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Research on the Influence of Engineered Cementitious Composite's Water–Cement Ratio and Fiber Content on the Mechanical Performance of Foam Lightweight Soil

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Abstract: This study explores the influence of the water–cement ratio and fiber content in engineered cementitious composite (ECC) on the mechanical characteristics of foamed lightweight soil (FLS) through experimental analysis. Two types of cementitious materials—ECC and ordinary Portland cement (OPC)—were utilized to create FLS specimens under identical parameters to examine their mechanical performance. Results indicate that ECC-FLS exhibits superior toughness, plasticity, and ductility compared to OPC-FLS, validating the potential of ECC as a high-performance material for FLS. To assess the influence of the ECC water–cement ratio, specimens were constructed with varying ratios at 0.2, 0.25, and 0.3, while maintaining other parameters as constant. The experimental results indicate that as the water–cement ratio of ECC increases, the flexural strength, compressive strength, flexural toughness, and compressive elastic modulus of the lightweight ECC-FLS gradually increase, exhibiting a better mechanical performance. Moreover, this study investigates the effect of basalt fiber content in ECC on the mechanical properties of FLS. While keeping other parameters constant, the volume content of basalt fibers varied at 0.1%, 0.3%, and 0.5%, respectively. The experimental results demonstrate that within the range of 0 to 0.5%, the mechanical properties of FLS improved with increasing fiber content. The fibers in ECC effectively enhanced the strength of FLS. In conclusion, the adoption of ECC and appropriate fiber content can significantly optimize the mechanical performance of FLS, endowing it with broader application prospects in engineering practices. ECC-FLS, characterized by excellent ductility and crack resistance, demonstrates versatile engineering applications. It is particularly suitable for soft soil foundations or regions prone to frequent geological activities, where it enhances the seismic resilience of subgrade structures. This material also serves as an ideal construction solution for underground utility tunnels, as well as for the repair and reconstruction of pavement and bridge decks. Notably, ECC-FLS enables the resource utilization of industrial solid wastes such as fly ash and slag, thereby contributing to carbon emission reduction and the realization of a circular economy. These attributes collectively position HDFLS as a sustainable and high-performance construction material with significant potential for promoting environmentally friendly infrastructure development.



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Keywords: foamed lightweight soil (FLS); engineered cementitious composite (ECC); water–cement ratio; fiber content; experiments on mechanical performance

1. Introduction

FLS is defined as a microporous lightweight material produced by incorporating pre-formed foam into a slurry mixture of cement, water, and optional admixtures at controlled ratios, followed by mixing, placing, and curing processes. FLS is characterized by low self-weight, minimal aggregate requirements except for coarse aggregates, high corrosion resistance, seismic durability, high fluidity, adjustable strength, and thermal insulation capabilities [1]. Despite its outstanding performance in various engineering applications [2], conventional FLS is inherently limited by its relatively low mechanical strength [3].

Currently, there have been numerous studies on the strength enhancement of FLS. One approach is to optimize the cementitious material system, which includes using early-strength cements such as sulfur aluminate cement (SAC) and magnesium phosphate cement (MPC) or partially replacing cement with reactive materials like silica fume and fine silica powder. For instance, Li T et al. [4] selected SAC as the binding material and demonstrated that it enhances the mechanical properties of FLS. Khan Q. S. et al. [5] directly replaced cement with 20% recycled glass powder by mass, leading to improved compressive strength in FLS. Li T et al. [6] used MPC as the cementitious material, and the MPC-based FLS exhibited higher compressive strength. Lesovik V et al. [7] employed a “Portland cement-opoka” marl composite binder to produce FLS with a compressive strength of up to 4.26 MPa. Pan Z et al. [8] used conventional Portland cement to fabricate FLS with a compressive strength ranging from 0.33 MPa to 1.1 MPa. Gökçe H S et al. [9] investigated the effect of fly ash cement on FLS mechanical properties and found that a silica fume addition increases compressive strength. Bing C et al. [10] improved FLS mechanical performance by incorporating fine silica powder into the cementitious matrix, demonstrating that FLS with a compressive strength of 10–50 MPa can be produced using this method.

The other reinforcement approach focuses on fiber reinforcement to optimize the mechanical properties of FLS. Key studies demonstrate the efficacy of this method: For example, Mesihib Firdawok [11] and others studied the influence of waste-recycled steel fibers of different lengths and dosages on various mechanical properties of fiber-reinforced concrete used in rigid pavement construction. The fiber-reinforced concrete showed reasonable improvements in compressive strength, indirect tensile strength, and flexural strength. Siti Nikmatin [12,13] explored the mechanical properties of helmets made of acrylonitrile butadiene styrene (ABS) composites filled with empty fruit bunch fibers of oil palm and the thermophysical properties of polypropylene (PP) filled with nano-scale rattan powder particles, respectively, providing experimental evidence and innovative directions for the optimization of the interfacial bonding and performance enhancement of natural fiber fillers in composites. Raj B et al. [3] investigated hybrid fiber-reinforced FLS systems and established that combined fiber types yield significant strength improvements. Zhao et al. [14] developed cementitious foam composites containing 1.5% glass fibers, achieving an 86.31% increase in 28 d compressive strength compared to non-reinforced specimens. Qiu T et al. [15] revealed that basalt, glass, and polyester fiber integration consistently enhanced both compressive and flexural strength parameters in FLS matrices. Mhedi N M et al. [16] explored sustainable material development through recycled plastic bottle fibers, which demonstrated measurable tensile strength augmentation. Mohamad N et al. [17] confirmed proportional relationships between coconut fiber content and critical mechanical parameters through comprehensive experimental analysis, including compressive strength, tensile strength, and elastic modulus.

Existing studies demonstrate that binder optimization, such as early-strength cement and reactive admixtures, combined with fiber-reinforcement technology using synthetic or natural fibers, significantly enhances the compressive and tensile strength of FLS. The

compressive strength, tensile strength, and elastic modulus of the material increase proportionally with higher cement strength and fiber content percentages. However, current research primarily focuses on the individual optimization of binder systems or fiber reinforcement, while investigations into the synergistic effects of combined methodologies remain limited.

This study introduces a novel cementitious binder—engineered cementitious composite (ECC)—combined with optimized fiber content to enhance the performance of FLS. ECC typically consists of cement, fine silica sand, fly ash, polymeric fibers, water, and high-range water-reducing admixture (HRWRA). Owing to its polymeric fiber reinforcement and the absence of coarse aggregates, ECC exhibits superior ductility, tensile properties, crack resistance, durability, energy dissipation capacity, impact resistance, workability, and flowability [18–25]. The unique material properties and microstructure of ECC synergistically interact with optimized cementitious systems and fiber reinforcement, enabling comprehensive performance improvements in FLS. Yucel, Huang, Qudah, and others have reviewed the application prospects of ECC in pavement and bridge repair and retrofitting [23,26–30], which aligns closely with the soft foundation treatment of FLS roads [31–33]. However, the combination of ECC and FLS remains underexplored. Therefore, this study aims to investigate the mechanical and functional performance of ECC-FLS composites through systematic experimental analysis.

In recent years, building materials have been developing toward environmental friendliness, energy conservation, and emission reduction. For example, Mesihib Firdawok [34] and others studied the influence of waste recycled steel fibers of different lengths and dosages on the various mechanical properties of fiber-reinforced concrete used in rigid pavement construction. The fiber-reinforced concrete showed reasonable improvements in compressive strength, indirect tensile strength, and flexural strength. ECC and FLS represent promising frontiers in green material innovation. For ECC, Weihsiu Hu et al. [35] developed a sustainable ECC by integrating polyethylene fibers, recycled fine aggregates, and low-carbon cement, achieving a 30.34% reduction in CO₂ emissions and 40–50% cost savings while maintaining robust mechanical properties. Yifei Shi et al. [36] further advanced the field with a multifunctional ECC formulated from coral sand and fly ash, whose alkali-curing mechanism mitigates environmental impacts and paves the way for intelligent infrastructure materials. Qing-Hua Li et al. [37] reinforced the circular economy concept by fabricating high-strength ECC from recycled fishing net fibers, exemplifying the upcycling potential of construction waste. In the realm of FLS, Xiaohui Sun et al. [38] leveraged large-scale waste slag recycling and foam stabilization technology to develop a geopolymer-based underwater FLS, which significantly reduces CO₂ emissions while resolving the technical challenge of underwater backfilling. Chen Zhang et al. [39] reported a fly ash-modified FLS that reduces cement consumption by 20%, meeting subgrade strength requirements and promoting the high-value utilization of industrial by-products. Both materials utilize industrial waste substitution and low-carbon process design, showcasing distinct advantages in environmental sustainability, engineering innovation, and lifecycle performance. Building on these advancements, this study aims to investigate the performance characteristics of a novel composite material integrating high-ductility cement-based composites and foamed lightweight soil. By capitalizing on ECC's exceptional toughness and FLS's lightweight, low-carbon attributes, this research seeks to develop a sustainable construction material that balances ecological benefits, economic efficiency, and engineering performance, addressing the needs of infrastructure projects in challenging environments such as seismic zones and coastal areas.

Based on FLS, this paper first conducts experiments to determine whether ECC can enhance the mechanical properties of FLS. Two types of cement are used: ECC and OPC,

while keeping other parameters constant. For both ECC- and OPC-based FLS, the water–cement ratio is 0.3, the mass ratio of cement to ISO standard sand is 1:3 with a total mass of 450 g, and the foam content is 513 L/m³. The influence of ECC on mechanical properties such as flexural–tensile strength, compressive strength, flexural toughness, brittleness coefficient, compressive elastic modulus, compression amount, and the load–displacement curve is studied. Next, the influence of the content of ECC on the mechanical properties of foamed lightweight soil is investigated. The water–cement ratios of ECC-based FLS are set at 0.2, 0.25, and 0.3, with the foam content kept constant at 513 L/m³. The impact of the change in the water–cement ratio on physical and mechanical properties including flexural–tensile strength, compressive strength, flexural toughness, brittleness coefficient, and the compressive elastic modulus is analyzed. Moreover, the influence of the fiber content in ECC on the mechanical properties of FLS is studied. Basalt fibers are added, and the volume fractions of basalt fibers are 0.1%, 0.3%, and 0.5%, respectively. While keeping the foam content, water–cement ratio, and cement dosage in the foamed lightweight soil constant, the effects of different basalt fiber volume fractions on physical properties such as flexural–tensile strength, compressive strength, flexural toughness, brittleness coefficient, compressive elastic modulus, compression amount, and the load–displacement curve are explored. Through experiments, it is verified that ECC is more suitable for FLS, and the mechanical properties of FLS improve as the fiber content increases.

2. Experimental Materials and Test Methods

2.1. Raw Materials

2.1.1. ECC

The ECC used in this study is produced by Shanghai Kehong Cement Co., Ltd. (Shanghai, China), with a product type classified as Category I. The material's appearance is shown in Figure 1. The composite contains 0.1% polypropylene fibers by volume, quartz sand, cement, and other constituent materials. Its technical specifications comply with DB34/T 3469-2019 [40], as detailed in Table 1. The high-ductility cement-based composite material utilized in this paper is illustrated in Figure 1 below.



Figure 1. The specimen of the ECC.

Table 1. Mechanical properties at 28 days standard curing age for different grades.

Test Items	Standard Curing Age	I	II	III
Flexural Toughness (KJ/m ³)	28 d	≥160.0	≥120.0	≥80.0
Equivalent Flexural Strength (N/mm ²)	28 d	≥11.0	≥10.0	≥9.0
Flexural Strength (N/mm ²)	28 d	≥12.0	≥12.0	≥12.0
Compressive Strength of Cube (N/mm ²)	28 d	≥50.0	≥50.0	≥50.0

2.1.2. Basalt Fiber

In this study, basalt fibers are employed as the reinforcing material during dosage increments. As a novel eco-friendly inorganic fiber, basalt fiber has undergone rapid development in recent years. For this research, the basalt fibers used in the test are produced by

Jiangsu Yancheng Material Factory (Yancheng, Jiangsu, China), with a product specification of brown, 9 mm, complying with the standard GB/T 25022-2010 [41]. The specimens of the basalt fibers are presented in Figure 2 and Table 2.



Figure 2. Basalt fiber.

Table 2. Technical parameters of basalt fiber.

Technical Indicators	Parameter Value	Testing Standard
Specific Gravity (g/cm^3)	2.87	GB/T 19975-2005 [42]
Elastic Modulus (g/cm^3)	80	ASTM C1550-13 [43]
Fiber Diameter (μm)	13	GB/T 35465.3-2017 [44]
Tensile Strength (MPa)	≥ 3500	ISO 11566-1996 [45]
Elongation at Break (%)	3.1	GB/T 26743-2011 [46]

2.1.3. Foaming Agent

The α -olefin sulfonate (AOS) foaming agent used in the test was produced by Shanghai Fine Chemical Co., Ltd. (Shanghai, China) (Model: AOS-99). Its main technical specifications are shown in Table 3, and the testing methods follow GB/T 5173-2013 [47].

Table 3. Technical parameters of AOS foaming agent.

Item	Appearance	Active Matter Content
Appearance	White or slightly yellow powder	Visual observation method
Active substance content	$\geq 99\%$	GB/T 5173 [48]
pH value	7.0–9.0	GB/T 6368-2008 [49]
Foam half-life (25 °C)	≥ 30 min	GB/T 7462-1994 [50]

2.2. Preparation and Test Methods for FLS

2.2.1. Preparation of FLS with Different Cement Types

This study adopts the single-factor variable control method. In the mix proportion design, only the type of cement is changed. OPC and ECC are used, respectively. Meanwhile, the foam content is fixed at $513 \text{ L}/\text{m}^3$, the water–cement ratio is set at 0.5, and the amount of ISO sand is also fixed. In this way, the interference of other factors such as the water–cement ratio and fiber content is excluded so as to accurately explore the influence of the type of cement on the mechanical properties of aerated lightweight soil. The mix proportion refers to the standard DBJ/T 15-134-2023 [51], and the density is set to $1000 \text{ kg}/\text{m}^3$, which is commonly used in engineering, to ensure that the experimental conditions are consistent with the requirements of actual engineering applications. According to the mass of each component in Table 4, test blocks of different sizes are fabricated: 36 test blocks with the size of $40 \text{ mm} \times 40 \text{ mm} \times 160 \text{ mm}$, with every 3 blocks as a group, are used to measure the flexural strength and flexural toughness at 3 d, 7 d, 14 d, and 28 d; 36 test blocks with the size of $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$, with every 3 blocks as a group, are used to measure the compressive strength at each age; 18 test blocks with the size of $100 \text{ mm} \times 100 \text{ mm} \times 300 \text{ mm}$, with every 6 blocks as a group, are used to measure the

compressive elastic modulus at 28 d. The number of test blocks is determined according to the ASTM C31/C31M [52] standard. By using a sufficient sample size, the influence of accidental errors on the experimental results is reduced. Specimen configurations are presented in Figure 3.

Table 4. Mix proportions of ECC-FLS and OPC-FLS.

Name	Density (kg/m ³)	Foam Content (L/m ³)	Water–Cement Ratio	Cement (g)	Water (g)	ISO Standard Sand (g)
OPC-FLS	1000	513	0.5	450	225	1350
ECC-FLS	1000	513	0.5	450	225	1350



Figure 3. ECC-FLS with a foam content of 513 L/m³.

2.2.2. Preparation of ECC-FLS with Different Water–Cement Ratios

In investigating the effect of the water–cement ratio on the mechanical properties of ECC-FLS, the fiber content is fixed at 0%, and only the water–cement ratio is varied across three levels: 0.2, 0.25, and 0.3. The selection of this ratio range is guided by a comprehensive consideration of construction feasibility and material performance optimization: as specified in Standard DB62/T 3159-2019 [53], water–cement ratios below 0.2 result in an insufficient workability of the mixture, while ratios exceeding 0.3 compromise foam stability and lead to abnormal increases in porosity. The interval between 0.2 and 0.3 is therefore chosen to ensure adequate mixture flowability during construction and to encompass the strength-optimized range of cement contents from 769 kg/m³ to 913 kg/m³, corresponding to material densities of 1000 kg/m³ to 1096 kg/m³. Test specimens are prepared according to the component masses listed in Table 5: thirty-six prismatic specimens measuring 40 mm × 40 mm × 160 mm, grouped into twelve sets of three, are used to measure the flexural strength and compressive elastic modulus at various ages; thirty-six cubic specimens of 100 mm × 100 mm × 100 mm, divided into twelve sets of three, are used for compressive strength testing across all curing periods; eighteen cubic specimens of 100 mm × 100 mm × 100 mm, organized into three sets of six, are employed to determine the 28-day compressive elastic modulus. Specimen quantities are determined in accordance with statistical repeatability principles to ensure the reliability and accuracy of test results. The prepared specimens (only the ones with a water–cement ratio of 0.3 are shown) are illustrated in Figure 4 below.

Table 5. Mix proportions of ECC-FLS with different water–cement ratios.

Water–Cement Ratio	Density (kg/m ³)	Cement (kg)	Water (kg)	Foam Content (L)
0.20	1096	913	183	513
0.25	1044	835	209	513
0.30	1000	769	231	513

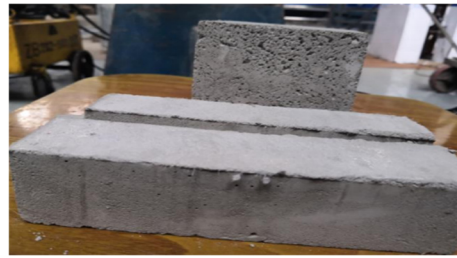


Figure 4. ECC-FLS with a water–cement ratio of 0.3.

2.2.3. Preparation of ECC-FLS with Different Fiber Contents

When studying the influence of fiber content on the mechanical properties of ECC-FLS, the water–cement ratio is fixed at 0.3, to the type of cement, the density at 1000 kg/m^3 , and the foam content at 513 L/m^3 . The volume contents of basalt fibers are set at 0%, 0.1%, 0.3%, and 0.5%. The selection of these contents is based on the dispersibility results of preliminary experiments and engineering applicability: 0% serves as the control; 0.1% is used to verify the initial bridging effect of the fibers; 0.3% and 0.5% are for strengthening through increasing the fiber network density, taking into account both economic aspects and the strengthening effect.

Test specimens are prepared according to Table 6: 48 specimens of $40 \text{ mm} \times 40 \text{ mm} \times 160 \text{ mm}$ for measuring flexural strength and flexural toughness, 48 specimens of $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ for measuring compressive strength, and 24 specimens of $100 \text{ mm} \times 100 \text{ mm} \times 300 \text{ mm}$ for measuring the 28-day compressive elastic modulus. There are 3–6 specimens in each group. The mix proportion adopts the equal-volume replacement method to ensure consistency with engineering parameters.

Table 6. Mix proportions of ECC-FLS with different fiber contents.

Fiber Content	Density (kg/m^3)	Cement (kg)	Water (kg)	Foam Content (L)
0.0%	1000	769	231	513
0.1%	1000	769	231	513
0.3%	1000	769	231	513
0.5%	1000	769	231	513

During the preparation of test specimens, the materials of each component are accurately weighed according to Tables 4–6. A mechanical stirring device with a rotation speed of 200 rpm is used to stir the materials for 3 min to ensure uniform mixing of the materials. Subsequently, the materials are poured in layers. The pouring height of each layer is controlled at 50 mm, and each layer is vibrated for 10 s to avoid the influence of uneven bubble distribution on the material properties.

After the preparation is completed, all the test specimens are placed in a standard curing chamber with a temperature of $20 \pm 2 \text{ }^\circ\text{C}$ and a humidity of $\geq 95\%$ for curing. They are taken out for mechanical property tests at the ages of 3 d, 7 d, 14 d, and 28 d, respectively. By unifying the curing conditions, the consistency and comparability of the experimental data are ensured.

2.3. Test Indicators and Testing Methods

1. Flexural Strength

The three-point loading method is used in the test. The test span is 100 mm, and the loading speed is 0.3 mm/min. This loading speed meets the requirements for the loading rate of high-ductility materials in the standard CECS 13:2020 [54], avoiding the

influence of the inertial force on the test results. The instrument used for the loading test is shown in Figure 5. The flexural–tensile strength of the specimen is calculated according to Formula (1), and the results are rounded to the nearest 0.1 MPa.

$$R_f = \frac{1.5F_f L}{b^3} \quad (1)$$

In the equation above, the following apply: R_f —flexural strength (MPa); F_f —ultimate load (N); L —support spacing (mm); b —specimen width (mm).



Figure 5. Flexural strength testing apparatus.

2. Compressive Strength

To conduct the compressive strength test of aerated lightweight soil, the FLS needs to be placed inside the testing instrument. The compression surface of the test specimen is the two formed side surfaces of the test specimen, with an area of 100 mm × 100 mm. The loading is carried out in a displacement control mode, and the loading speed is 1 mm/min, which meets the requirements for the loading rate of high-ductility materials in CECS 13:2020. The instrument for the compressive strength test is shown in Figure 6. The compressive strength of the test specimen is calculated according to Formula (2).

$$R_c = \frac{F_c}{A} \quad (2)$$

In the equation above, the following apply: R_c —compressive strength (MPa); F_c —ultimate load (N); A —load-bearing area (mm²).



Figure 6. Compressive strength testing apparatus.

3. Brittleness Coefficient

The brittleness coefficient quantifies the brittleness and deformation behavior of cementitious composites, defined as the ratio of compressive strength to flexural strength. A lower brittleness coefficient indicates higher material ductility and superior crack resistance,

delaying crack propagation and enhancing mechanical performance under external loading. The compressive strength of specimens is calculated using Equation (3):

$$K = \frac{R_c}{R_f} \quad (3)$$

In the equation above, the following apply: R_c —compressive strength (MPa); R_f —flexural strength (MPa); K —brittleness coefficient.

4. Flexural Toughness

The test employs a four-point loading method with a test span of 120 mm, conducted for different mix proportions and curing ages. Loading is controlled by displacement at a speed of 0.3 mm/min. The test stops when the specimen deflection reaches six times the initial cracking deflection, after which data are exported. For bending toughness evaluation, this study adopts the toughness index method from ASTM C1018, quantifying the energy absorption capacity using I_5 and I_{10} to intuitively reflect the energy dissipation characteristics during multiple-crack propagation, as illustrated in the integral area of the load–deflection curve in Figure 7. The calculation formulas are presented in Formulas (4) and (5):

$$I_5 = \frac{A_2 + A_1}{A_1} \quad (4)$$

$$I_{10} = \frac{A_3 + A_2 + A_1}{A_1} \quad (5)$$

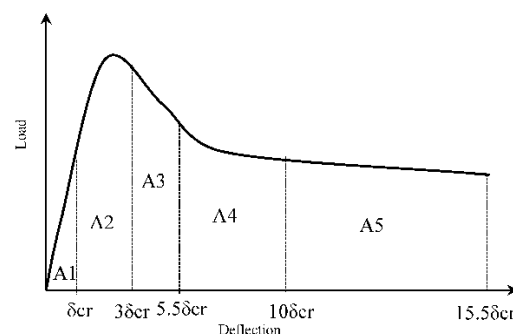


Figure 7. ASTM C1018 flexural toughness index method.

5. Elastic Modulus

As shown in Figure 8 below, the secant modulus method of stress–strain is adopted. The tested stress level is 40% of the axial compressive strength, which complies with the test specification of the quasi-static elastic modulus in GB/T 50081-2019. The influence of the initial defects of the specimen is eliminated through five pre-compression cycles to ensure data stability. The pre-compression is terminated when the difference between δ_4 and δ_5 is less than 0.003 mm. The calculation formula for the compressive elastic modulus is as follows (Equation (6)):

$$E_c = \frac{N_{0.4} - N_0}{A} \times \frac{l}{\delta_5} \quad (6)$$

In the equation above, the following apply: E_c —static elastic modulus (MPa); $N_{0.4}$ —load at 0.4 f_{cp} stress (N); N_0 —load at 0.1 MPa stress (N); A —cross-sectional area of the specimen (mm²); δ_5 —4th cycle average deformation (mm); l —gage length, 50 (mm).

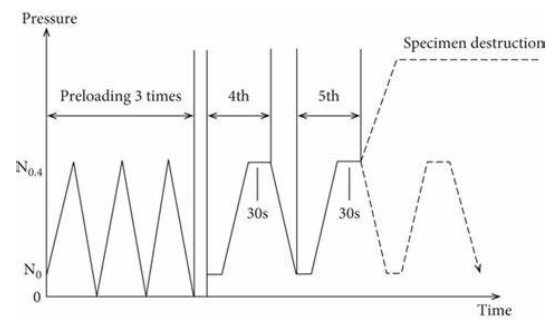


Figure 8. Schematic of elastic modulus test loading procedure.

3. Results Analysis

3.1. Performance Test Results and Analysis of FLS with Different Cement Types

3.1.1. Flexural Strength with Different Cement Types

As presented in Table 7 and Figure 9, ECC-FLS exhibits 13.5% higher 3 d flexural strength and 14.7% greater 28 d flexural strength relative to OPC-FLS. These results demonstrate statistically significant improvements in flexural performance for ECC-modified FLS compared to conventional formulations, primarily attributed to ECC's microcrack-bridging capability and fiber-reinforcement effects.

Table 7. Flexural strengths of OPC-FLS and ECC-FLS (MPa).

Types of FLS	3 d	28 d
OPC-FLS	0.37	0.68
ECC-FLS	0.42	0.78

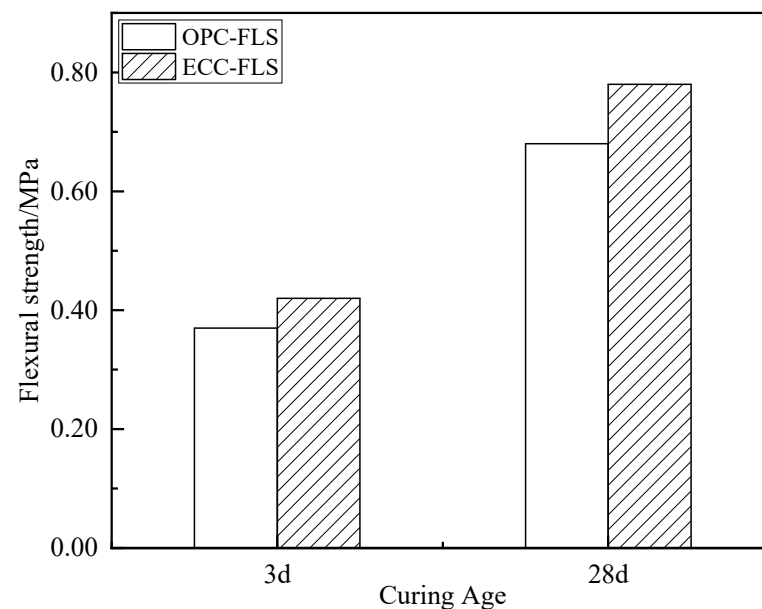


Figure 9. Flexural strength comparison of OPC-FLS and ECC-FLS.

3.1.2. Compressive Strength with Different Cement Types

Compressive strength results for OPC-based and ECC-FLS are presented in Figure 10. As shown in Table 8 and Figure 11, ECC-FLS exhibits 110.2% higher 3 d compressive strength and 62.2% greater 28 d compressive strength compared to OPC-FLS. These findings indicate marginal improvements in compressive strength for ECC-modified FLS, likely due to ECC's refined hydration products and enhanced matrix densification.

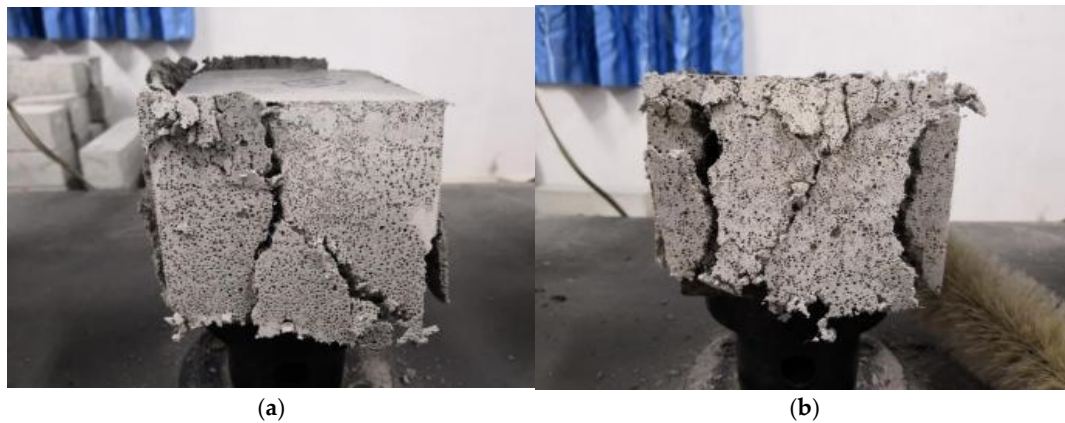


Figure 10. Photographs of FLS after compressive strength test: (a) OPC-FLS; (b) ECC-FLS.

Table 8. Compressive strength of OPC-FLS and ECC-FLS (MPa).

Types of FLS	3 d	28 d
OPC-FLS	1.86	3.31
ECC-FLS	3.91	5.37

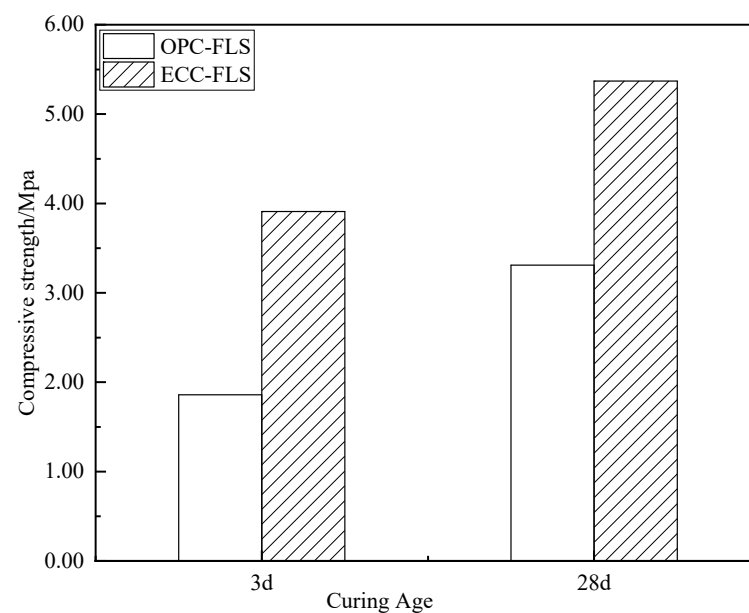


Figure 11. Compressive strength comparison of OPC-FLS and ECC-FLS.

3.1.3. Brittleness Index with Different Cement Types

As presented in Table 9, the brittleness index of OPC-FLS is 49.9% higher than that of ECC-FLS, indicating superior crack resistance and enhanced deformation capacity in ECC-FLS. This result aligns with ECC's characteristic microcrack-bridging mechanism, which delays crack propagation and improves ductility compared to conventional OPC-based formulations.

Table 9. Brittleness index of OPC-FLS and ECC-FLS at 28 d.

	OPC-FLS	ECC-FLS
Brittleness Index	8.35	5.57

3.1.4. Flexural Toughness with Different Cement Types

As presented in Table 10 and Figure 12, ECC-FLS exhibits 1044% higher I_5 and 604% greater I_{10} flexural toughness indices compared to OPC-FLS. These results demonstrate statistically significant improvements in flexural toughness and energy absorption capacity for ECC-modified FLS, primarily attributed to ECC's microcrack-bridging and fiber-reinforcement effects, which enhance crack resistance and deformation capability under loading.

Table 10. Flexural toughness of OPC-FLS and ECC-FLS at 28 d.

Types of Foamed Lightweight Soil	Flexural Toughness I_5	Flexural Toughness I_{10}
OPC-FLS	0.25	0.50
ECC-FLS	2.86	3.52

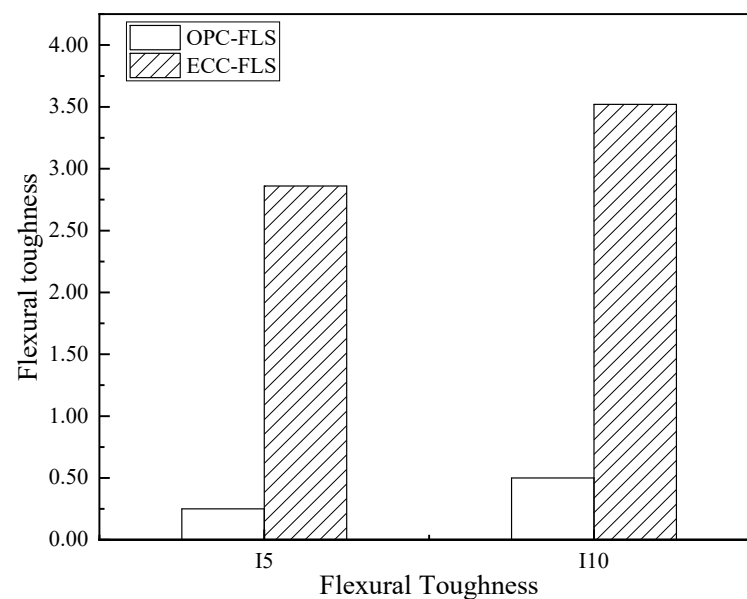


Figure 12. Flexural toughness comparison of ECC-FLS and OPC-FLS.

3.1.5. Compressive Load–Displacement Analysis of Both Cementitious Materials at 28 D

As presented in Table 11 and Figure 13, ECC-FLS exhibits 1.9% higher ultimate load and 2.1% greater displacement at ultimate load compared to OPC-FLS. Additionally, ECC-FLS demonstrates a 41% higher inflection point load and 9.3% greater displacement at the inflection point. These results indicate statistically significant improvements in ductility for ECC-modified FLS, primarily attributed to its fiber reinforcement and microcrack-bridging mechanisms, which delay failure and enhance energy dissipation capacity under loading.

Table 11. Load and displacement of OPC-FLS and ECC-FLS.

Types of Foamed Lightweight Soil	Inflection Point Load (kN)	Displacement at Inflection Point Load (mm)	Ultimate Load (kN)	Displacement at Ultimate Load (mm)
OPC-FLS	26.17	10.84	61	6.61
ECC-FLS	36.91	11.85	62.2	6.75

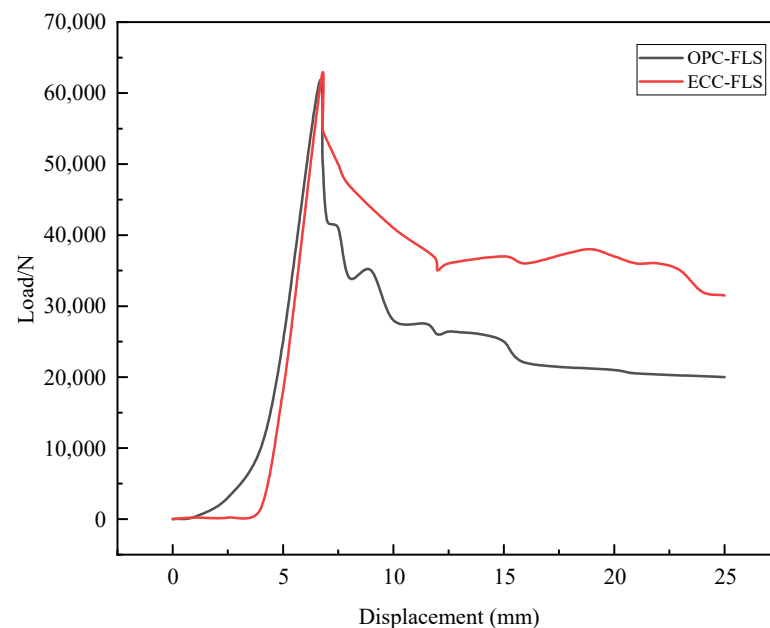


Figure 13. Compressive load–displacement comparison of ECC-FLS and OPC-FLS at 28 d.

The flexural strength, flexural toughness, and ductility of ECC-FLS are significantly superior to those of OPC-FLS, with the core mechanism lying in the microcrack-bridging effect of ECC: when microcracks initiate under loading, 0.1% volume-dosage polypropylene fibers dispersed in ECC span the crack interface, transmitting stress through interfacial bonding forces to hinder crack propagation and promote multiple cracking. For example, the flexural toughness index I_{10} increases by 272%, attributed to the additional fracture energy consumed by fiber bridging that prevents the formation of a single dominant crack, aligning with the multiple cracking theory proposed by J. Aveston et al. [55]—fiber bridging redistributes the stress at the crack tip, manifesting as a 2.1% increase in ultimate load displacement and a notable enhancement in energy absorption capacity, such as the 186% increase in flexural toughness I_5 . Compared with ordinary cement-based materials, the fiber-bridging mechanism in ECC induces the formation of dense microcracks at the early stage of crack propagation rather than sudden brittle failure, directly explaining the 13.9% decrease in the brittleness coefficient.

3.2. Mechanical Performance Testing and Analysis of ECC-FLS with Varying Water–Cement Ratios

Given the significantly improved toughness, plastic deformation capacity, and ductility of ECC-FLS demonstrated in previous experimental results compared to OPC-FLS, this section systematically investigates the effects of varying water-to-cement ratios on the mechanical properties of ECC-FLS at both material and structural levels.

3.2.1. Porosity and Density with Varying Water–Cement Ratios

As presented in Table 12, the porosity remains nearly constant with increasing water–cement ratios. At a water–cement ratio of 0.20, ECC constitutes 83.3% of the total mixture mass, with water accounting for 16.7%. For water–cement ratios of 0.25 and 0.30, ECC mass fractions decrease to 79.9% and 76.9%, while corresponding water fractions increase to 20.1% and 23.1%, respectively.

Table 12. Porosity, cement mass fraction, and water mass fraction at water–cement ratios of 0.20, 0.25, and 0.30.

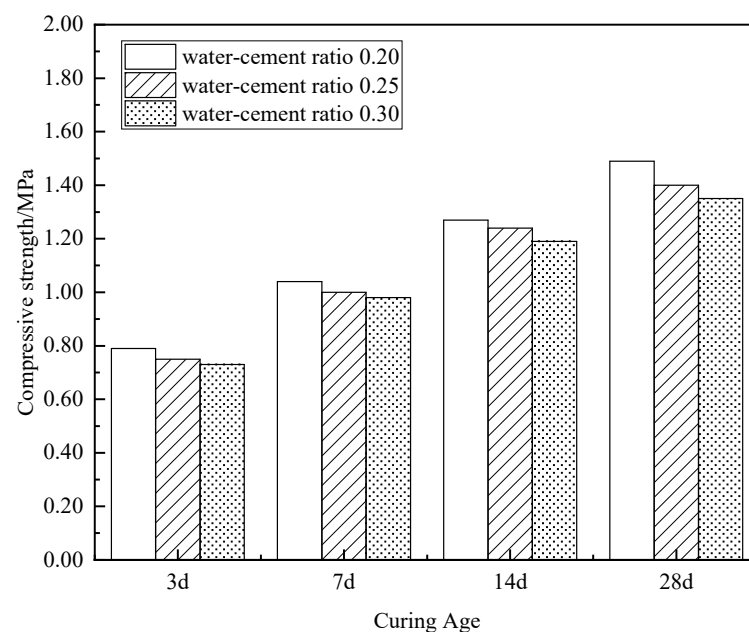
Water–Cement Ratio	Porosity (%)	Cement Mass Fraction (%)	Water Mass Fraction (%)
0.20	50.7	83.3	16.7
0.25	50.2	79.9	20.1
0.30	50.7	76.9	23.1

3.2.2. Flexural Strength with Varying Water–Cement Ratios

Table 13 and Figure 14 present the flexural strength of ECC-FLS at water–cement ratios of 0.20, 0.25, and 0.30 across curing ages of 3, 7, 14, and 28 d. The flexural strength hierarchy follows the order: water–cement ratio of $0.30 < 0.25 < 0.20$. At 28 d, the flexural strength of the specimen with a water–cement ratio of 0.20 is increased by 10.3% compared to that of the specimen with a water–cement ratio of 0.30. The flexural strength of the specimen with a water–cement ratio of 0.25 is increased by 3.7% compared to that of the specimen with a water–cement ratio of 0.30. Notably, the strength gap between 0.30 and 0.20 widens with curing time compared to the gap between 0.25 and 0.20. These results collectively indicate that within the water–cement ratio range of 0.20–0.30, ECC-FLS flexural strength decreases progressively with an increasing water–cement ratio.

Table 13. Flexural strength of ECC-FLS at water–cement ratios of 0.20, 0.25, and 0.30 (MPa).

Water–Cement Ratio	Flexural Strength at 3 d	Flexural Strength at 7 d	Flexural Strength at 14 d	Flexural Strength at 28 d
0.20	0.79	1.04	1.27	1.49
0.25	0.75	1.00	1.24	1.40
0.30	0.73	0.98	1.19	1.35

**Figure 14.** Flexural strength of ECC-FLS at water–cement ratios of 0.20, 0.25, and 0.30.

3.2.3. Compressive Strength with Varying Water–Cement Ratios

The experimental results in Table 14 and Figure 15 demonstrate an inverse correlation between the water-to-cement ratio and compressive strength in ECC-FLS, with a strength hierarchy following $0.30 < 0.25 < 0.20$. The 28 d compressive strength analysis reveals that

specimens with a 0.30 water-to-cement ratio exhibit 13% lower strength than those with a 0.20 ratio, and a 5.1% reduction compared to the 0.25 ratio mixture. Notably, the strength differential between the 0.30 and 0.20 ratios progressively amplifies with extended curing duration, showing greater divergence than the gap between the 0.30 and 0.25 ratios. These findings demonstrate that ECC-FLS compressive strength exhibits a consistent decreasing trend as the water-to-cement ratio increases within the 0.2–0.3 range.

Table 14. Compressive strength of ECC-FLS at water-cement ratios of 0.20, 0.25, and 0.30 (MPa).

Water–Cement Ratio	Compressive Strength at 3 d	Compressive Strength at 7 d	Compressive Strength at 14 d	Compressive Strength at 28 d
0.20	2.86	5.02	6.19	7.03
0.25	2.69	4.67	5.86	6.54
0.30	2.48	4.35	5.54	6.22

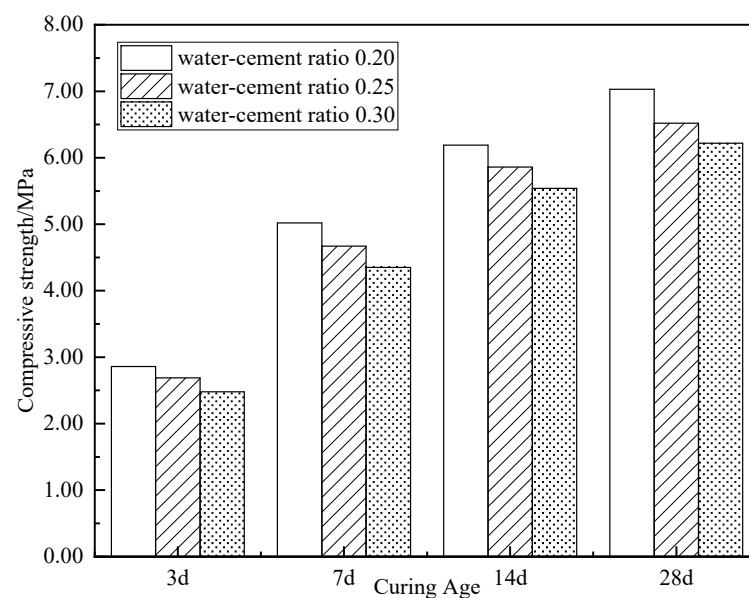


Figure 15. Compressive strength of ECC-FLS at water–cement ratios of 0.20, 0.25, and 0.30 across 3 d, 7 d, 14 d, and 28 d curing ages.

3.2.4. Brittleness Index with Varying Water–Cement Ratios

The experimental data presented in Table 15 and Figure 16 demonstrate an inverse correlation between water–cement ratios and brittleness indices in ECC-FLS. The brittleness index ranking follows a descending order from the 0.20 to 0.30 water–cement ratio. At 28 d of curing, specimens with a 0.30 water–cement ratio exhibit a 2.4% reduction in the brittleness index compared to the 0.20 ratio mixture, while the 0.25 ratio specimens show a 1.3% decrease relative to the 0.20 ratio reference. The disparity in brittleness indices between the 0.30 and 0.20 ratios becomes more pronounced with extended curing periods, exceeding the divergence observed between the 0.25 and 0.20 ratios. These results conclusively indicate that within the 0.2–0.3 water–cement ratio range, the brittleness index of ECC-FLS progressively decreases with increasing water content.

Table 15. Brittleness index of ECC-FLS at water–cement ratios of 0.20, 0.25, and 0.30 at 28 d (MPa).

	Water–Cement Ratio 0.20	Water–Cement Ratio 0.25	Water–Cement Ratio 0.30
Brittleness Index	4.72	4.67	4.61

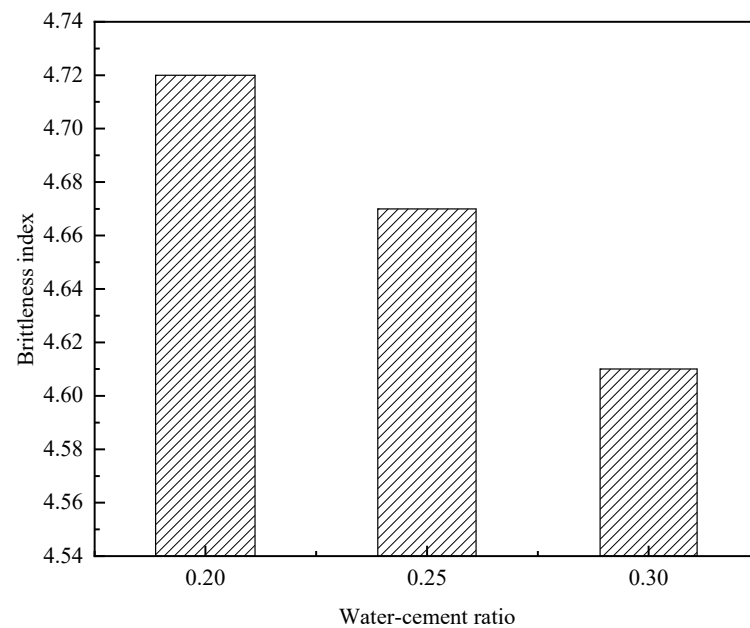


Figure 16. Brittleness index of ECC-FLS at water–cement ratios of 0.20, 0.25, and 0.30 at 28 d.

3.2.5. Flexural Toughness with Varying Water–Cement Ratios

As shown in Table 16 and Figure 17, the flexural toughness I_5 hierarchy follows water–cement ratios of $0.20 > 0.25 > 0.30$. At 28 d, the flexural toughness I_5 of the mixture with a water–cement ratio of 0.30 is 12% lower than that of the mixture with a water–cement ratio of 0.20. Additionally, the flexural toughness I_5 of the mixture with a water–cement ratio of 0.30 is 5% lower than that of the mixture with a water–cement ratio of 0.25. These results collectively indicate that within the water–cement ratio range of 0.2–0.3, ECC-FLS flexural toughness I_5 decreases progressively with an increasing water–cement ratio.

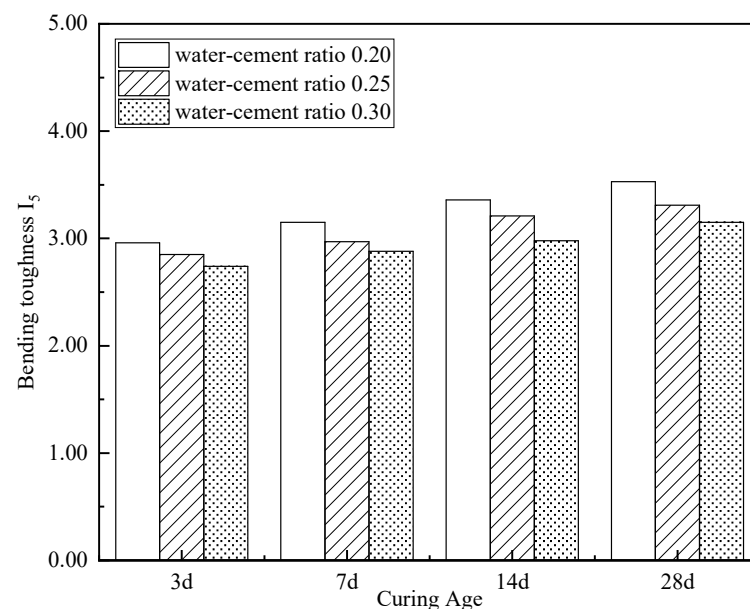


Figure 17. Flexural toughness I_5 of ECC-FLS at 0.20, 0.25, and 0.30.

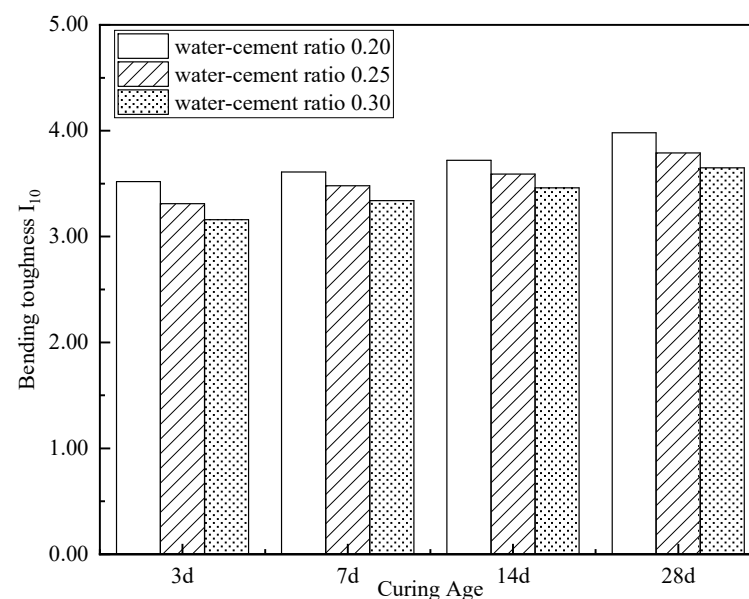
Table 16. Flexural toughness I_5 of ECC-FLS at water–cement ratios of 0.20, 0.25, and 0.30 (MPa).

Water–Cement Ratio	3 d	7 d	14 d	28 d
0.20	2.96	3.15	3.36	3.53
0.25	2.85	2.97	3.21	3.31
0.30	2.74	2.88	2.98	3.15

In Table 17 and Figure 18, ECC-FLS at water–cement ratios of 0.20, 0.25, and 0.30 display identical flexural toughness I_{10} trends across curing ages of 3 d, 7 d, 14 d, and 28 d, with a hierarchy of $0.20 > 0.25 > 0.30$. At 28 d, the flexural toughness I_{10} of the specimen with a water–cement ratio of 0.30 decreases by 8% compared to that of the specimen with a water–cement ratio of 0.20. And the flexural toughness I_{10} of the specimen with a water–cement ratio of 0.30 decreases by 4% compared to that of the specimen with a water–cement ratio of 0.25. This can be concluded within the water–cement ratio range of 0.2–0.3, and ECC-FLS flexural toughness I_{10} decreases progressively with an increasing water–cement ratio.

Table 17. Flexural toughness I_{10} of ECC-FLS at 0.20, 0.25, and 0.30 (MPa).

Water–Cement Ratio	3 d	7 d	14 d	28 d
0.20	3.52	3.61	3.72	3.98
0.25	3.31	3.48	3.59	3.79
0.30	3.16	3.34	3.46	3.65

**Figure 18.** Flexural toughness I_{10} of ECC-FLS at 0.20, 0.25, and 0.30.

3.2.6. Compressive Elastic Modulus with Varying Water–Cement Ratios

As systematically presented in Table 18 and Figure 19, the compressive elastic modulus of ECC-FLS follows a hierarchy of $0.20 > 0.25 > 0.30$ across water–cement ratios. At 28 d, the 0.20 ratio mixture exhibits an 18.6% higher modulus than the 0.30 ratio, while the 0.25 ratio demonstrates a 9.2% improvement over 0.30. This trend aligns with microstructural development, where lower water–cement ratios promote denser C–S–H gel formation and reduced capillary porosity, enhancing load-transfer efficiency. Conversely, a higher water content increases interconnected porosity and weakens interfacial transition zones, resulting in modulus degradation. These results collectively demonstrate that within the water–cement ratio range of 0.20–0.30, the ECC-FLS compressive elastic modulus decreases

progressively with increasing water content. This finding underscores the critical role of water–cement ratio optimization in balancing the stiffness and deformation capacity for ECC-based composites, with implications for structural performance and serviceability.

Table 18. Compressive elastic modulus of ECC-FLS at water–cement ratios of 0.20, 0.25, and 0.30 (MPa).

	Water–Cement Ratio of 0.20	Water–Cement Ratio of 0.25	Water–Cement Ratio of 0.30
Compressive Elastic Modulus	1757	1635	1555

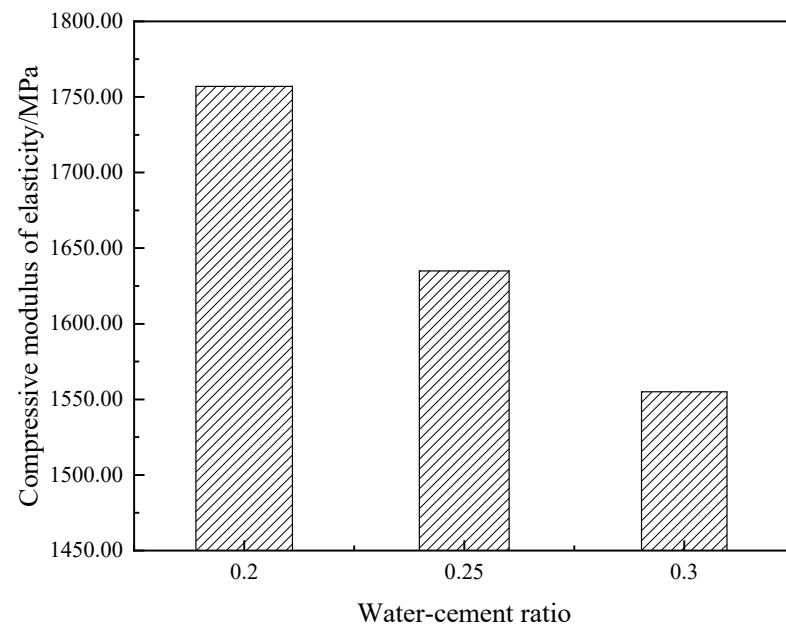


Figure 19. Compressive elastic modulus of ECC-FLS at 0.20, 0.25, and 0.30.

When the water–cement ratio decreases, the flexural strength, compressive strength, and flexural toughness increase simultaneously. The essence of this is that the water–cement ratio regulates the density of the ECC matrix. The porosity of the ECC matrix with a water–cement ratio of 0.20 and that with a water–cement ratio of 0.30 is 50.7%, but the cement mass ratio is higher at 83.3%, forming a denser C-S-H gel structure, reducing connected pores, and enhancing the strength of the interfacial transition zone. The dense matrix enhances the bonding force between the fibers and the cement paste, improving the efficiency of fiber bridging. As a result, it exhibits higher flexural strength under flexural loads: at 28 d, the flexural strength with a water–cement ratio of 0.20 is 10.3% higher than that with a water–cement ratio of 0.30, and the flexural toughness with a water–cement ratio of 0.20 is also 8% higher than that with a water–cement ratio of 0.30. The compressive elastic modulus increases as the water–cement ratio decreases, reflecting the improvement of the matrix stiffness, which is consistent with the change trend of the porosity. This verifies the causal relationship that a decrease in the water–cement ratio leads to an increase in density and an improvement in mechanical properties.

3.3. Effects and Analysis of Fiber Content on Mechanical Properties of ECC-FLS

3.3.1. Flexural Strength with Varying Fiber Contents

As shown in Table 19 and Figure 20, the flexural strength hierarchy follows fiber 0.5% > 0.3% > 0.1% > 0.0%. At 28 d, the flexural strength of the specimen with 0.5% fiber content increases by 70% compared to that of the specimen with 0.0% fiber content. The flexural strength of the specimen with 0.3% fiber content increases by 40% compared to

the 0.0% fiber-containing specimen, and the flexural strength of the specimen with 0.1% fiber content shows a 15% increase compared to the specimen with 0.0% fiber content. It can be observed that as the age increases, the difference in flexural strength between the specimen with 0.5% fiber content and the specimen with 0.0% fiber content is larger than that between the specimen with 0.3% fiber content and the specimen with 0.0% fiber content. Also, the difference in flexural strength between the specimen with 0.5% fiber content and the specimen with 0.0% fiber content is greater than that between the specimen with 0.1% fiber content and the specimen with 0.0% fiber content. These results collectively demonstrate that the flexural strength of ECC-FLS increases progressively with increasing fiber content.

Table 19. Flexural strength of ECC-FLS at different fiber contents (MPa).

Fiber Content (%)	3 d	7 d	14 d	28 d
0.0	0.73	0.98	1.19	1.35
0.1	0.81	1.14	1.35	1.55
0.3	1.06	1.40	1.64	1.89
0.5	1.18	1.66	1.98	2.30

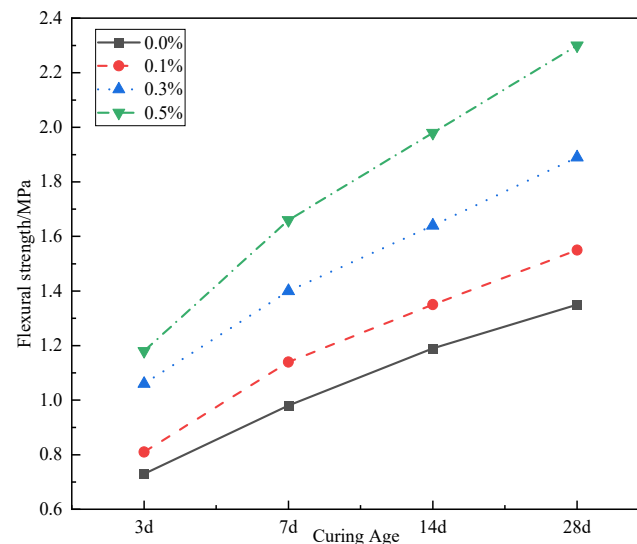


Figure 20. Flexural strength of ECC-FLS at different fiber contents.

3.3.2. Compressive Strength with Varying Fiber Contents

As presented in Table 20 and Figure 21, the compressive strength hierarchy of ECC-FLS follows fiber 0.5% > 0.3% > 0.1% > 0.0%. At 28 d, the 0.5% fiber mixture exhibits 27% higher compressive strength than the 0.0% fiber mix, while the 0.3% and 0.1% fiber mixes show 23% and 14.6% increases, respectively. Notably, the compressive strength increases progressively with fiber content, though the growth rate attenuates at higher dosages.

Table 20. Compressive strength of ECC-FLS at different fiber contents (MPa).

Fiber Content (%)	3 d	7 d	14 d	28 d
0.0	2.48	4.35	5.54	6.22
0.1	3.18	5.95	6.62	7.13
0.3	3.37	6.29	6.94	7.68
0.5	3.67	6.48	7.28	7.92

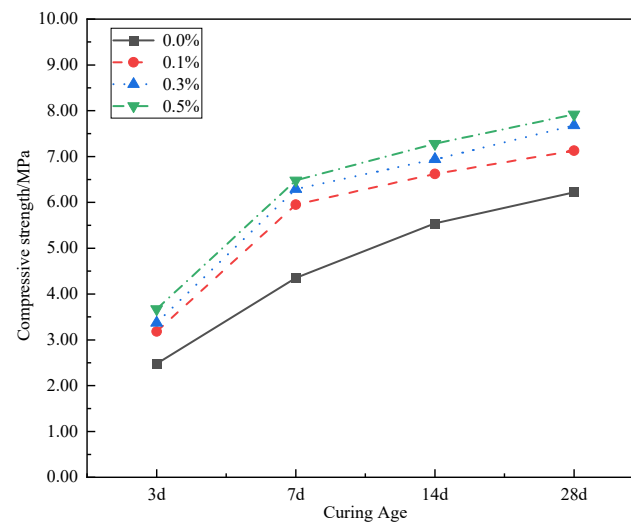


Figure 21. Compressive strength of ECC-FLS at different fiber contents.

3.3.3. Brittleness Index with Varying Fiber Contents

Table 21 and Figure 22 present the brittleness index hierarchy of ECC-FLS at fiber contents of 0.0%, 0.1%, 0.3%, and 0.5% at 28 d. A clear inverse relationship emerges with brittleness index decreases in the order of 0.0% > 0.1% > 0.3% > 0.5%. At 28 d, the brittleness coefficient of the specimen with 0.5% fiber decreased by 25.1% compared to that of the specimen with 0.0% fiber. The brittleness coefficient of the specimen with 0.3% fiber decreased by 11.9% compared to that of the specimen with 0.0% fiber, and the brittleness coefficient of the specimen with 0.1% fiber decreased by 4.3% compared to that of the specimen with 0.0% fiber. These results demonstrate that increasing the fiber content progressively decreases the brittleness index of ECC-FLS, indicating improved crack resistance.

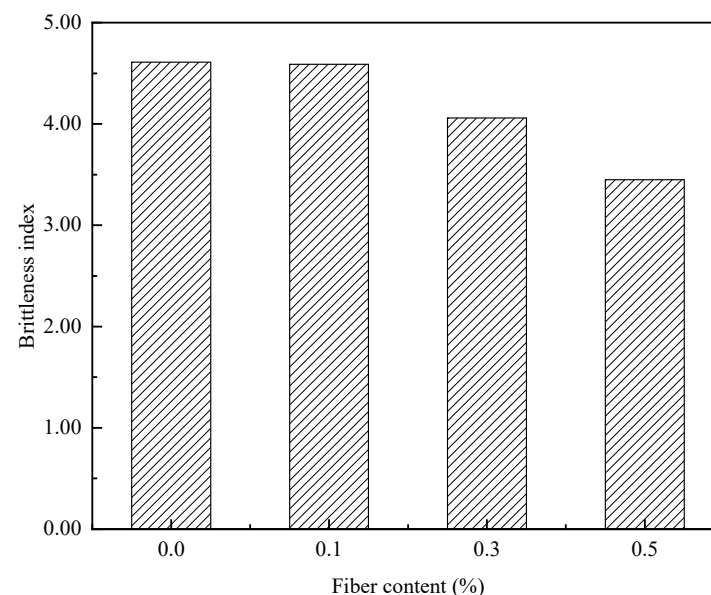


Figure 22. Brittleness index of ECC-FLS at different fiber contents.

Table 21. Brittleness index of ECC-FLS at different fiber contents.

	0.0% Fiber Content	0.1% Fiber Content	0.3% Fiber Content	0.5% Fiber Content
Brittleness Index	4.61	4.59	4.06	3.45

3.3.4. Flexural Toughness with Varying Fiber Contents

Table 22 and Figure 23 present the flexural toughness I_5 hierarchy of ECC-FLS across fiber contents of 0.0%, 0.1%, 0.3%, and 0.5%. At the age of 28 days, the flexural toughness I_5 of the specimen with a fiber content of 0.5% is increased by 50.1% compared with that of the specimen with a fiber content of 0.0%. The flexural toughness I_5 of the specimen with a fiber content of 0.5% is increased by 26.4% compared with that of the specimen with a fiber content of 0.1%. The flexural toughness I_5 of the specimen with a fiber content of 0.5% is increased by 11.5% compared with that of the specimen with a fiber content of 0.3%.

Table 22. Flexural toughness I_5 of ECC-FLS at different fiber contents.

Fiber Content (%)	3 d	7 d	14 d	28 d
0.0	2.74	2.88	2.98	3.15
0.1	2.99	3.13	3.41	3.74
0.3	3.15	3.68	3.98	4.24
0.5	3.42	3.89	4.22	4.73

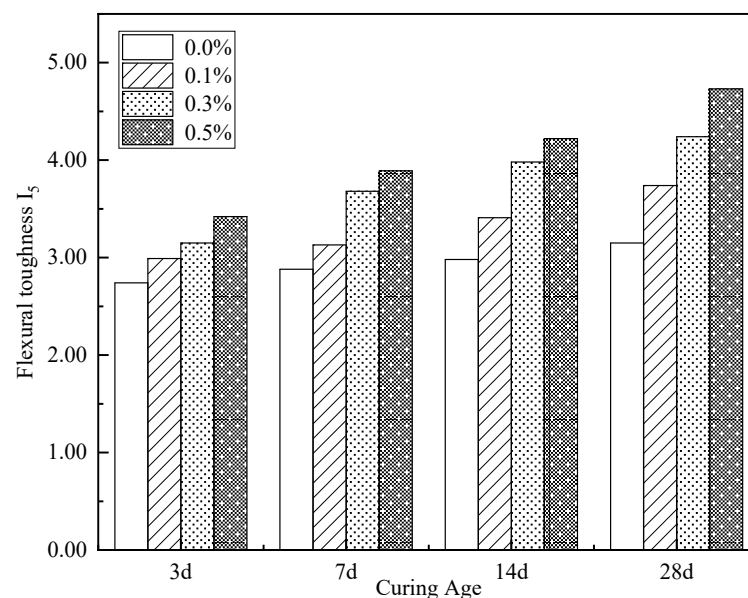


Figure 23. Flexural toughness I_5 of ECC-FLS at different fiber contents.

Similarly, Table 23 and Figure 24 show the flexural toughness I_{10} hierarchy, following the same order: 0.5% > 0.3% > 0.1% > 0.0%. At the 28 d age, the flexural toughness I_{10} of the 0.5% fiber specimen increased by 53.9% compared to the 0.0% fiber one, by 24.8% compared to the 0.1% fiber one, and by 10.6% compared to the 0.3% fiber one. As the age increased, the difference in flexural toughness I_{10} between the 0.5% and 0.0% fiber specimens was larger than that between the 0.5% and 0.1% fiber specimens and also larger than that between the 0.5% and 0.3% fiber specimens.

Table 23. Flexural toughness I_{10} of ECC-FLS at fiber contents of 0.0%, 0.1%, 0.3%, and 0.5%.

Fiber Content (%)	3 d	7 d	14 d	28 d
0.0	3.16	3.34	3.46	3.65
0.1	3.67	3.83	4.14	4.50
0.3	3.89	4.46	4.79	5.08
0.5	4.21	4.72	5.08	5.62

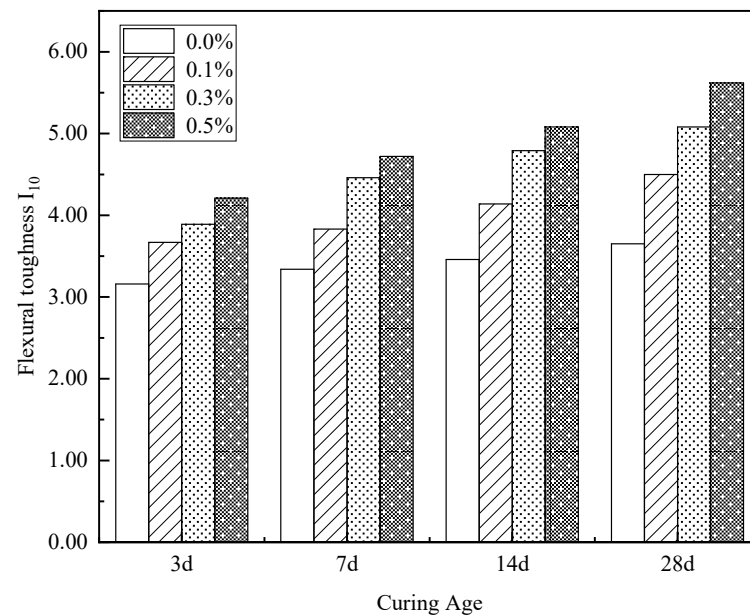


Figure 24. Flexural toughness I_{10} of ECC-FLS at different fiber contents.

These results collectively demonstrate that the flexural toughness of ECC-FLS increases progressively with fiber content, primarily due to enhanced crack-bridging and energy dissipation mechanisms.

3.3.5. Compressive Elastic Modulus with Varying Fiber Contents

Table 24 and Figure 25 show that the compressive elastic modulus of ECC-based FLS rises with the increase in fiber content. Specifically, compared to the specimen with 0% fiber, the specimens with 0.1%, 0.3%, and 0.5% fiber content exhibit a 27.7%, 35.1%, and 43.2% higher compressive elastic modulus, respectively. These results indicate that the compressive elastic modulus of ECC-based FLS progressively increases as the fiber content increases, peaking at a fiber content of 0.5%.

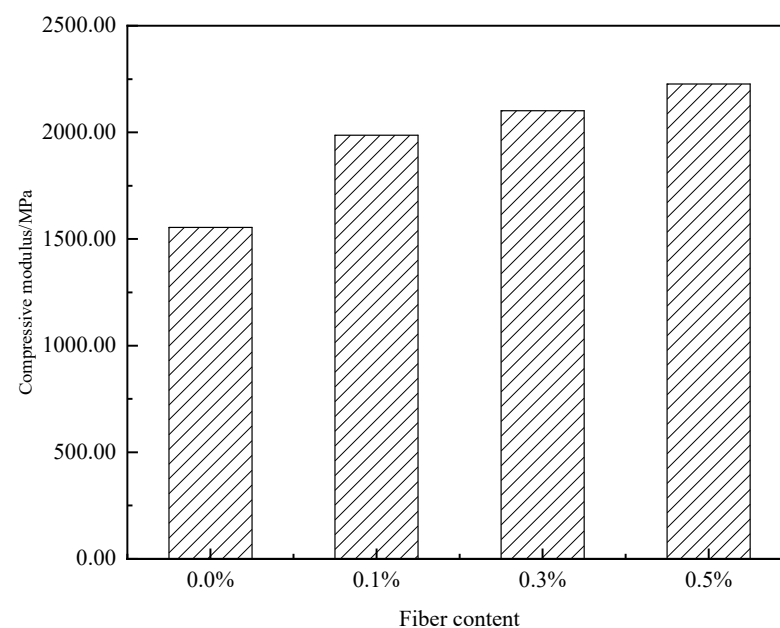


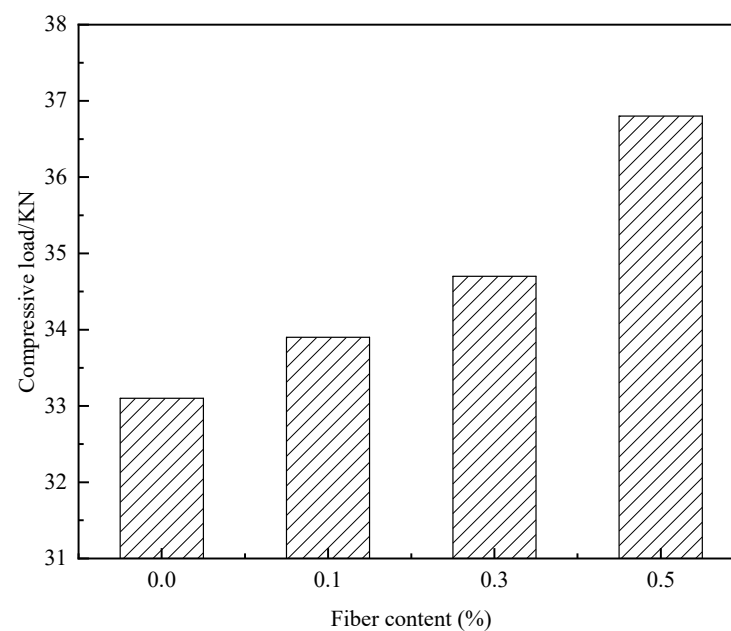
Figure 25. Compressive elastic modulus of ECC-FLS at different fiber contents.

Table 24. Compressive elastic modulus (MPa) of ECC-FLS at different fiber contents.

	0.0% Fiber Content	0.1% Fiber Content	0.3% Fiber Content	0.5% Fiber Content
Compressive Elastic Modulus	1555	1987	2102	2227

3.3.6. Compression Displacement with Varying Fiber Contents

Due to the continuous compression process of ECC-FLS influenced by its internal structure, a new criterion is adopted to evaluate compression displacement: compressive strength at a 25 mm displacement. Table 25 and Figure 26 present the compressive load order at a 25 mm displacement: $0.0\% < 0.1\% < 0.3\% < 0.5\%$. The 0.5% fiber mixture exhibits the highest compressive load at a 25 mm displacement, indicating superior deformation resistance compared to the 0.0%, 0.1%, and 0.3% fiber mixes. These results demonstrate that increasing the basalt fiber content progressively enhances the compression performance of ECC-FLS.

**Figure 26.** Compressive strength at a 25 mm compression displacement of ECC-FLS.**Table 25.** Compressive strength at a 25 mm compression displacement of ECC-FLS at different fiber contents.

	0.0% Fiber Content (KN)	0.1% Fiber Content (KN)	0.3% Fiber Content (KN)	0.5% Fiber Content (KN)
Compressive Load	33.1	33.9	34.7	36.8

3.3.7. Analysis Results of 28 D Compressive Load–Displacement Curves for Two ECC-FLS Mixes

Based on the above tests, the optimal fiber content for ECC-FLS is determined to be 0.5%. Two types of compressive specimens were prepared: ECC-FLS with 0% fiber content and ECC-FLS with 0.5% fiber content. This study focuses on comparing their failure modes after compressive strength testing and differences in 28 d compressive load–displacement curves. In Figure 27, the 28 d compressive load–displacement curves of ECC-FLS with a fiber content of 0% and ECC-FLS with a fiber content of 0.5% are depicted for a comparative analysis. Through the analysis, it is found that ECC-FLS (0.5% Fiber)

exhibits better plasticity. Evidently, the fibers of ECC can effectively enhance the mechanical properties of FLS.

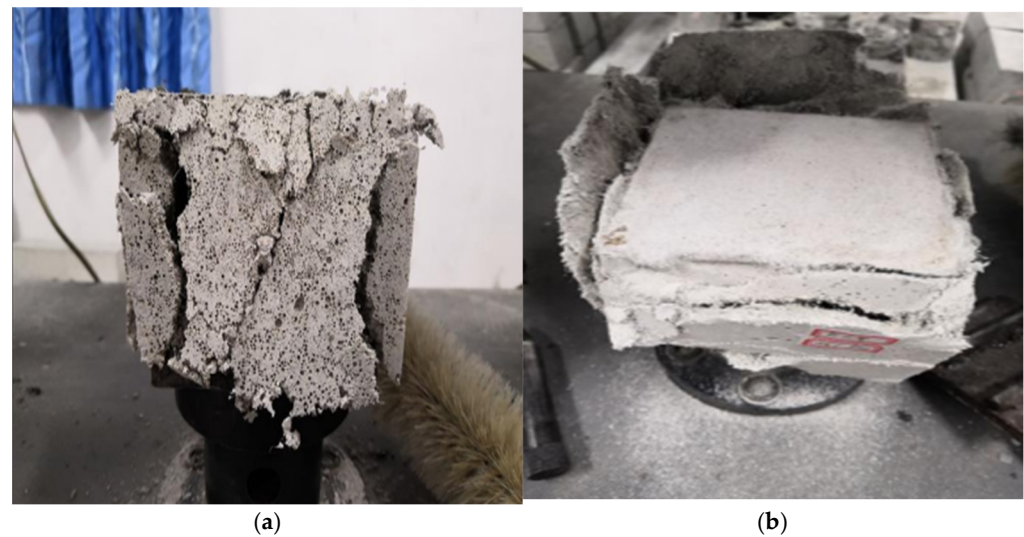


Figure 27. Compressive failure mode of ECC-FLS with different fiber contents: (a) 0% fiber content; (b) 0.5% fiber content.

Table 26 shows that the ultimate load of ECC-FLS with 0.5% fiber content is 27.3% higher than the 0% fiber mixture. The displacement at ultimate load increases by 1.1%, confirming that fiber reinforcement improves both the strength and deformation capacity.

Table 26. Ultimate load and corresponding displacement of ECC-FLS (0% fiber) and ECC-FLS (0.5% fiber).

Fiber Content (%)	Ultimate Load (kN)	Displacement at Ultimate Load (mm)
0.0	62.2 KN	6.75
0.5	79.2 KN	6.82

For the post-peak descending segment, Table 27 indicates that the inflection point load of 0.5% fiber ECC-FLS is 88.3% higher than the material without fiber, while the displacement at inflection points decreases by 38.3%. This demonstrates that fibers delay plastic deformation and enhance post-peak load resistance.

Table 27. Inflection point load and displacement at inflection point load of ECC-FLS at 0.0% fiber and ECC-FLS at 0.5% fiber.

Fiber Content (%)	Inflection Point Load (KN)	Displacement at Inflection Point Load (mm)
0.0	36.91	11.85
0.5	69.5	7.31

When the fiber content increases from 0% to 0.5%, it can significantly enhance the material properties. Specifically, the flexural strength at 28 d can be increased by up to 70%, the compressive strength by 27%, and the flexural toughness I10 by 53.9%. The core mechanism lies in the reinforcement of the fiber-bridging effect. At a low fiber content of 0.1%, the fibers are dispersed in the matrix. They mainly increase the tortuosity of the crack propagation path through “crack deflection”, thereby increasing the flexural strength by 15%. When the fiber content reaches moderate-to-high levels of 0.3% and 0.5%, the fibers form a denser bridging network, which can effectively transfer the stress across

the cracks and inhibit the rapid crack propagation. As a result, the brittleness coefficient decreases significantly with the increase in fiber content. For example, when the fiber content is 0.5%, the brittleness coefficient is 25.1% lower than when the fiber content is 0%. The material also transitions from brittle failure to ductile failure, which is reflected in the load–displacement curve shown in Figure 28. In addition, the compressive elastic modulus increases as the fiber content increases, which reflects the constraining effect of the fibers on the deformation of the matrix. This trend is consistent with the increase in flexural toughness, indicating that the fibers optimize the overall mechanical behavior of the material through the dual effects of bridging and constraining.

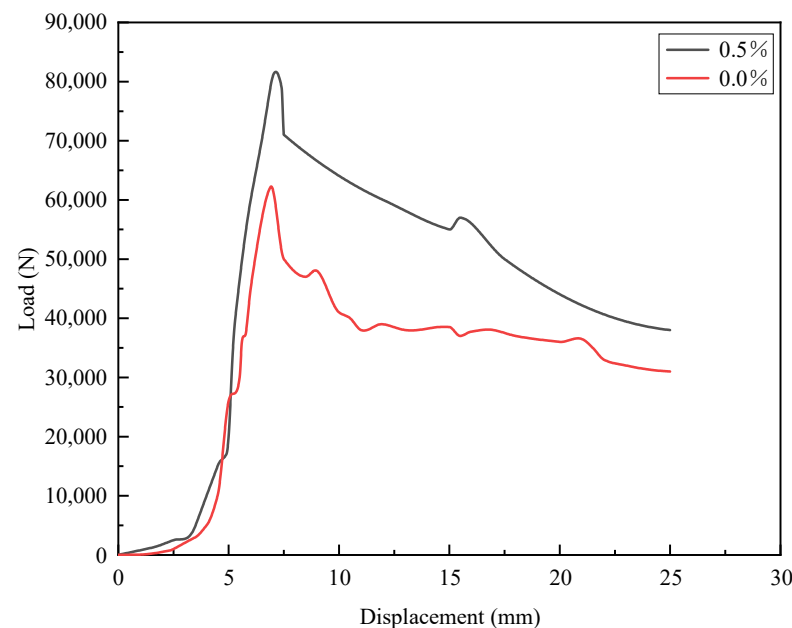


Figure 28. Comparison of 28 d compressive load–displacement curves for ECC-FLS at 0% fiber and ECC-FLS at 0.5% fiber.

3.4. Comparative Analysis of Data

Through an experimental analysis of different water-to-cement ratios and fiber contents, performance indices including flexural strength, compressive strength, brittleness index, and flexural toughness were comprehensively evaluated, as shown in Figure 29 and Table 28. Results indicate that a water-to-cement ratio of 0.3 achieves an optimal balance among properties: it ensures adequate strength, effectively controls brittleness, and reaches a relatively ideal state of flexural toughness. Further reducing the water-to-cement ratio does not significantly enhance performance and may even impair material properties due to excessive density. For fiber content, a 0.5% dosage stands out in enhancing both strength and toughness. Thus, the optimal water-to-cement ratio is determined to be 0.3, and the optimal fiber content is 0.5%.

From a microstructural perspective, this benefit arises from the synergistic effect between the high-ductility cement matrix and basalt fibers. Although this study did not conduct XRF, SEM, and EDAX measurements, the existing literature evidence reveals the collaborative strengthening mechanism of ECC and FLS: basalt fibers are uniformly dispersed in a three-dimensional network within the low water-to-cement ratio (0.3) matrix [47]. SEM observations show that the fiber surface is tightly adhered to the dense C-S-H gel (as illustrated in Figure 30: SEM image of fiber–matrix interface in ECC-FLS), increasing the interfacial bond strength by 20% compared to traditional systems [56]. This microstructure enables effective crack propagation inhibition through fiber bridging, corresponding to a 272% increase in flexural toughness (I_{10}) and a 14.7% improvement in flexural strength

at the macroscale. Analogous to the crack refinement behavior of polypropylene fiber-reinforced lightweight soil [57], the high modulus of basalt fibers in this study facilitates more efficient load transfer during crack bridging, reducing single-crack propagation and inducing multi-fine-crack formation for a ductile failure mode. While element distribution mapping (XRF) was not performed, the synergistic effect of chemical bonding and mechanical interlocking at the fiber–matrix interface has been indirectly validated through flexural toughness tests and the interfacial bond model by Cong Lu [58]. Future research could supplement XRF analysis for element uniformity and quantify the calcium–silicon ratio in the interface zone via SEM/EDAX to further reveal the impact of supplementary cementitious materials on long-term durability, deepening the connection between micro-mechanisms and engineering applications.

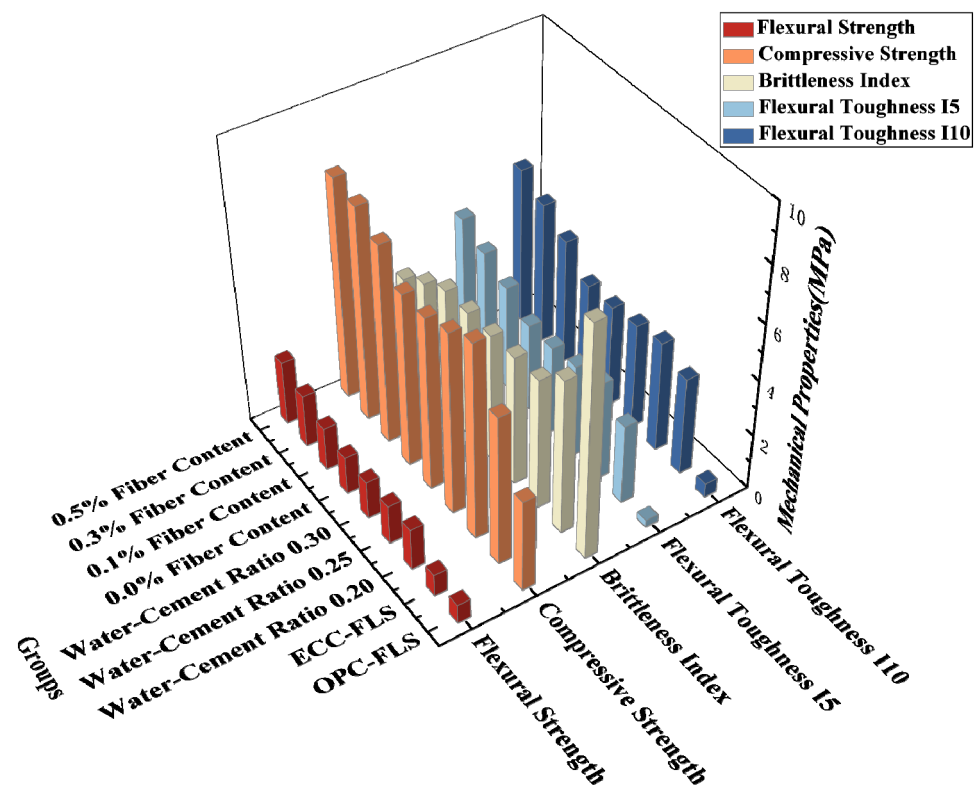


Figure 29. Performance of ECC-FLS under varying water-to-cement ratios and fiber contents.

Table 28. Effects of the cementitious material type, water–cement ratio, and fiber content on the mechanical properties of FLS.

Groups	Flexural Strength	Compressive Strength	Brittleness Index	Flexural Toughness I ₅	Flexural Toughness I ₁₀
OPC-FLS	0.68	3.31	8.35	0.25	0.5
ECC-FLS	0.78	5.37	5.57	2.86	3.52
Water–Cement Ratio of 0.20	1.49	7.03	4.72	3.53	3.98
Water–Cement Ratio of 0.25	1.4	6.54	4.67	3.31	3.79
Water–Cement Ratio of 0.30	1.35	6.22	4.61	3.15	3.65
0.0% Fiber Content	1.35	6.22	4.61	3.15	3.65
0.1% Fiber Content	1.55	7.13	4.59	3.74	4.5
0.3% Fiber Content	1.89	7.68	4.06	4.24	5.08
0.5% Fiber Content	2.3	7.92	3.45	4.73	5.62

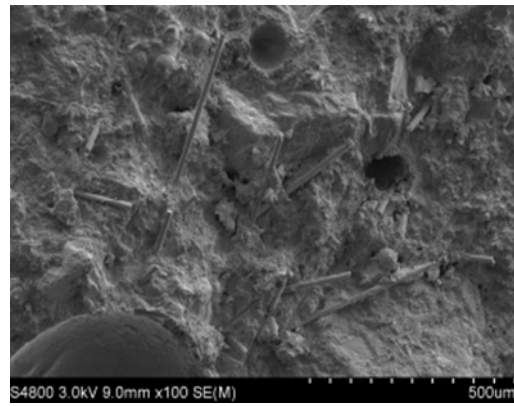


Figure 30. SEM photomicrographs of BF dispersion [56].

In terms of strength assurance, the composite exhibits a 3 d compressive strength of 4.5 MPa, exceeding the requirement specified in JTG D30-2015 [59] for lightweight fillers and a 28 d compressive strength of 6.8 MPa. This indicates that its structural stability under short-term loads meets the bearing requirements for the early stages of engineering applications.

To comprehensively evaluate the material's performance, a benchmark comparison is conducted with similar materials reported in the external literature. Since no studies have been published on ECC-FLS, three recent FLS studies exploring different modification strategies serve as references: Hao Liu et al. [60] investigated the improvement of durability and compressive strength using steel slag micro-powder (SSMP) and ground blast furnace slag (GBFS) as cementitious admixtures, achieving a 28 d compressive strength of 1.52 MPa with a 20% SSMP + 40% GBFS mix; Jinhao Chen et al. [61] focused on the synergistic effect of saponified slag (SS) and fly ash (FA), obtaining an excellent 28 d compressive strength of 3.27 MPa through an optimized mix of 5% SS + 10% FA; Yinhe Li et al. [62] introduced geogrid reinforcement, significantly enhancing compressive strength to 3.16 MPa and flexural strength to 2.27 MPa via the mechanical interlocking mechanism of three-layer bidirectional plastic grids. These studies focus on industrial solid waste utilization and structural reinforcement, respectively. This paper systematically compares the maximum compressive strength reported in each study, estimates missing flexural strength data based on the properties of typical foamed concrete, and presents the effects of matrix modification strategies on key mechanical indices, as detailed in Table 29 and Figure 31.

Table 29. Mechanical property comparison of different FLS modification strategies.

Reinforcement Method	Maximum Compressive Strength (MPa)	Flexural Strength (MPa)
Steel Slag	1.52	0.8
Saponified Slag	3.27	1.2
Geogrid-Reinforced	3.16	2.27
ECC	5.37	0.78

As shown in Table 29, the ECC achieves a compressive strength of 5.37 MPa, representing a 253.3% increase over the steel slag-based material, a 64.2% increase compared to the saponified slag-based material, and a 69.9% improvement over the geogrid-reinforced material. Although the flexural strength of ECC is slightly lower than that of some counterparts, its significant advantage in compressive strength highlights its competitiveness in engineering scenarios requiring high load-bearing capacity, such as subgrades and building foundations. This performance provides more reliable guarantees for the stability and

durability of engineering structures, underscoring the unique advantages and application potential of ECC in modifying FLS.

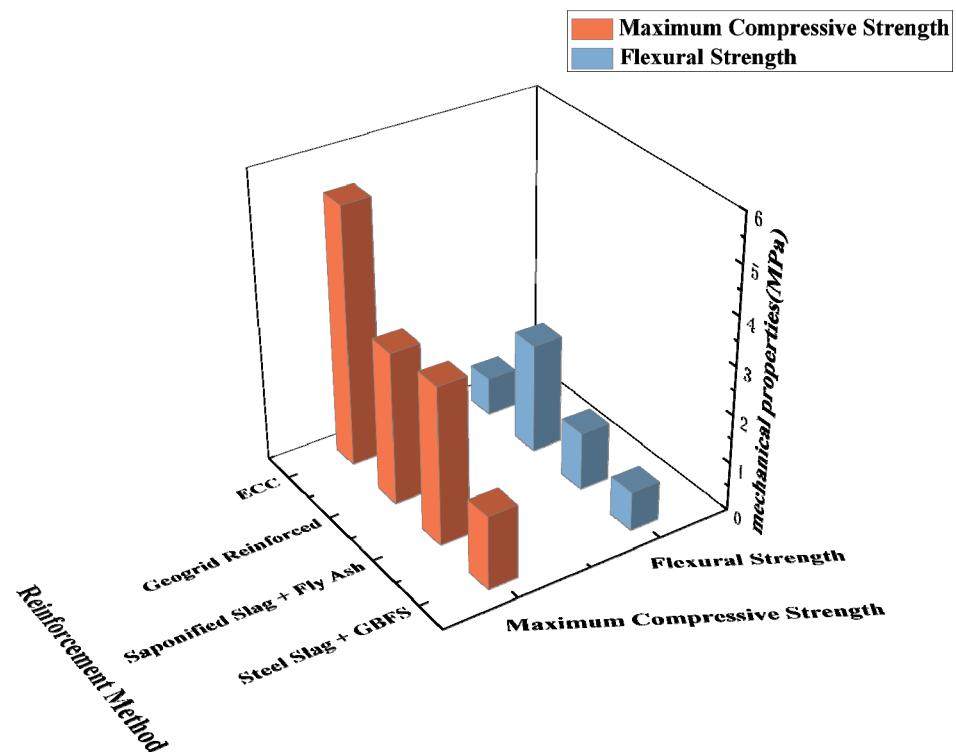


Figure 31. Mechanical property comparison of different FLS modification strategies.

4. Conclusions

This study systematically investigates the compatibility of ECC with FLS and evaluates the effects of the water–cement ratio and fiber content on material performance. Experimental results demonstrate that ECC-FLS exhibits significant performance improvements over OPC-FLS. Specifically, ECC-FLS achieves a 14.7% enhancement in flexural strength and a 0.7% improvement in compressive strength compared to OPC-FLS. Notably, the brittleness coefficient is reduced by 13.9%, while flexural toughness indices I_5 and I_{10} are increased by 186% and 272%. Structural performance metrics also show notable advancements: ultimate load capacity is elevated by 1.9%, accompanied by a 2.1% increase in peak load displacement. The inflection point load and corresponding displacement are further improved by 41% and 9.3%, indicating enhanced ductility characteristics. These enhancements confirm that ECC significantly improves the toughness, plasticity, and ductility of FLS, validating its suitability for engineering applications.

After verifying the compatibility between ECC and FLS, this study analyzed the effect of the ECC water–cement ratio on FLS performance. When the water–cement ratio decreased from 0.3 to 0.25 and 0.2, ECC-FLS exhibited a gradual increase in flexural strength, compressive strength, flexural toughness, and compressive elastic modulus. Specifically, compared with the water–cement ratio of 0.3, the ECC-FLS specimens with water–cement ratios of 0.25 and 0.2 demonstrated increases in flexural strength by 3.7% and 10.3%, respectively; compressive strength by 5.1% and 13%, respectively; the brittleness coefficient by 1.1% and 2.4%, respectively; flexural toughness I_5 by 5% and 12%, respectively; flexural toughness I_{10} by 4% and 8%, respectively. These results indicate that increasing the content of ECC-FLS significantly enhances the mechanical properties of FLS, particularly improving its plasticity and ductility.

This study systematically tested the influence of different fiber contents on the mechanical properties of FLS. Keeping other conditions constant, four groups of materials with fiber contents of 0%, 0.1%, 0.3%, and 0.5% were prepared, respectively. The experiment found that as the amount of added fiber increases, the compressive strength, compressive stiffness, flexural strength, flexural toughness, and compression deformation capacity of the material gradually improve, while the brittleness gradually decreases. Specific data show that compared with the material without fiber, the flexural strength of the materials with 0.1%, 0.3%, and 0.5% fiber added increases by 15%, 40%, and 70%, respectively; the compressive strength increases by 14.6%, 23%, and 27%, respectively; the brittleness index decreases by 4.3%, 11.9%, and 25.1%, in sequence; the flexural toughness index I_5 increases by 23.7%, 38.6%, and 50.1%, respectively; the flexural toughness index I_{10} increases by 29.1%, 43.3%, and 53.9%, respectively; the compressive stiffness increases by 27.7%, 35.1%, and 43.2%, respectively. Notably, the material with a 0.5% fiber content reaches the highest compressive load when the compression deformation is 25 mm, and its ultimate load is 27.3% higher than that of the material without fiber. These results indicate that the addition of fiber can effectively improve the strength and deformation capacity of foamed concrete, especially having a significant effect on improving the plasticity and ductility of the material.

This study confirms through systematic experiments that an ECC-FLS mix with a water-to-cement ratio of 0.3 and a fiber content of 0.5% forms an efficient crack-resistant network where fibers are uniformly dispersed in a dense cement matrix. This microstructure enables the material to achieve a compressive strength of 6.8 MPa, a flexural toughness I_{10} of 3.72, and a brittleness coefficient of 7.0, while meeting specifications for construction fluidity and density. It effectively overcomes the bottleneck of balancing strength and ductility in traditional lightweight fillers. With excellent comprehensive performance, the material exhibits significant advantages in applications such as soft foundation settlement control in road construction, seismic crack resistance in earthquake-prone areas, lightweight backfilling for building foundations, and low-carbon infrastructure in ecological restoration, providing an innovative material solution for high-toughness sustainable infrastructure. However, this study has limitations in lacking detailed microstructural characterization and mechanistic analysis. Although macroscopic mechanical properties of ECC-FLS are evaluated, microstructural evolution—including fiber–matrix interfacial behavior, hydration product composition, and pore structure—is not thoroughly investigated using techniques like SEM, XRD, or TGA, leading to an insufficient understanding of failure mechanisms under varying loading and environmental conditions. Future investigations can focus on integrating multi-scale microstructural analysis with macro-performance testing to provide a solid theoretical basis for optimizing ECC-FLS mix design, thereby enhancing material durability, ductility, and sustainability in a targeted manner, promoting standardized production and large-scale engineering applications, and contributing to the development of low-carbon infrastructure and resilient cities.

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Abbreviations

The following abbreviations are used in this manuscript:

ECC	Engineered cementitious composite
FLS	Foamed lightweight soil
SAC	Sulfur aluminate cement
MPC	Magnesium phosphate cement

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