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Development of Next-Generation High-Ductility Engineered Cementitious Composites Using Hybrid Nano Fibers

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Abstract

Engineered Cementitious Composites (ECC) are new generations of construction materials that can be used to overcome the brittleness and poor tensile properties of traditional concrete. This paper explores the synthesis of an innovative high-toughness ECC containing hybrid nano micro reinforcements such as polyvinyl alcohol fibres and multi-walled carbon nanotubes. In this research, attempts have been made to improve the mechanical properties, tensile toughness, crack resistance, and durability behaviour of ECC using different multi-scale reinforcement techniques. To develop hybrid ECC composites, ordinary Portland cement, class F fly ash, fine aggregate, superplasticizer, polyvinyl alcohol fibres, and multi-walled carbon nanotubes were utilized. To evaluate the effectiveness of reinforcement, different tests were performed on ECC composite specimens, including compressive test, tensile test, flexural test, chloride permeability test, and scanning electron microscope. The outcome of this investigation proved to be effective in enhancing the structural and durability properties of ECC. Of all the mixtures tested, the mixture named ECC-2 with 1.5% PVA fibres and 0.10% CNT gave the best results, having a compressive strength of 57.8 MPa, tensile strain of 6.2%, flexural strength of 9.3 MPa, and a decrease in chloride permeability by 41.98%. Scanning electron microscopy tests demonstrated that the inclusion of CNTs caused improved matrix densification, a decrease in porosity, decreased connectivity of pores, and an increase in interface bonding strength. It was further shown through statistical analysis that the test results were accurate, repeatable, and had low standard deviations. The combination of crack bridging at the micro level and crack arresting at the nano scale was found to be responsible for the excellent strain hardening property and better durability performance.

Keywords: Engineered Cementitious Composites (ECC), Hybrid Nanofibers, Carbon Nanotubes, PVA Fibers, Tensile Ductility, Durability Performance.

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Introduction

Concrete is the most popular construction material in terms of compressive strength, cost-effectiveness, and versatility of applications in structures. Nevertheless, regular concrete has an inherent brittle nature with a relatively poor capacity for tensile strains, resulting in instantaneous cracking and ultimate failure under tensile loads Qi et al., (2026). The development of micro-cracks in regular cement-based materials leads to a decrease in their durability, lifetime, and protection from any aggressive environment. Therefore, as an improvement to regular concrete, fibre-reinforced cement-based composite materials have been developed, providing higher toughness, better crack resistance, and strain hardening properties of the structure. Although fibre-reinforced concrete shows better mechanical properties than regular concrete, there are still certain problems in relation to localized cracking and limited strain-hardening capabilities (Rahmati et al., 2023).

Engineered Cementitious Composites (ECCs), which may also be called strain-hardening cementitious composites, are developed for dealing with the problem of brittleness in common concrete mixes. The most distinguishing properties of ECCs include the ability to provide high tensile ductility and develop multiple cracking through micromechanically controlled mechanisms (Uddin & Hossain, 2024). In contrast to common concretes, ECCs can attain tensile strains from 3% up to 8%, which is higher compared to other cementitious materials (Yu et al., 2018). This is possible because of developing controlled microcracks with dimensions not greater than 100 μm, resulting in enhanced resistance, self-healing ability, and better durability Zhu et al., (2024).

Due to recent technological developments in nanotechnology, new potential areas have been opened for enhancing the microstructure and performance aspects of the cement matrix composite materials (Sannasi & Rajarethinam, 2025). Some notable nanomaterials, which include CNTs (carbon nanotubes), graphene oxide, nano-silica, and nano-alumina, have proven their abilities to refine the pore structures and accelerate the cement hydration reaction process, as well as strengthen the interfacial bonding between them in the cement matrix. Particularly, carbon nanotubes are unique among other nanomaterials due to their extraordinary tensile strength and high modulus of elasticity (Das & Choudhury, 2018).

Even with all these developments, it is still difficult to achieve improvement in terms of increasing both ductility and strength, in addition to enhancing the durability of the material. Although conventional fibres like PVA microfibers offer improved ductility and cracking prevention within a microscale range, these fibres do not help in tackling issues arising from nanoscale porosity and other microstructural flaws (Gurbuz et al., 2024). On the other hand, CNTs are effective in densifying the matrix and transition zone but are unable to offer sufficient crack-bridging capability when dealing with larger microcracks because of their nanoscale structure. Misaligned dispersing of CNTs leads to reduced efficiency in reinforcing the composite (Lu et al., 2017).

In this regard, hybrid nano-micro fibre composite reinforcements present an excellent approach towards developing future ductile ECC composites. The use of PVA fibres alongside CNTs creates a unique synergy in terms of the bridging effect of micropores and the arresting effect of nanopores (Qin et al., 2020). In this type of hybrid reinforcement system, the presence of CNTs makes the matrix denser, improves the hydration process, and increases the bonding between the matrix and the fibres. At the same time, PVA fibres increase the ductility, energy dissipation, and multiaxial cracking ability.

Though various works have been reported on ECC reinforced by nanomodification and fibre-reinforced cementitious composites using hybrid fibres, there is very limited literature addressing the optimization of the hybrid PVA-CNT fibre ratio in order to achieve improvement of tensile strain capability, compressive strength, and durability of the composite materials simultaneously. In this context, the current study attempts to develop a state-of-the-art hybrid nanocomposite ECC material utilizing PVA fibres along with carbon nanotubes. This work analyses the effect of hybrid fibre combinations in terms of mechanical performance, crack resistance, microstructure, and durability properties through detailed experimentation.

Key Contributions

- Derived a novel hybrid nano-micro reinforced ECC composite incorporating PVA fibres and CNTs, which exhibits superior performance of crack control properties.
- Shown remarkable enhancements in material characteristics by obtaining a compressive strength up to 57.8 MPa and tensile strain up to 6.2% for the optimized ECC-2 mixture.
- Concluded a decrease of up to 41.98% in the amount of chloride permeability due to higher densification at the nano-scale level and improved fibre-matrix bonding.

- Showcased the validity of hybrid reinforcement principles through experimentation, statistical analysis, and microstructure examination.

The rest of the paper is structured as follows. Literature review on Engineered Cementitious Composites (ECC), hybrid fibers reinforcement system, and nano-engineering on cementitious materials is discussed in detail in Section 2. Materials employed, mix proportioning, specimen preparation, and experimental approach for developing hybrid PVA-CNT ECC are explained in Section 3. Experimental results on the compressive strength, tensile strain capacity, flexural behavior, durability, and microstructure properties are presented in Section 4. The conclusion, engineering importance, and future research recommendations are presented in Section 5.

Literature Review

Engineered Cementitious Composites (ECC) have gained much attention in the research community owing to their high tensile ductility, strain hardening property, and crack resistance. Recent research work was dedicated to developing improved properties of ECC by using hybrid fibre reinforcement and nanocomposite technology. Some researchers stated that adding hybrid reinforcement to the composite improves its crack resistance, strain capacity, and post-cracking characteristics (Odeyemi et al., 2025). This interaction provides enhanced energy absorption capability and efficient stress transmission through the composite matrix.

The studies on high-performance ECC structures revealed that optimal fibre reinforcement would enhance their bending and reliability properties under different loading regimes Al-Baghdadi & Kadhum, (2025). It was observed that the inclusion of synthetic fibres in ECC materials would lead to improved tensile properties, fracture resistance, and the ability to prevent crack propagation (Saljoughian et al., 2024). Furthermore, the advanced ECC materials exhibited increased use in the field of structural engineering due to their ductility and durability properties in both static and dynamic load environments (Singh & Munjal, 2020).

The use of nanomaterials in cement composite matrices has significantly improved the microstructure properties of ECC. The nano-ECC systems showed improvement in compressive strength, lower porosity, and better interface zone properties because of the refined nature of hydration products and pore structure (Yang et al., 2026). Microstructure studies have revealed that nanomaterials have been successful in contributing to the densification of the matrix, besides having a positive effect on the fibre-matrix bond (Hu & Gao, 2022).

Recently, the use of hybrid reinforcement techniques involving microfibers and nanofillers has been proven to be an efficient solution for controlling cracks on multiple scales within ECC composites. Researchers found that the tensile ductility, flexural strength, and energy dissipation capacity were enhanced considerably in hybrid fibre reinforcement systems as opposed to those with individual fibres (Wu & Li, 2017). Additionally, sustainable ECC materials reinforced with nanoscale modifiers had higher mechanical properties and environmentally friendly characteristics (Shumuye et al., 2023).

The most recent research on the modification of ECC mixes using nano-silica and carbon nanotubes has resulted in a significant improvement in fresh properties, compressive strength, and crack-resistant behaviour of ECC (Mohammed et al., 2018). In addition, the application of carbon nanotubes in ECC mixes based on PVA has positively influenced shear resistance and bonding between fibres and matrix (Lee et al., 2025).

Despite considerable advancement in the field of nano-modified and hybrid fibre ECC systems, there are only a few studies that consider the optimization of the ratio of PVA-CNT hybrid reinforcement, considering the improvement of tensile ductility and compressive strength, along with increased durability properties of concrete. Moreover, it still needs to be studied experimentally how the cracking behaviour at the nano-level affects the micro-level cracking of the composite. Thus, this research seeks to design next-generation hybrid nanofiber ECC by using PVA fibres and carbon nanotubes.

Methodology

Materials

Incorporation of ECC material for hybridization included the use of ordinary Portland cement, fly ash, fine aggregate, polyvinyl alcohol (PVA) fibre, carbon nanotube (CNTs), water, and superplasticizer. Selection of the materials aimed at providing improved ductility, crack resistance, and mechanical performance due to multiple reinforcing mechanisms.

The Ordinary Portland Cement (OPC) of grade 53 according to IS 12269 specifications has been employed as the principal binder. Class F fly ash was added as the supplementary cementitious material to improve workability, decrease heat generation, and increase durability properties. The fine river sand with a predetermined particle size distribution was used as the filler material.

The PVA fibres with a length of 12mm were employed in this study to enhance the ductile nature and the crack-bridging effect at the microscale level. MWCNTs were introduced as the nanofiller to enhance the densification process of the matrix, bonding, and cracking arrest at the nanoscale level. The superplasticizer that was applied in the ECC formulation process was the Polycarboxylate ether superplasticizer. Potable water was employed in the process.

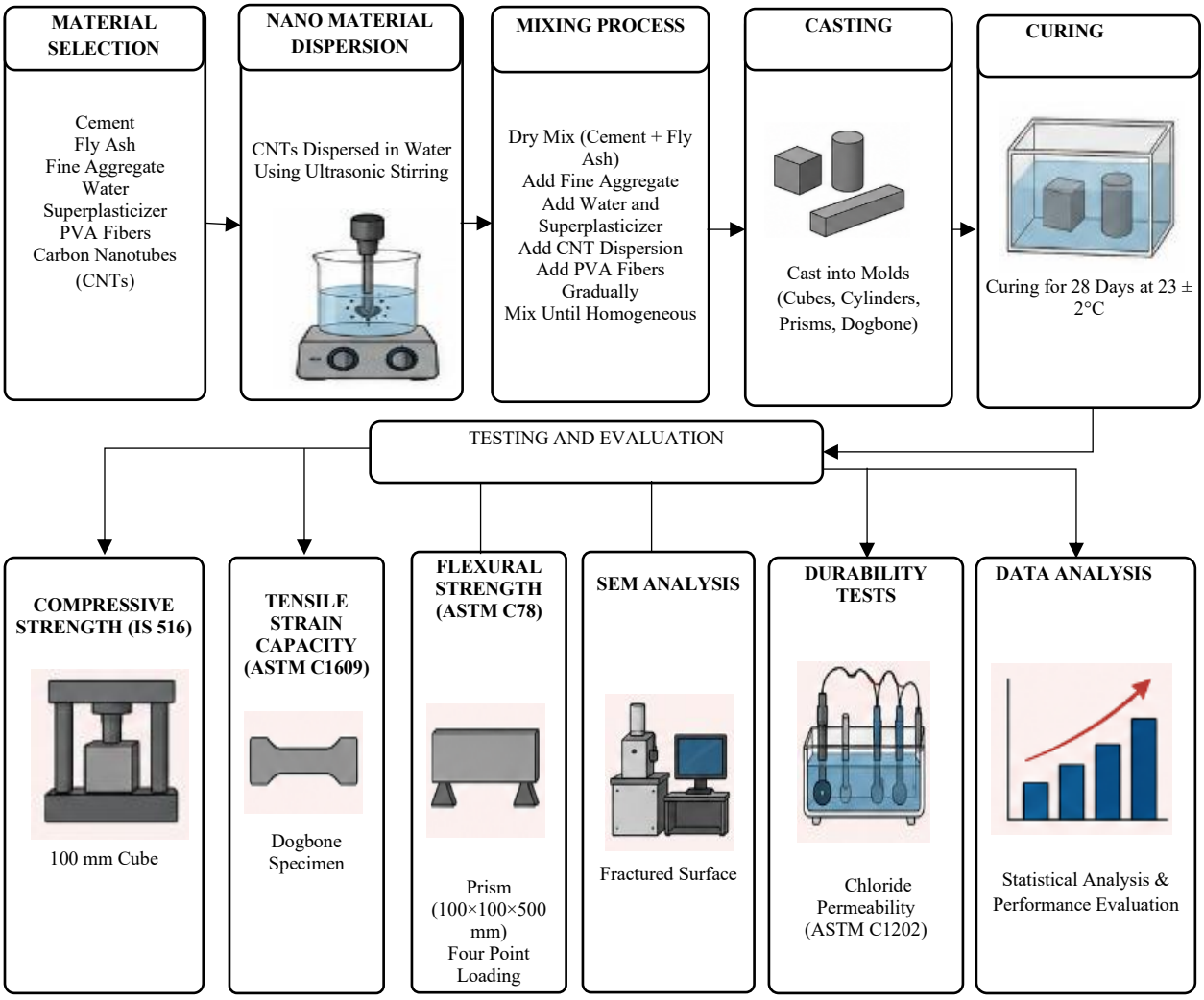


Fig. 1: Methodology Flowchart for Development and Experimental Evaluation of Hybrid PVA–CNT Engineered Cementitious Composite

The schematic diagram of fig. 1 shows the entire methodology that was used for the formulation of hybrid nano-fiber reinforced Engineered Cementitious Composite (ECC). This starts from selecting materials such as cement, fly ash, fine aggregate, PVA fibers, carbon nanotubes (CNTs), water, and superplasticizer. The dispersion of CNTs is done through ultrasonication to ensure the homogeneous dispersion of these nanoparticles within the cement matrix. In the process of mixing hybrid ECC, the dry and wet materials are added sequentially, and the PVA fibers are gradually mixed. After preparation, the mixtures are poured into molds in the form of cubes, cylinders, prisms, and dogbones and then allowed to cure in controlled conditions for 28 days. Later, the mixtures are subjected to tests such as compressive strength, tensile strain, flexural strength, scanning electron microscopy, and chloride permeability test. Finally, the results obtained from the experiments are analyzed to find out the ideal hybrid reinforcement ratio of PVA–CNT composite fibers.

Table 1: Material Properties and Functional Characteristics

S. No	Material	Specification / Standard	Physical Characteristics	Functional Role
1	Cement	OPC 53 Grade (IS 12269)	Specific Gravity: 3.15	Primary binder
2	Fly Ash	Class F Fly Ash	Fine pozzolanic powder	Improves durability and workability
3	Fine Aggregate	River Sand	Particle size < 1.18 mm	Matrix filler material
4	Water	Potable Water	pH ≈ 7	Cement hydration
5	Superplasticizer	Polycarboxylate Ether	High-range water reducer	Improves flowability
6	PVA Fiber	12 mm length	Diameter: 39 μm	Enhances ductility and crack control
7	Carbon Nanotubes (CNTs)	Multi-Walled CNTs	Diameter: 10–20 nm	Improves bonding and nano-crack resistance

In table 1 gives an account of the characteristics of the individual materials utilized in the hybrid ECC, which includes their specifications and roles within the composite structure. It demonstrates the function of each material in creating the matrix, enhancing workability, gaining strength, and increasing durability.

Mix Proportion Design

Preparation of ECC composite materials involved altering the ratio of hybrid reinforcements of PVA fibres and CNTs while keeping the binder material proportion fixed. The formulation of the ECC mix was optimized such that its tensile ductility, compressive strength, and durability properties can be improved without deteriorating its workability.

Table 2: Mix Proportion of Hybrid ECC Specimens

Mix ID	Cement (kg/m³)	Fly Ash (kg/m³)	Sand (kg/m³)	Water/Binder Ratio	PVA (%)	CNT (%)	Superplasticizer (%)
ECC-0	550	650	450	0.32	0	0	1.0
ECC-1	550	650	450	0.32	1.0	0.05	1.0
ECC-2	550	650	450	0.32	1.5	0.10	1.0
ECC-3	550	650	450	0.32	2.0	0.15	1.0

The table 2 indicates variations in the mix designs for various ECC samples with various PVA and CNT amounts, but with the same binder content. From table 2, it is clear that different combinations of the hybrid reinforcement ratio have been used for studying the material performance.

The volume percentages of fibers have been chosen from earlier ECC studies to get an effective combination of nano-reinforcement with micro-reinforcement.

Hybrid Fiber Reinforcement Mechanism

The hybrid reinforcing approach makes use of both microcrack bridging through PVA fibres and nanocrack arresting through CNTs. The combined effect of both reinforcements is responsible for efficient load distribution, crack arrest, higher tensile strain capacity, and more uniform pore structure.

The efficiency of fibre reinforcement was analyzed based on the formula given below for the fibre reinforcement index given by equation (1):

$$FRI = V_f \times \frac{L_f}{D_f} \quad (1)$$

Where, V_f represents the fibre volume fraction, L_f denotes the fibre length, and D_f represents the fibre diameter.

The hybrid efficiency factor used for evaluating combined nano–micro reinforcement performance is expressed as equation (2):

$$H_e = \alpha(PVA) + \beta(CNT) \quad (2)$$

Where, α and β represent reinforcement contribution coefficients of PVA fibers and CNTs, respectively.

Preparation and Mixing Procedure

The mixture was thoroughly planned in such a manner that the dispersion of the nanomaterials as well as fibre distribution in the cement matrix becomes even. Firstly, a dry mix of cement and fly ash was done using a mechanical stirrer in a time duration of around 2 minutes. Later, fine aggregate was added.

Dispersion of CNTs individually took place in water with superplasticizer with the help of ultrasonication for about 30 minutes to reduce aggregation and get good nano-dispersion. CNTs suspension was then introduced gradually into the dry mixture during the mixing process. Later, PVA fibres were introduced to the mixture slowly so that the fibres do not aggregate.

Mixing continued for about 5 to 7 minutes until a good ECC mixture was attained. Prepared mixtures were cast into various moulds, such as cubes, prisms, cylinders, and dogbones, according to test specifications. No mechanical vibration was used to avoid segregation.

Specimen Casting and Curing

ECC fresh mixes were cast in lubricated molds suitable for various test purposes. Specimens of cube shapes measuring 100 mm × 100 mm × 100 mm were produced to measure compressive strength, whereas those of prism shapes with measurements of 100 mm × 100 mm × 500 mm were employed in flexural strength testing. Dogbone-shaped specimens were also prepared for tensile strain testing.

Once the specimens were moulded, they were covered using polyethylene sheets to retain moisture, and they were left in a room for a day before being demoulded and submerged in water at 23 ± 2°C for a period of 28 days prior to any test conducted on them.

Experimental Program

This experiment was carried out with the aim of determining the mechanical behaviour, durability, and microstructure characteristics of hybrid ECC composites. In each mixture design, three samples were tested, and the results were averaged to maintain the validity of the experiment.

Table 3: Experimental Testing Program

Test	Specimen Type	Standard	Equipment Used
Compressive Strength	Cube (100 mm)	IS 516	Universal Testing Machine
Direct Tensile Test	Dogbone Specimen	ASTM C1609	Servo-Controlled Testing Frame
Flexural Strength	Prism Specimen	ASTM C78	Four-Point Loading Setup
SEM Analysis	Fractured Surface	—	JEOL JSM-7600F
Chloride Permeability	Cylindrical Specimen	ASTM C1202	RCPT Apparatus

The experimental setup is described in table 3, which lists test categories, specimen configuration, standards used, and testing apparatus. This setup guarantees the validity and consistency of mechanical, durability, and microstructure tests.

Mechanical Characterization

The compressive strength of ECC specimens was determined using a universal testing machine according to IS 516 standards. The compressive stress was calculated using equation (3):

$$\sigma_c = \frac{P}{A} \tag{3}$$

Where, P represents the applied load and A denotes the loaded area of the specimen.

The flexural strength under four-point loading conditions was evaluated using equation (4):

$$f_r = \frac{PL}{bd^2} \tag{4}$$

Where, P denotes applied load, L is span length, b is specimen width, and d is specimen depth.

The tensile strain capacity of ECC specimens was evaluated using equation (5):

$$\varepsilon_t = \frac{\Delta L}{L_0} \times 100 \tag{5}$$

Where, ΔL represents the elongation developed during tensile loading and L_0 denotes the original gauge length of the specimen.

The percentage improvement in compressive strength was determined using equation (6):

$$PI = \frac{f_h - f_c}{f_c} \times 100 \quad (6)$$

In this expression, f_h represents the compressive strength of hybrid ECC, while f_c denotes the compressive strength of the control mixture.

The durability improvement percentage was calculated using equation (7):

$$DI = \frac{C_c - C_h}{C_c} \times 100 \quad (7)$$

In this equation, C_c represents the chloride permeability of the control mixture, while C_h denotes the chloride permeability of the hybrid ECC mixture.

Statistical Analysis

Statistical analysis of the experiment findings was done to assess the consistency and repeatability of hybrid ECC behaviour. The mean, standard deviation, and variance for all mechanical properties were calculated.

Mean value was calculated using the following equation (Equation 8):

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (8)$$

The standard deviation was calculated as in equation (9):

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{n-1}} \quad (9)$$

Statistical evaluation was performed using MS Excel and SPSS software to determine the reliability and performance variation among different hybrid reinforcement ratios.

Results and Discussion

From the experimental research, it is evident that using hybrid PVA-CNT as the reinforcement considerably improved the mechanical and durability properties of Engineered Cementitious Composites (ECC). The mutual interaction between micrometre-level PVA fibres and nanometre-scale CNTs led to better crack-bridging, densification of the matrix, and bonding properties. When compared among all mix designs, it can be stated that ECC-2, which contained 1.5% of PVA fibres and 0.10% of CNT, was the most balanced mixture in terms of various mechanical properties.

Compressive Strength Analysis

Table 4: Compressive Strength of Hybrid ECC Mixtures

Mix ID	PVA (%)	CNT (%)	Compressive Strength (MPa)	Percentage Improvement (%)
ECC-0	0	0	42.3	—
ECC-1	1.0	0.05	48.6	14.89
ECC-2	1.5	0.10	57.8	36.64
ECC-3	2.0	0.15	54.1	27.89

According to the results shown in table 4, there has been a significant increase in compressive strength in hybrid ECC mixes as opposed to ECC. The compressive strength was found to be highest for ECC-2, amounting to 57.8 MPa, an improvement of 36.64% compared to the control mixture. This is due to the nano filling nature of the CNTs used, which improved the structure of the pores and increased matrix compactness. The use of the PVA fibres also helped arrest cracks in the cementitious matrix. On the other hand, the compressive strength was slightly low in ECC-3 because of excess fibre concentration.

Tensile Strain Capacity and Flexural Performance

The mechanical properties for tensile and flexural tests, as presented in table 5, supported the ability of the hybrid nano-micro reinforcement to enhance the ECC ductility and crack control performance. The ECC-2 combination obtained the highest value for tensile strain capacity of 6.2% and flexural strength of 9.3 MPa. Both PVA fiber and carbon nanotubes allowed efficient stress transmission and inhibition of crack formation using multiple crack bridging. There was a marked reduction in crack widths for hybrid combinations, demonstrating effective strain hardening.

Table 5: Tensile and Flexural Performance of Hybrid ECC

Mix ID	Tensile Strain Capacity (%)	Flexural Strength (MPa)	Average Crack Width (μm)
ECC-0	2.8	6.5	128
ECC-1	4.7	7.9	82
ECC-2	6.2	9.3	54
ECC-3	5.4	8.5	67

Durability Performance

Table 6: Durability Characteristics of Hybrid ECC

Mix ID	Chloride Permeability (Coulombs)	Water Absorption (%)	Durability Improvement (%)
ECC-0	3120	5.8	—
ECC-1	2485	4.6	20.35
ECC-2	1810	3.4	41.98
ECC-3	1965	3.9	37.01

As is apparent from the findings presented in table 6, the use of CNTs in ECC greatly enhanced its resistance to chloride ions as well as water permeation. The lowest value of chloride permeability was obtained in ECC-2 at 1810 Coulombs, and minimal water absorption at 3.4%. The decreased permeability was mainly due to the densification of the matrix, as a result of the shrinkage of pores at the nanoscale level. In addition, this hybrid reinforcement system helped minimize microcracks and, consequently, prevented fluid entry routes.

Statistical Analysis

Table 7: Statistical Evaluation of Mechanical Properties

Property	Mean	Standard Deviation	Variance
Compressive Strength (MPa)	50.7	6.84	46.78
Tensile Strain Capacity (%)	4.78	1.47	2.16
Flexural Strength (MPa)	8.05	1.21	1.46

The statistical evaluation presented in table 7 proved the reliability and reproducibility of experimental results derived from hybrid ECC samples. The relatively smaller values of standard deviation confirm sufficient repeatability in sample preparation, dispersion of fibres, and conducting tests. It has been proven that the controlled addition of PVA fibres and CNTs positively influenced mechanical behaviour, minimizing experimental discrepancies. The most repeatable results were received for the ECC-2 mixture due to the proper reinforcement-matrix interaction at the nano-microscale level.

Graphical Analysis

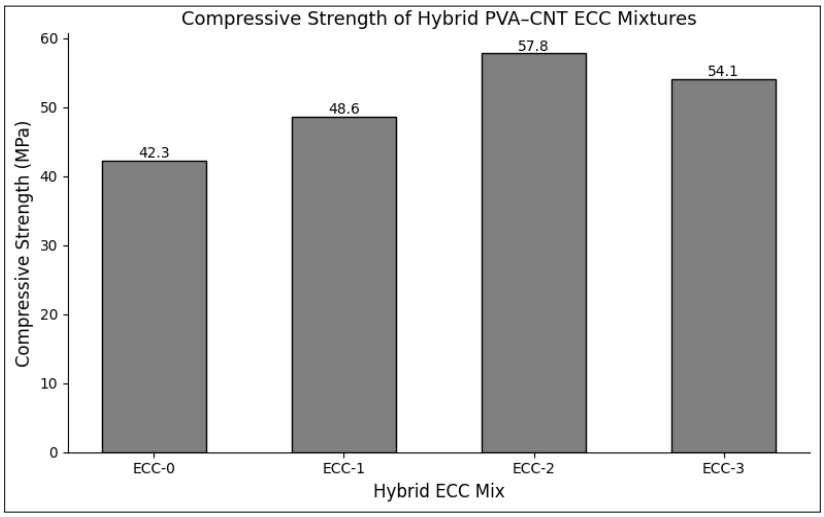


Fig. 2: Variation of Compressive Strength with Hybrid PVA–CNT Reinforcement Ratio

Graphical illustration of fig. 2 below shows how the incorporation of hybrid fibre affects the compressive strength of ECC. An increasing trend of compressive strength was recorded when comparing ECC-0 through ECC-2, since better densification and bond formation between matrix and fibres, together with efficient crack arresters in terms of CNTs

and PVA fibre, contribute to this trend. On the other hand, a marginal decrease in compressive strength is seen for ECC-3 because of too much addition of fibres, which makes the mixture difficult to mix and disperse.

Microstructural Discussion

According to SEM analysis results, there was improved compactness of the matrix and increased interfacial bonding between fibres and matrix in ECC hybrid compositions containing carbon nanotubes. Effective distribution of carbon nanotubes decreased the connectivity of pores and provided enhanced nano-crack arresting ability for the cement-based matrix. Many densely distributed micro-cracks of less than 60 μm in width were seen in ECC-2 composition samples, which indicated strain-hardening ability.

On the whole, the experiment results have proven that the inclusion of a PVA-CNT composite into ECC considerably increased its compression strength, tensile ductility, bending resistance, cracking behaviour, and durability. Among all tested compositions, ECC-2 proved to be the most promising with regard to the balance between the mechanical properties and durability.

Conclusion and Future Work

This paper successfully designed a new generation hybrid nano-fibre reinforced Engineered Cementitious Composite (ECC) by using PVA fibres and carbon nanotubes (CNTs) for improving the properties of cementitious composites in terms of mechanical properties and durability. This experiment clearly indicated the synergistic effect of PVA fibres and CNTs on the composite structure with regard to enhancing the mechanical properties and durability of the concrete structures. From all the specimens tested, the sample ECC-2, having 1.5% PVA fibres and 0.10% CNTs, possessed the optimum performance with the compressive strength, tensile strain capacity, flexural strength, and 41.98% enhancement in durability performance. CNT addition helped in optimizing pore distribution and fibre-matrix interfacial bonding, whereas PVA fibres assisted in arresting the propagation of micro-cracks and increased strain hardening characteristics. The SEM analysis was carried out to confirm uniform nanoscale dispersion and matrix compactness in the hybrid ECC material. The statistical analysis based on mean, variance, and standard deviation indicated the accuracy of the experimental data with no major variations among the repeated samples.

The proposed hybrid ECC shows promising prospects for implementation in various resilient and sustainable infrastructure systems such as earthquake-resistant building constructions, pavement layers, repair and patching materials, as well as durable construction works. The next steps in research may include optimizing the hybrid reinforcement with the help of artificial intelligence. The use of novel nanomaterials, such as graphene oxide and nano-silica, along with hybrid fibre reinforcement, can further improve multifunctional properties, including self-sensing and self-healing capabilities. Moreover, fatigue performance, thermal, and freeze-thaw resistance studies on hybrid ECC in combination with field testing are required to assess the actual behaviour and durability of the material under operational conditions.

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