Bulgarian Chemical Communications, Volume 57, Special Issue B (pp. 173-179) 2025 DOI: 10.34049/bcc.57.B.A0019

Performance evaluation of engineered cementitious composite utilizing manufactured sand

S. Jaggi*, S. Nag, P. Kumar Sharma

School of Civil Engineering, Lovely Professional University, Phagwara - 144411, Punjab

Revised: February 06, 2025

Escalation of environmental concerns and depletion of natural resources have prompted a shift towards sustainable and innovative alternatives in construction materials. Addressing the same, this research explores the usefulness of utilizing manufactured sand (M-sand) and waste fly ash as a substitute for river sand and cement, respectively, in engineered cementitious composites (ECCs), with a focus on its effects on workability, durability and mechanical properties. The study investigated various combinations of M-sand and river sand in ECC mixtures, ranging from 0% to 100% substitution rates. Key rheological parameters like flowability were evaluated to determine the workability of mixtures. Various mechanical characteristics such as compressive strength, direct and indirect tensile strength, and flexural strength were assessed at varying curing durations. Additionally, durability parameters such as water absorption, chloride penetration, and sulfate-attack were examined. Critical rheological indices, such as flowability, were scrutinized to ascertain the workability of the compositions. Furthermore, diverse mechanical properties encompassing compressive strength, both direct and indirect tensile strength, and flexural strength were examined across different curing durations.

Keywords: Engineered cementitious composite (ECC), manufactured sand, fresh properties, mechanical properties, durability.

INTRODUCTION

Since many decades, concrete has been the backbone of innumerable structures, from towering skyscrapers to sprawling bridges, all over the world. Nonetheless, its inherent brittleness, a tendency to crack and break under tensile stress, has always posed a significant challenge. Recognizing this limitation, Professor Victor C. Li spearheaded a revolution in construction materials with the introduction of ECC which is abbreviated from Engineered Cementitious Composites known to be 'bendable concrete' [1]. ECC transcends the limitations of conventional concrete by employing the principles of micromechanics and fracture mechanics to achieve remarkable ductility [2]. Unlike its traditional counterpart, ECC incorporates specially engineered short fibers, typically made of polymers, that act as microscopic bridges within the cementitious matrix. When subjected to stress, these fibers strategically pull out and transfer the load, preventing catastrophic cracks from propagating. This remarkable phenomenon not only enhances the material's ductility, allowing it to deform significantly before failure but also significantly improves its crack resistance beyond its flexibility [3]. ECC boasts several other unique characteristics that set it apart from conventional concrete. The exclusion of coarse aggregates in its formulation makes it significantly lighter compared to traditional concrete. This translates to reduced dead load on structures, making it particularly advantageous in high-rise construction, where every kilogram saved contributes to structural efficiency and cost savings [1]. Additionally, the exceptional crack resistance of ECC makes it ideal for applications like bridge link slabs, by eliminating the need for traditional expansion joints, which are prone to deterioration and require frequent maintenance [1]. ECC offers a more durable and aesthetically pleasing solution for infrastructure projects. Delving deeper into the composition of ECC, a carefully selected blend of ingredients is imperative. The base typically comprises ordinary Portland cement (OPC), providing the foundation for the composite. Finely graded aggregates play a crucial role, such as river sand manufactured sand, or micro silica sand, contributing to the overall strength and workability of the mix. To enhance durability and sustainability, the inclusion of cementitious composites like fly ash (Class F) bagasse ash, or silica fume is encouraged [4]. These supplementary cementitious materials not only improve the material's performance but also offer environmental benefits.

To achieve the desired workability with lower water content, essential for optimal strength and durability, high range water reducers (HRWR),

* To whom all correspondence should be sent:
E-mail: sahiljaggi.lpu@gmail.com

© 2025 Bulgarian Academy of Sciences, Union of Chemists in Bulgaria

sometimes with a blend of viscosity modifying agents (VMA), are employed. Essential rheological parameters such as flowability were analyzed to determine the workability of the formulations. Additionally, a range of mechanical properties, including compressive strength, direct and indirect tensile strength, and flexural strength, were investigated over varying curing timeframes. Finally, the critical ingredient responsible for ECC's signature ductility is the fiber reinforcement [5]. While polyvinyl alcohol (PVA) fibers are commonly used due to their effectiveness and cost-efficiency, researchers are actively exploring other options like steel fibers, tier wire fibers, and even shape memory alloys (SMAs) for specific applications. Each fiber type offers unique properties and potential benefits, paving the way for further innovation and customization of ECC for diverse applications. The potential of ECC extends far beyond the traditional realm of concrete. Due to its exceptional fracture toughness and capacity for intricate geometries, this material is well-suited for diverse applications, such as seismic-resistant structural elements, precast segmental concrete bridge pier systems, damping elements, concrete repair systems, etc.

MATERIAL

In this experimental investigation, 43-grade ordinary Portland cement (OPC) sourced from Shree Cement, Phagwara, Punjab, was utilized. Fly ash of class F was procured from the Rajpura Thermal Power station located in Punjab. The specific gravity of fly ash was determined in accordance with the standards of IS 4031 part 1 and IS 1727. Tables 1 and 2 presents physical and chemical properties of the cement and fly ash. Two types of fine aggregates (FA) were employed in this investigation, river sand and manufactured sand. The river sand and manufactured sand were sourced locally from Sutlej River and Kunal stone crusher, Pathankot, respectively. The sieve analysis test for both fine aggregates was conducted in accordance with the specifications outlined in IS 2386 Part 1. Both fine aggregates were found to adhere to the specifications mentioned in IS 383, meeting the Zone-IV requirements. PVA (polyvinyl alcohol) fiber was used, and its properties are given in Table 3. Also, Auramix was utilized as a water-reducing agent, in Table 4 the details of its properties are presented.

EXPERIMENTAL PROGRAM

Material preparation

The ECC matrix was formulated utilizing conventional Portland cement, Class F fly ash, river sand, manufactured sand, tap water, and superplasticizer. Polyvinyl alcohol (PVA) fibers were incorporated to enhance the matrix's strength. The PVA fibers measure 12 mm in length and 40 μm in diameter, possessing a nominal fiber modulus of 40 GPa and a strength of 1600 MPa. Table 5 provides an overview of the blend ratios for the ECC.

A three-gear planetary mixer was utilized for the formulation of the ECC mixture. All components, excluding fibers, underwent dry blending for a duration of two min. To achieve the desired rheological properties, water and superplasticizer were introduced into the mixture at a low mixing rate for one min, followed by a medium mixing rate for an additional two min.

Table 1. Physical properties of cement and fly ash

Material	Specific gravity	Density
Cement	3.13	1410 kg/m^3
Fly ash	2.21	1230 kg/m^3

Table 2. Chemical properties of cement and fly ash

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	TiO_2	K_2O	Na_2O	Others
Content % in cement	63.2	24.8	5.59	3.01	1.71	0.69	0.61	0.36	0.3
Content % in in fly ash	3.01	60.01	22.89	3.16	1.57	0.92	2.14	0.87	5.46

Table 3. Properties of PVA fiber

Characteristics	Elongation (%)	Young's modulus (GPa)	Tensile strength (MPa)	Fiber length (mm)	Fiber diameter (μm)
Value	6	40	1600	12	40

Table 4. Properties of Auramix 400

Type	Auramix 400
Appearance	Light yellow colored liquid
pH	Up to 6
Volumetric mass @ 20 °C	1.09 kg per liter
Alkali content	Less than 1.5 g Na_2O equivalent per liter of admixture

Table 5. Mix proportioning of all the ECC Mixes with Mix IDs

Mix ID	Cement (kg/m³)	Fly ash (kg/m³)	Sand (kg/m³)	Manufactured sand (kg/m³)	Water (kg/m³)	Superplasticizer (kg/m³)	Fiber (kg/m³)
M0	586.03	613.46	681.62	0	323.86	5.99	26
M25	586.03	613.46	511.22	170.40	323.86	5.99	26
M50	586.03	613.46	340.81	326.43	323.86	5.99	26
M75	586.03	613.46	170.41	511.21	323.86	5.99	26
M100	586.03	613.46	0	652.87	323.86	5.99	26

For uniform dispersion of the short polyvinyl alcohol (PVA) fibers, they were gradually incorporated into the mixture at a low mixing rate for one min, followed by a medium mixing rate for three min [4]. Following this, the resulting mixture was poured into molds and underwent consolidation on a vibration table to reduce air entrapment. The specimens were demolded after one day and subsequently subjected to curing at predetermined intervals as per testing requirements.

TESTS

Workability

The workability of ECC mixtures was initially assessed using the mini-slump cone test, using a mini-slump cone with upper diameter of 70 mm, lower diameter of 100 mm, and height of 60 mm [6]. Following the prescribed procedure, ECC mixtures were prepared and poured into the slump cone positioned at the center of the base plate. Once filled, the cone was slowly lifted, allowing the ECC to spread on a plate. Following this, the diameter of the spread was measured and recorded as the slump flow value.

Mechanical strength tests

- *Compressive strength test.* In this experimental setup, ECC cubes were subjected to compressive forces to determine their compression strength, a crucial parameter for assessing the materials ability to withstand axial loads without deformation or failure. The dimensions of the ECC cube specimens were measured precisely at 70.6 mm by 70.6 mm by 70.6 mm [7]; and this test was conducted after different curing periods. The compression test apparatus utilized in this investigation boasts a high-capacity of 1000 KN. The testing process adhered to the standard rate of loading as prescribed by IS 4031-1988 (part 6). This standard dictates the speed at which the compressive force is applied to the specimens during testing.
- *Split tensile test.* The split tensile test serves as an indirect means of evaluating the tensile strength of concrete. In this method, a cylindrical specimen measuring 200 mm in height and 100 mm in diameter is positioned horizontally, and a radial force is exerted on the surface of the cylinder, resulting in the formation of a vertical fracture along its diameter [8]. The split tensile test for this experimental work was conducted in compliance with IS 5816 (1999).

Durability tests

- *Water absorption test.* The test for water absorption, in alignment with IS 1124 (1974), is crucial for measuring the amount of water absorbed by the concrete specimen. The experimental procedure entails the utilization of concrete cube specimens measuring 150 mm on each side. Initially, the specimen was dried until it reaches a constant weight as prescribed in the IS code, to ensure precise measurements. This weight of the specimen was taken as the initial mass. Following this, the concrete cube was submerged in water for a predetermined period, allowing it to absorb moisture. After the specified immersion time, the specimen was removed from the water and weighed again. The disparity between the weights before and after immersion indicates the quantity of water absorbed by the concrete.
- *Acid attack.* To assess the resistance to acidic conditions of ECC, cube specimens of 70.6 mm by 70.6 mm by 70.6 mm were cast and cured for days as per the requirement to conduct the test. After the curing duration, the moisture within the specimens was removed by exposing them to sunlight. Subsequently, the weight of the dried specimens was recorded. Subsequently, the ECC cube specimens were immersed in a solution of water mixed with 1% hydrochloric acid for a period of 180 days, as prescribed. During this period, the deterioration caused by the acid was monitored every 30 days by weighting the specimens and measuring the loss in weight [8]. Furthermore, a compressive strength assessment was conducted on the degraded specimens to evaluate the decline in strength.
- *Sulfate attack.* The test for sulfate exposure was conducted on cubic specimens measuring 70.6 mm on each side. Following the initial curing period, the specimens were submerged in water for 7 days as part of the hydration process. Subsequently, the

specimens were weighed and then immersed in a solution of water diluted with 5% sodium sulfate (Na_2SO_4) powder to initiate sulfate exposure testing [8]. Subsequent tests were conducted according to curing days to assess strength under compression.

FINDINGS AND INTERPRETATION

Workability

The slump flow measurements expressed in cm, for various replacement ratios (0%, 25%, 50%, 75% and 100% of manufactured sand in ECC) revealed distinct characteristics of workability. Notably, M50 exhibited the highest slum flow value at 40.1 cm, indicative of superior fluidity compared to other mixtures. Conversely, M100 demonstrated lowest slump flow value at 31.9 cm, suggesting reduced workability attributed to complete replacement of natural river sand with manufactured sand. Intermediate replacement ratios, such as M25 and M75, manifested moderate workability. The result is depicted in graphical form in Figure 1.

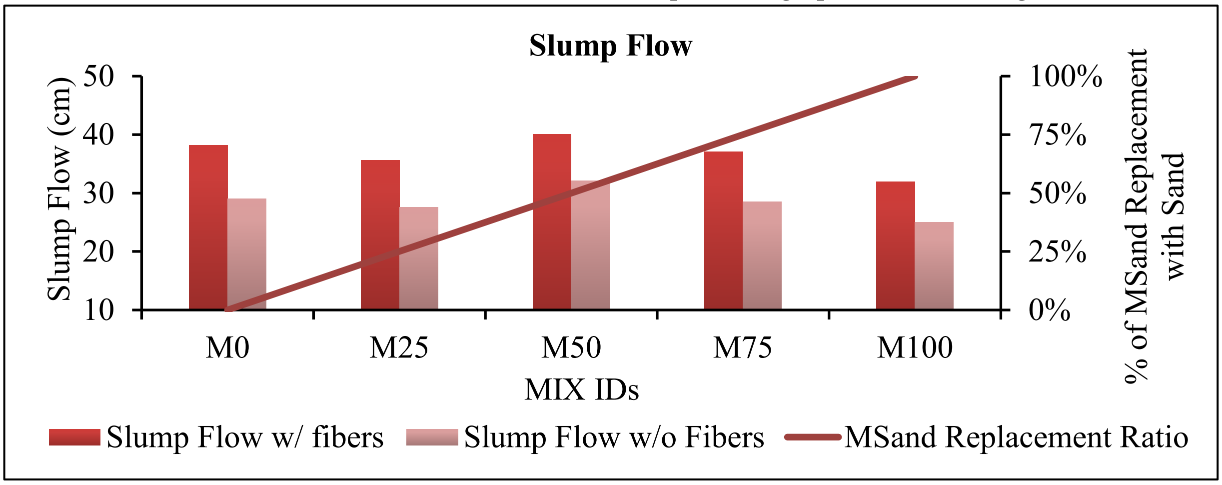

Figure 1. Slump flow of all five mixes with and without fibers

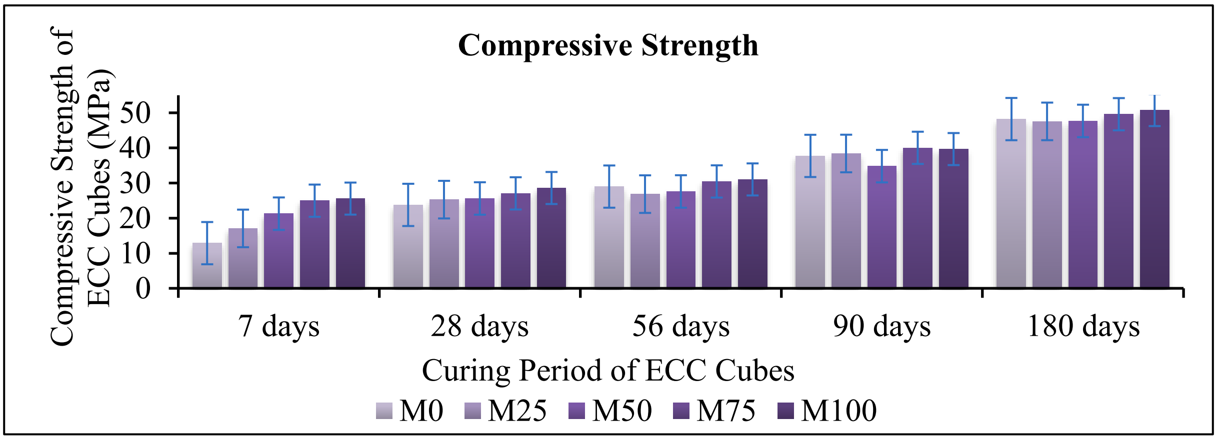

Figure 2. Compressive strength of all five mixes for 7, 28, 56, 90 and 180 days

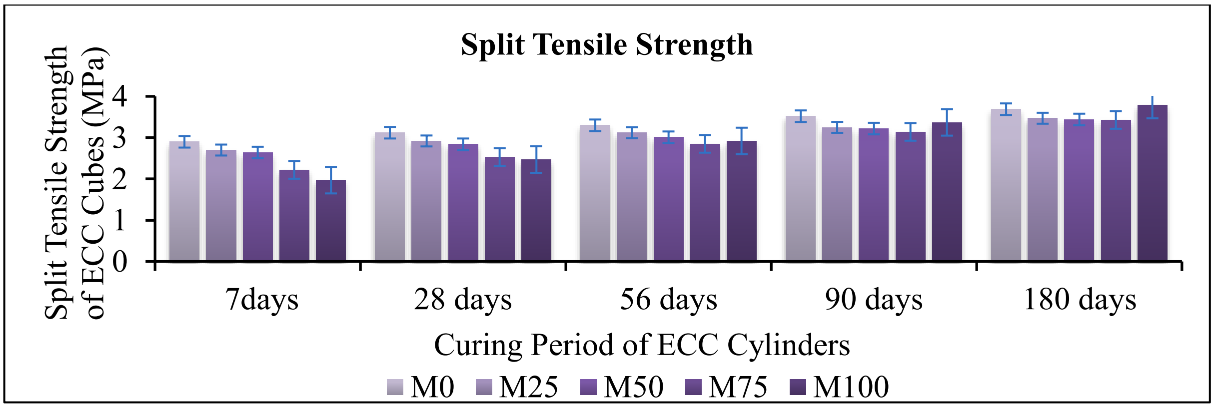

Figure 3. Split tensile strength of all five mixes for 7, 28, 56, 90 and 180 days

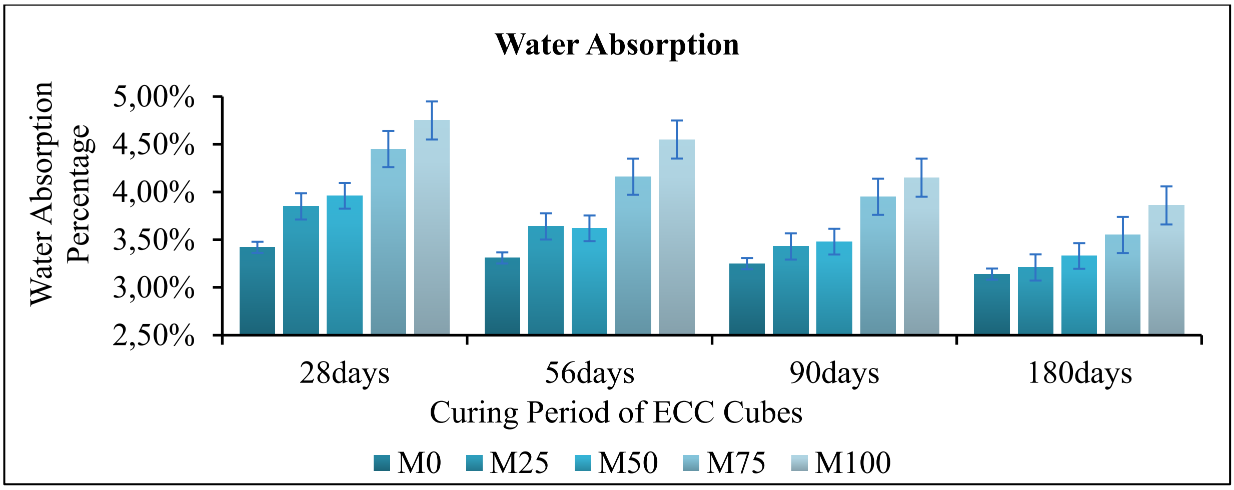

Figure 4. Water absorption rate of all five mixes for 28, 56, 90 and 180 days

Mechanical strength

- *Compressive strength.* The data regarding compressive resistance for five ECC formulations at intervals of 7, 28, 56, 90 and 180 days are depicted graphically in Figure 2. As illustrated in graphical representation and in tabular data the M100 mix exhibits a gradual increase in compressive strength over time, reaching 50.78 KN after 180 days, indicating excellent long- term strength development. Whereas the compressive strength on M75 mix peaks at 49.6 KN after 90 days, showing significant improvement compared to earlier stages. Again, with a peak strength of 47.68 KN after 180 days, the M50 mix demonstrates consistent strength development over the curing period. M25 mix achieves a compressive strength of 47.55KN after 180 days, showcasing steady strength gain throughout the curing duration. Among the mixes tested, the M100 mix attains the highest compressive strength of 50.78 KN after 180 days, indicating its superior performance in long-term strength development.
- *Split tensile strength.* The split tensile stress measurements for five formulations of ECC at a time interval of 7 28 56 90 and 180 days are visually represented in Figure 3. Across various concrete mixes, including M100, M75, M50, M25and M0, a consistent trend of improvement in split tensile strength is observed over the 180-day curing period. Specifically, M100 and M75 demonstrate gradual but steady enhancements, achieving 3.79 MPa, respectively, highlighting their effectiveness in withstanding tensile forces. Similarly, the M50 mix exhibits significant improvement, reaching a split tensile strength of 3.44 MPa after 180 days. Notably, M25 displays notable enhancement, peaking at 3.47 MPa, indicating improved tensile performance. Furthermore, M0 stands out with a split tensile strength of 3.69 MPa after 180 days.

Durability tests

- *Water absorption test.* The results of water absorption for various concrete mixes (M100, M75, M50, M25, and M0) at different curing periods indicate a consistent decrease in water absorption over time for all mixtures. Initially, higher percentages of water absorption are observed, gradually decreasing as curing progresses. Notably, the M0 mix exhibits the lowest water absorption rates across all curing periods, highlighting its superior resistance to water penetration as shown in Figure 4. This trend suggests that as the curing duration increases, the concrete mixes become denser and more impermeable, resulting in reduced water absorption capacities. These findings highlight the significance of extended curing in augmenting the durability and functionality of concrete structures, especially in addressing potential concerns associated with water penetration and moisture-induced deterioration.
- *Acid attack.* The compressive strength data for ECC samples with varying ratios of manufactured sand to river sand at different curing periods indicated distinct trends. Initially, at 28 days of curing, all mix ratios exhibited relatively high compressive strengths, with MO recording the highest value of 42.5 N/mm^2 and M100 the lowest at 26.4 N/mm^2. However, as the curing period progressed to 56, 90, and 180 days, a consistent decline in compressive strength was observed across all mix ratios. Notably, mixtures with higher proportions of river sand, such as M75 and M100, demonstrated the most significant reduction in compressive strength over time.

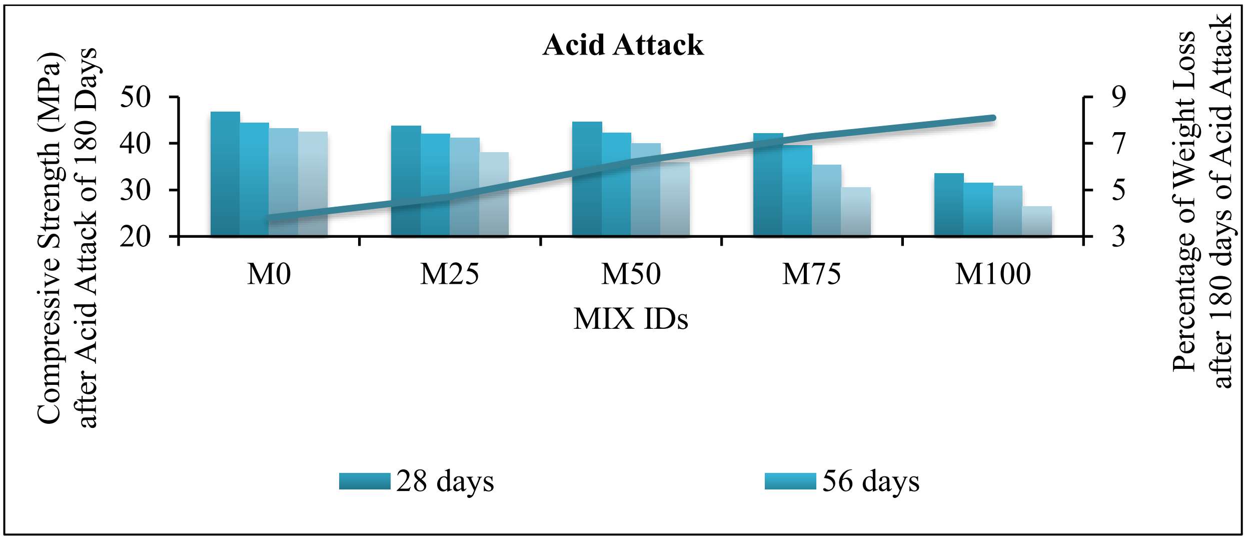

Figure 5. Acid attack results of all five mixes for 28, 56, 90 and 180 days

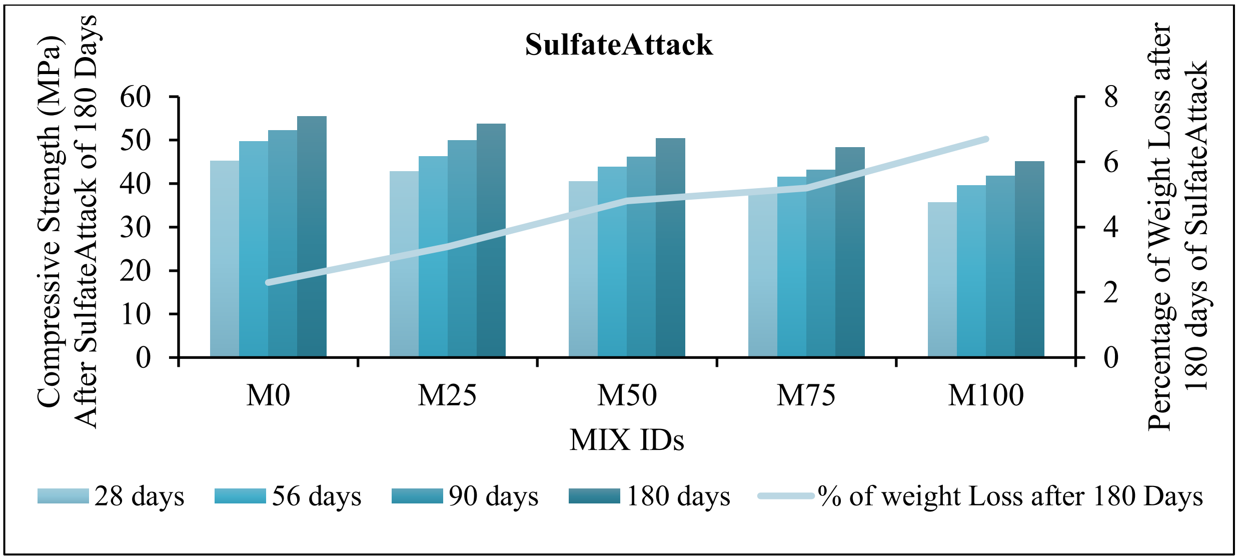

Figure 6. Sulfate attack results of all five mixes for 28, 56, 90 and 180 days

Similarly, as the curing period was extended to 56 days, 90 days, and finally 180 days, the weight loss percentage for all mixtures continued to rise, indicating degradation over time. Notably, at 180 days, the weight loss percentage ranged from 3.8% for MO to 15.3% for M100. This trend implies that the inclusion of river sand impacts the material's extended-term durability. The comprehensive findings are illustrated in Figure 5 depicting the fluctuations in compressive properties and mass degradation rate throughout diverse curing durations for each mixture ratio. These figures provide valuable insights into the performance characteristics of ECC with varying sand compositions, highlighting the importance of optimizing mix designs to achieve desired durability and strength properties.

- *Sulfate attack.* The sulfate attack test results for ECC samples exhibited a notable trend of decreasing compressive strength over time across all mix ratios. At 28 days of curing, all mix ratios demonstrated relatively high compressive strengths, with MO recording the highest value of 45.2 MPa and M100 the lowest at 35.7 MPa. However, as the curing period progressed to 56, 90, and 180 days, there was a consistent decline in compressive strength observed across all mix ratios shown in Figure 6. Mixtures with higher proportions of river sand, such as M75 and M100, demonstrated the most significant reduction in compressive strength over time. These findings suggest that the presence of river sand influences the susceptibility of ECC to sulfate attack, highlighting the importance of carefully optimizing mix designs to enhance the material's resistance to chemical degradation and ensure long-term durability in environments prone to sulfate exposure.

CONCLUSION

- The slump flow measurements demonstrate that the workability of ECC is significantly influenced by the proportion of manufactured sand, with higher ratios leading to decreased fluidity.
- Consistent improvement in compressive strength was observed over time for ECC formulations, with each mixture demonstrating distinctive long-term development patterns.
- Uniform improvement observed in split tensile stress measurements across ECC formulations over the 180-day curing period, with M100 and M75 demonstrating gradual but steady enhancements, while M50, M25, and M0 exhibit significant and notable improvements.
- Consistent decrease in water absorption was observed over time for various concrete mixes, attributed to prolonged curing enhancing concrete densification, thereby reducing water absorption capacities and improving durability and moisture resistance, with M0 mix demonstrating superior resistance to water penetration.
- The compressive strength data for ECC samples reveals that mixtures with higher proportions of river sand, such as M75 and M100, exhibit a significant reduction in strength over time, indicating susceptibility to acid attack. This deterioration is further supported by the increasing weight loss. These trends the influence of river sand content on the long-term durability of ECC against acid-attack, highlighting the necessity for precise mix design optimization to enhance resistance to chemical degradation.
- The sulfate attack test results indicate a consistent decline in compressive strength over time for all mix ratios of ECC, with mixtures containing higher proportions of river sand exhibiting more reduction in strength. This underscores the influence of river sand content on ECC's susceptibility to sulfate attack, emphasizing the necessity for mix design optimization to strengthen the resistance to chemical degradation and to ensure sustained durability in a sulfate-exposed environment.

REFERENCES

1. V. C. Li, Introduction to Engineered Cementitious Composites, In *Engineered Cementitious Composites (ECC)*, 1 (2019). https://doi.org/10.1007/978-3-662-58438-5_1
2. V. C. Li, Micromechanics and Engineered Cementitious Composites (ECC) Design Basis, in: Engineered Cementitious Composites (ECC), 2019. https://doi.org/10.1007/978-3-662-58438-5_2
3. V. C. Li, Processing of Engineered Cementitious Composites (ECC), *Engineered Cementitious Composites (ECC)*, 73 (2019). https://doi.org/10.1007/978-3-662-58438-5_3
4. V. C. Li, Processing of Engineered Cementitious Composites (ECC), *Engineered Cementitious Composites (ECC)*, 73 (2019). https://doi.org/10.1007/978-3-662-58438-5_3
5. V. C. Li, S. Wang, C. Wu., *ACI Materials Journal*, **98** 483 (2001). https://doi.org/10.14359/10851
6. M. Li, V. C. Li, *Mater. Structures* **46** 405 (2013). https://doi.org/10.1617/s11527-012-9909-z
7. N. Shanmugasundaram, S. Praveenkumar, *Construct. Building Mater.*, 309 (2021). https://doi.org/10.1016/j.conbuildmat.2021.125038
8. T. Singh, R. Siddique, S. Sharma, *Eur. J. Environ. Civil Eng.*, ***26***, 73592 (2022). https://doi.org/10.1080/19648189.2021.1988715
9. G. Ajith, N. Shanmugasundaram, S. Praveenkumar, *J. Building Pathol. Rehabil.* **6**, 1 (2021). https://doi.org/10.1007/s41024-021-00137-y
10. Z. S. Qian, J. Zhou, & E. Schlangen, *Cement & Concrete Composites*, **32**, 686 (2010).. https://doi.org/10.1016/j.cemconcomp.2010.07.015
11. Zhang, Z., Yang, F., Liu, J. C., Wang, S, *Cement & Concrete Res.*, ***137***, 106200 (2020). https://doi.org/10.1016/j.cemconres.2020.106200