flexural strength of different mixes were evaluated at 7, 14 and 28 days.

Each mix was tested with three specimens and the average value was used for analysis. The average strength for each mix was determined using:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \text{----7}$$

where xi represents the individual test values and n is the number of specimens.

The variation in experimental results was assessed using the standard deviation, which provides insight into the consistency of the mix:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}} \text{-----8}$$

A smaller standard deviation suggests good uniformity in fibre mixing and sample preparation. Compressive strength data were used to assess the role of mineral admixtures in enhancing matrix density and strength. The improvement in strength was expressed as the percentage gain over the control mix:

$$\%\,\text{Increase} = \frac{f_{mix} - f_{control}}{f_{control}} \times 100\text{----9}$$

where fmix is the strength of the modified ECC mix and fcontrol is the strength of the control mix. Likewise, the tensile and flexural strength of different mixes were compared to evaluate the effectiveness of hybrid fibre reinforcement. The factor of improvement in tensile strength was:

$$I\text{mprovement Factor} = \frac{f_{t,hybrid}}{f_{t,control}} \text{-----10}$$

where ft,hybrid and ft,control control are the tensile strength of hybrid and control mixes, respectively. The stiffness under loading of ECC was estimated by determining the modulus of elasticity (E) using:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \text{-----} 11$$

with Δσ being the stress change and Δε as strain. This index is useful to interpret the deformation of ECC. The ductility was determined from the load versus deflection curve. The ductility index was estimated as:

$$\text{Ductility Index} = \frac{\Delta_{ultimate}}{\Delta_{yield}} \text{----} 12$$

where Δultimate is the deformation at failure and Δyield is the deformation at yield point. In addition, the correlation between fibre content and strength was analysed. The correlation coefficient was calculated as:

$$r = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\sqrt{\Sigma(x-\bar{x})^2\,\Sigma(y-\bar{y})^2}} \text{----} 13$$

This analysis helps to understand the level of dependence of fibre reinforcement on mechanical strength. The data were also plotted in the form of graphs to show trends and variations between mixes. It was noticed that the hybrid fibre ECC mix (M3) performed better in terms of compressive, flexural, and tensile strength. This is due to the improved crack bridging, stress distribution, and bonding in the microstructural range resulting from the use of mineral admixtures.

IV. RESULTS AND DISCUSSION

The results of the experimental study of mechanical properties of Engineered Cementitious Composites (ECC) were examined to investigate the effect of hybrid fibres and mineral admixtures on the strength of ECC. The experimental results are reported in terms of compressive, tensile and flexural strength.

Table 1: Compressive Strength Results

Mix ID	28-Day Strength (MPa)
M1	40
M2	45
M3	48

Table 2: Tensile Strength Results

Mix ID	Tensile Strength (MPa)
M1	3.5
M2	4.2
M3	5.1

The tensile strength increased significantly with hybrid fibre reinforcement. Mix M3 showed approximately 45% improvement compared to M1.

Table 3: Flexural Strength Results

Mix ID	Flexural Strength (MPa)

M1	5.8
M2	6.5
M3	7.3

Flexural strength results demonstrate improved bending performance due to fibre bridging mechanisms. Mix M3 exhibited the highest flexural strength of 7.3 MPa.

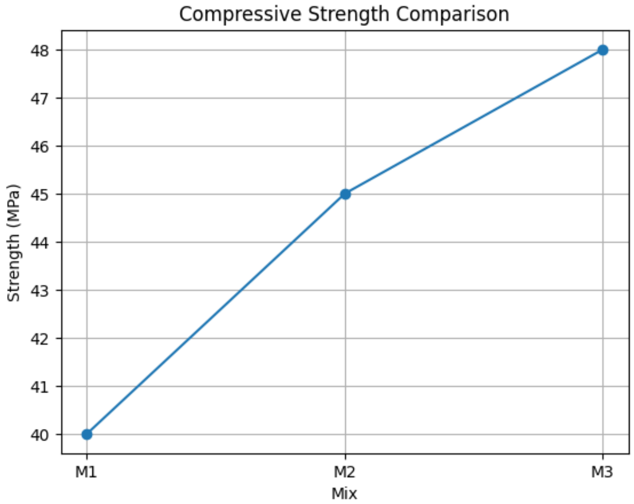

Figure 2: Compressive Strength Comparison

The 28-day compressive strength of various ECC mixes (M1, M2 and M3) is shown in Figure 2. As shown in Figure 2, the compressive strength of M1 to M3 increases. M1 is the weakest mix due to the lack of fibre reinforcement and M3 has the highest compressive strength (48 MPa). This is possibly due to the effect of mineral admixtures and hybrid fibres. Silica fume improves matrix density by filling up the micro-pores and fly ash imparts long-term strength gain due to pozzolanic reactions. Also, steel fibres enhance stress distribution in the matrix, resulting in higher load-carrying capacity. This suggests the combination of fibres and admixtures helps improve the overall compressive strength.

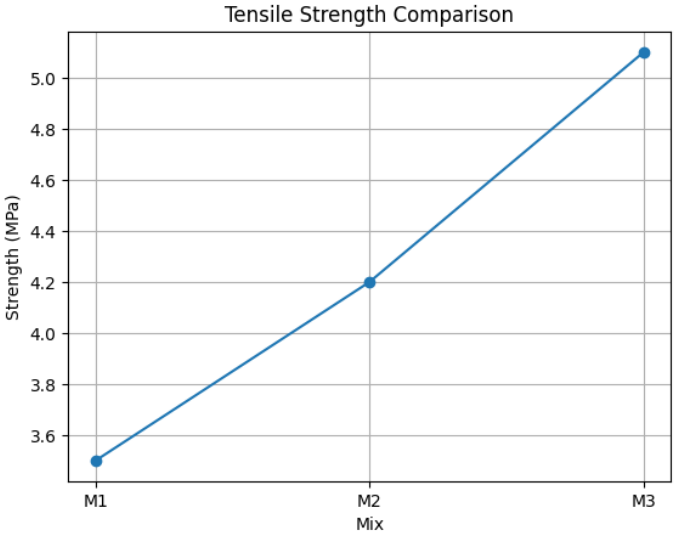

Figure 3: Tensile Strength Comparison

The tensile strength of ECC mixes is shown in Figure 3. Significant improvement in tensile strength is achieved with hybrid fibres. The maximum tensile strength of 5.1 MPa is observed with M3 mix and minimum with M1 mix (3.5 Mpa).

This increase in the tensile strength is associated with the fibre bridging of cracks. The steel fibres resist crack opening and the polypropylene fibres limit micro-cracking. This combination leads to improved tensile strength and strain. The chart shows that fibres have a significant effect on enhancing the tensile behaviour of ECC.

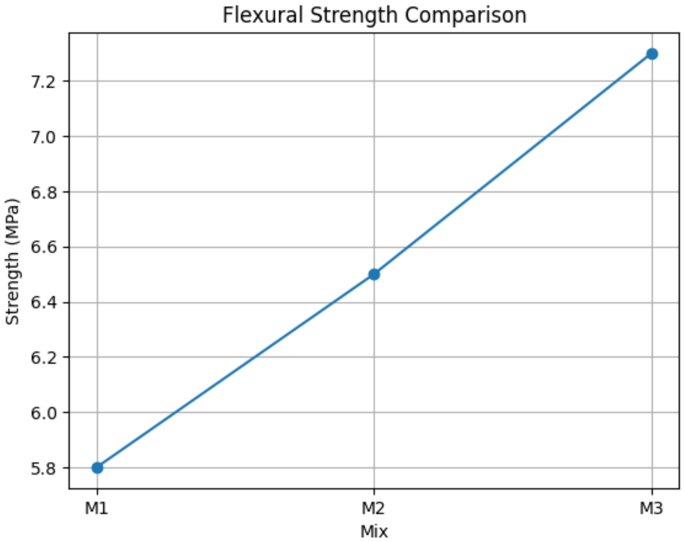

Figure 4: Flexural Strength Comparison

Flexural strength of various ECC mixes under bending is presented in Figure 4. It's clear that flexural strength rises with increasing fibre content; the highest flexural strength of 7.3 MPa is obtained for Mix M3.

This improvement in flexural strength is due to the stress redistribution and crack bridging effect of fibres. The use of hybrid fibre system provides improved resistance to flexural stresses by reducing crack growth and enhancing energy dissipation. The findings demonstrate that ECC has better flexural strength than normal concrete.

V. CONCLUSION

The paper discussed an experimental study on the strength properties of Engineered Cementitious Composites (ECC) with hybrid fibres and mineral admixtures. The findings of the study can be summarised as follows. The addition of hybrid fibres enhanced the strength of ECC. The mix containing both steel and polypropylene fibres improved strength and ductility through mechanisms such as crack bridging and redistribution of stress in the matrix. The hybrid fibre-reinforced mix (M3) showed a significant improvement in tensile and flexural strengths when compared to the control mix, with enhanced crack bridging and energy dissipation. Mineral admixtures like fly ash and silica fume were crucial in enhancing the compressive strength and durability of ECC. Fly ash aided in improving the long-term strength due to secondary hydration, and silica fume improved the densification and fibre-matrix bond. The synergistic effect of these admixtures led to a denser composite. The test results indicated that the control mix (M3) showed a significant gain in compressive strength (about 20%), flexural strength (about 26%) and tensile strength (about 45%) compared to the control mix. These enhancements verify the benefits of using hybrid fibre and mineral admixtures in ECC.

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