

Article

Effects of Gold Tailings Fineness and Dosage on the Rheology and Mechanical Properties of ECC

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Abstract

This study systematically investigates the effects of gold tailings (GT) sand substitution levels and particle fineness on the rheological behavior, mechanical properties, and microstructural characteristics of Engineered Cementitious Composites (ECC). The results demonstrate that incorporating moderate amounts of GT sand ($\leq 75\%$) effectively enhances both the compressive strength and fracture toughness of the composite. However, complete substitution (100% GT) significantly increases matrix porosity, leading to a consequent reduction in comprehensive mechanical strength. A critical size-dependent decoupling effect was observed: while the full replacement of fine aggregates with coarse GT severely degrades compressive strength due to excessive void formation, it unexpectedly increases the matrix fracture toughness by inducing significant crack deflection and tortuosity. Conversely, the incorporation of fine GT optimizes the distribution of matrix flaws and fosters a stable fiber pull-out mechanism. Consequently, despite a reduced pseudo-strain hardening (PSH) index, the fine GT-blended ECC achieves a remarkable tensile ductility of up to 3.0% by satisfying the fundamental multiple-cracking energy criteria while maximizing frictional energy dissipation. Furthermore, substituting natural silica sand with GT yields a highly sustainable composite, reducing carbon dioxide emissions by 41% and material costs by 20% without compromising core mechanical performance.

Keywords: engineered cementitious composite; gold tailings; mechanical properties; polyvinyl alcohol (PVA) fiber



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1. Introduction

Engineered Cementitious Composites (ECC) are a unique class of high-performance, fiber-reinforced cementitious materials known for their strain-hardening behavior and ability to accommodate multiple microcracks under tensile loading [1,2]. These defining characteristics arise from the careful interplay between fibers, matrix components, and the fiber–matrix interface, enabling ECC to achieve tensile ductilities several hundred times greater than conventional concrete. As a result, ECC has been applied to a range of structural and infrastructural projects, including earthquake-resistant systems, bridge retrofits, and durable, energy-efficient buildings [3].

One key to ECC's superior performance lies in its fine aggregates. Conventionally, high-quality micro-silica sand is employed to ensure dense packing, stable micro-

crack formation, and enhanced fiber bridging, improving both toughness and long-term durability [4–6]. However, the high cost and limited availability of this material have prompted researchers to seek alternative fine aggregates [7]. While river sand can lower costs, it often compromises strain-hardening capacity due to altered matrix microstructures [8,9]. These challenges have led to growing interest in valorizing industrial byproducts as fine aggregates for ECC, thereby promoting sustainable material use and reducing environmental burdens.

Gold tailings (GT) sand, a mining byproduct composed primarily of quartz and feldspar, stands out as a promising candidate [10]. Its finely graded particles and potential pozzolanic characteristics may help form robust and homogeneous matrices. Moreover, incorporating GT sand can mitigate environmental risks associated with tailings disposal, decrease landfill use, and reduce concrete costs by over 10% [11–13].

Previous studies have shown that aggregate type and dosage can significantly affect ECC properties. Chandrasekhar et al. [14] found that ECC mixtures incorporating coarser manufactured sand (M-sand) exhibited higher compressive strength and ultimate tensile strength but lower tensile ductility and fiber bridging characteristics as the percentage replacement of river sand increased. Similarly, Wu et al. [15] investigated the impact of morphological parameters of natural sand on ECC and concluded that sands with lower roundness and sphericity significantly improved the compressive and tensile properties of ECC. Their study demonstrated that decreasing sand particle roundness and sphericity led to enhancements in compressive strength, ultimate tensile strength, and tensile strain capacity, thereby highlighting the importance of sand morphology in ECC performance.

Further exploring the impact of sand fineness, researchers have investigated the effects of replacing silica sand with various types of aggregate in ECC formulations. For example, the incorporation of recycled glass sand in ECC has been observed to improve the flexural strength and the initial cracking strength with the increasing recycled glass powder particle size [16]. Moreover, Sahmaran et al. [17] demonstrated that the incorporation of larger aggregate sizes (1.19–2.5 mm) of lightweight fine aggregate in ECC led to improved tensile strain capacity and crack spacing but resulted in reduced compressive strength compared to mixtures with finer aggregates. This study highlights the significant role that aggregate size plays in dictating the mechanical behavior of ECC, particularly in balancing strength and ductility [18,19].

Despite these insights, the specific effects of GT sand—characterized by its unique fineness and chemical composition—remain underexplored, particularly concerning its synergistic interaction with the ECC matrix in terms of fiber dispersion and matrix homogeneity. Therefore, this study systematically investigates the effects of three distinct fineness levels of GT sand ($<300\ \mu\text{m}$, $300\text{--}600\ \mu\text{m}$, $>600\ \mu\text{m}$) at multiple replacement rates (25%, 50%, 75%, and 100%) relative to silica sand. Through a comprehensive experimental program—encompassing uniaxial tensile tests, fracture toughness and compressive strength evaluations, as well as fiber dispersion analyses via image processing—this research aims to elucidate the interplay between aggregate characteristics, matrix integrity, and fiber–matrix bonding, providing robust design strategies that balance costs, sustainability, and performance.

2. Materials and Methods

2.1. Materials

This study employed a comprehensive suite of materials to formulate the Engineered Cementitious Composite (ECC). The primary cementitious binder was Nanfang brand P.O 42.5-grade ordinary Portland cement sourced from China National Building Material Company Limited, Shanghai, China, complemented by fly ash sourced from Jining,

Shandong Province. To explore sustainable aggregate alternatives, gold tailings (GT) were incorporated and classified into three distinct particle size ranges: F ($<300\ \mu\text{m}$), M ($300\text{--}600\ \mu\text{m}$), and C ($>600\ \mu\text{m}$). Silica sand served as the reference fine aggregate against which GT substitution was evaluated, contributing to the composite matrix's homogeneity and mechanical properties.

Polyvinyl alcohol (PVA) fibers, produced by Kuraray Co., Ltd. (Tokyo, Japan), were integrated into the mixture to significantly improve the tensile performance of the ECC. The inclusion of these fibers necessitated precise adjustments to the mixture's workability. To achieve the desired flowability without compromising the mechanical integrity, a PCA[®]-10 polycarboxylate high-range water reducer from Jiangsu Sobute Co., Ltd. (Nanjing, Jiangsu) was employed. This water reducer provided a water reduction capacity of 16–22%, ensuring optimal dispersion of fibers and preventing segregation during mixing.

Furthermore, to enhance the stability of the fresh mixture and promote uniform fiber distribution, a hydroxypropyl cellulose sodium thickener with a viscosity ranging from 3500 to 4000 cps was added. This thickener, sourced from Changshu Weiyi Technology Co., Ltd. (Changshu, Jiangsu), played a crucial role in maintaining the consistency of the mixture, thereby facilitating effective fiber bridging and crack control in the hardened composite.

The physical and mechanical properties of the PVA fibers are detailed in Table 1. Table 2 presents the chemical composition of the ordinary Portland cement and fly ash used in this study. Additionally, Figure 1 illustrates the particle size distributions of raw materials. And the characteristic sizes of raw materials were summarized in Table 3.

Table 1. Physical and Mechanical Properties of PVA Fibers.

Fiber Type	Length (mm)	Diameter (μm)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Density (g/cm^3)	Elongation at Break (%)
Kuraray	12	39	1400–1600	35–39	1.3	17 ± 3

Table 2. Chemical Composition of Cement and Fly Ash (% by mass).

Material	SiO_2	CaO	SO_3	Al_2O_3	MgO	Fe_2O_3
Cement	24.99	51.42	2.51	8.26	3.71	4.03
Fly Ash	43	5.6	0.8	23	0.95	2.5

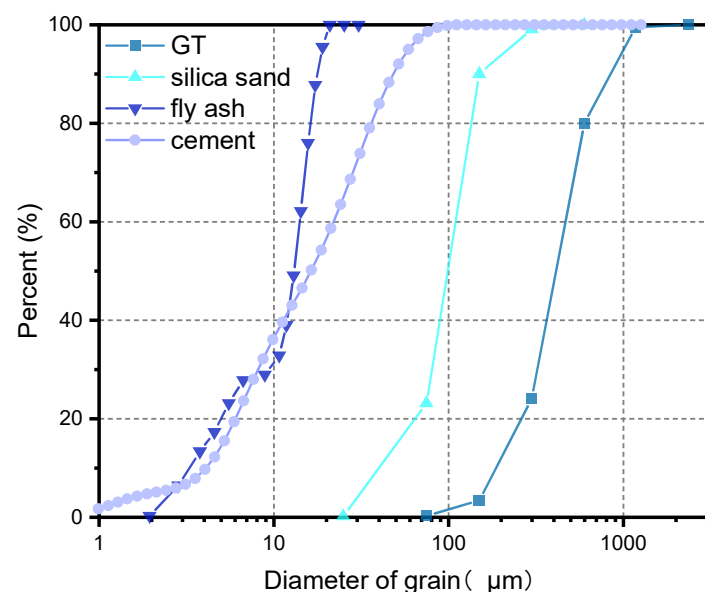


Figure 1. Particle size Distribution of raw materials.

Table 3. Characteristic particle sizes of fine aggregates (μm).

	GT	Silica Sand	Fly Ash	Cement
D10	198.55	46.52	3.30	4.09
D50	439.29	105.16	13.10	16.28
D90	897.44	150	17.80	48.37

2.2. Mix Design

The initial ECC mix designs, including the proportions of cement, fly ash, GT, silica sand, water, superplasticizer, thickener, and PVA fibers, are detailed in Table 4. The water-to-binder ratio and sand-to-binder ratio were 0.35 and 0.36, respectively. A constant volume fraction of 2% polyvinyl alcohol (PVA) fibers was maintained across all mixtures.

Table 4. ECC Mix Design (by Mass Ratio).

Mix ID	Cement	Fly Ash	Water	Fine Aggregate Composition	PVA Fibers	Thickener (%)	SP (%)
A-1	289 g	867 g	405 g	104 gG(F) + 312 gQ	23.6 g	0.25	0.2
A-2	289 g	867 g	405 g	104 gG(M)+ 312 gQ	23.6 g	0.1	0.25
A-3	289 g	867 g	405 g	104 gG(C)+ 312 gQ	23.6 g	0.4	0.1
A-4	289 g	867 g	405 g	208 gG(F)+ 208 gQ	23.6 g	0.4	0.1
A-5	289 g	867 g	405 g	208 gG(M)+ 208 gQ	23.6 g	0.1	0.1
A-6	289 g	867 g	405 g	208 gG(C)+ 208 gQ	23.6 g	0.15	0.1
A-7	289 g	867 g	405 g	312 gG(F)+ 104 gQ	23.6 g	0.15	0.1
A-8	289 g	867 g	405 g	312 gG(M)+ 104 gQ	23.6 g	0.1	0.1
A-9	289 g	867 g	405 g	312 gG(C)+ 104 gQ	23.6 g	0.1	0.1
A-10	289 g	867 g	405 g	416 gG(F)	23.6 g	0.2	0.1
A-11	289 g	867 g	405 g	416 gG(M)	23.6 g	0.1	0.1
A-12	289 g	867 g	405 g	416 gG(C)	23.6 g	0.15	0.1

Note: Q = Silica sand, G = GT sand; F (<300 μm), M (300–600 μm), C (>600 μm).

2.3. Methods

2.3.1. Preparation of ECC Specimens

The process commenced with dry mixing, where a combination of cement, fly ash, silica sand, gold tailings (GT) sand, superplasticizer, thickener, and two-thirds of the polyvinyl alcohol (PVA) fibers were thoroughly blended at a low mixing speed for five minutes using a standard mortar mixer.

Following the dry mixing, the superplasticizer and water were premixed separately to ensure even distribution of the chemical admixtures. This liquid mixture was then incorporated into the dry blend, and the mixture was subjected to higher-speed mixing for six minutes. To prevent fiber balling and ensure uniform dispersion, the remaining one-third of the PVA fibers were gradually introduced into the mixture in multiple increments. Mixing continued for an additional five minutes until the fibers were evenly distributed throughout the composite matrix.

Once the mixing process was complete, the resultant ECC mixture was carefully poured into standardized molds and compacted using vibration to eliminate air pockets and ensure optimal density. The molded specimens were then subjected to an initial curing period under laboratory ambient conditions for 24 h to facilitate initial setting. After this initial curing phase, the specimens were transferred to an 80 °C steam-curing chamber for 48 h. It should be noted that an 80 °C steam curing regime was deliberately employed in this study to counteract the delayed hydration kinetics associated with the high volumes of

fly ash. Steam treatment provides the necessary thermal activation energy to accelerate the dissolution of amorphous silica and alumina, promoting the rapid precipitation of calcium silicate hydrate (C-S-H) gels.

2.3.2. Rheological Test

To quantitatively assess the fresh-state rheological properties of the ECC mixtures, a computer-controlled rotational rheometer (TR-MPI) was employed. Prior to testing, the freshly mixed ECC mortar was carefully loaded into the rheometer's measuring cell, ensuring complete immersion of the measuring geometry and minimizing entrapped air bubbles.

A controlled shear rate (CSR) ramp-down procedure was initiated. The shear rate was progressively decreased from a maximum value (100 s^{-1}) to a minimum (0.1 s^{-1}) over a predetermined number of steps (15 data points). A sufficient waiting time (10 s) was allotted at each shear rate step to ensure that the shear stress reached a steady-state equilibrium before data acquisition.

2.3.3. Uniaxial Tensile Test

In this study, dog-bone-shaped specimens (as shown in Figure 2) were subjected to tensile loading using a specialized concrete tensile testing machine (Model WDW-300H, Jinan Zhonglu Chang Testing Machine Co., Ltd. (Jinan, China), as depicted in Figure 3. To ensure accurate strain measurements, two Linear Variable Differential Transformers (LVDTs) were strategically mounted on opposite sides of each specimen, covering a gauge length of 80 mm.

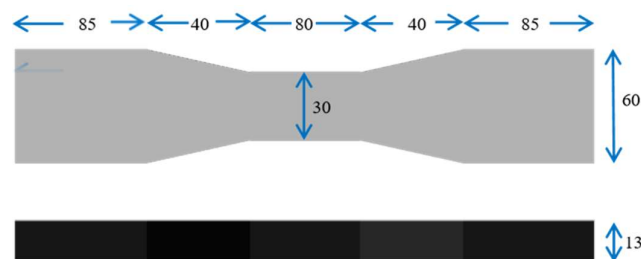


Figure 2. Schematic Diagram of Dog-Bone Specimen.

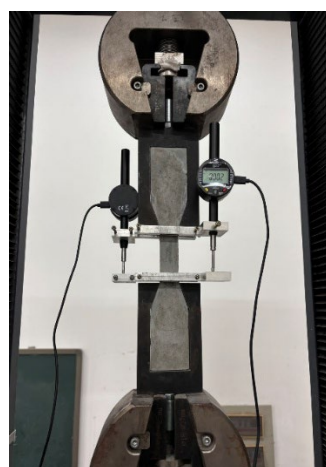


Figure 3. Uniaxial Tensile Test Setup.

The testing procedure employed a displacement-controlled loading protocol, applying a consistent loading rate of 0.5 mm/min . During the test, the LVDTs continuously monitored the specimen's elongation, providing precise measurements of strain over the

specified gauge length. This setup facilitated the determination of key tensile properties, including ultimate tensile strength and strain capacity, thereby enabling a comprehensive evaluation of the ECC's mechanical performance.

To ensure the statistical reliability of the experimental data, a minimum of three replicate specimens were tested for each mixture proportion across all mechanical evaluations (compressive, fracture, and uniaxial tensile tests). The experimental results reported in this study represent the arithmetic mean of these replicates. Standard deviations were calculated and are presented as error bars in all corresponding graphical results to indicate data dispersion and experimental repeatability.

2.3.4. Fracture Toughness Test

To accurately assess the fracture toughness of the ECC matrix, plain (unreinforced) notched specimens were meticulously prepared in accordance with the designated mix proportions. Each specimen measured $40\text{ mm} \times 40\text{ mm} \times 160\text{ mm}$ and featured a centrally positioned notch to simulate crack initiation points.

A small iron insert, measuring $50\text{ mm} \times 12\text{ mm} \times 1\text{ mm}$, was strategically placed along the longitudinal centerline of the mold. Upon removal of the iron insert, the resulting notch dimensions were standardized at $40\text{ mm} \times 12\text{ mm} \times 1\text{ mm}$.

The fracture toughness tests were conducted using a computer-controlled electronic universal testing machine (Model WDW-100C). A displacement-controlled loading regime was employed, applying a consistent loading rate of 0.05 kN/s . The span between the supports was meticulously set to 100 mm , as depicted in Figure 4, to maintain uniform stress distribution and prevent unintended stress concentrations that could skew the results.



Figure 4. Fracture Toughness Test Setup.

2.3.5. Compressive Strength Test

Following the completion of the matrix fracture toughness tests, the fractured ECC specimens were repurposed for compressive strength evaluation to assess the residual structural integrity of the composites.

The dimensions of the compression fixtures were standardized at $40\text{ mm} \times 40\text{ mm}$, matching the size of the fractured segments to maintain consistency across all tests. The compressive strength tests were conducted using a computer-controlled electronic universal testing machine (Model WDW-100C, Jinan Zhonglu Chang Testing Machine Co., Ltd.). A displacement-controlled loading approach was employed, applying a consistent loading rate of 0.05 kN/s .

2.3.6. Single-Crack Tensile Test

To further investigate the fiber bridging behavior and matrix fracture toughness of the composite, a single-crack tensile test was employed. This test enables the precise measurement of the fiber bridging stress versus crack opening displacement (COD) relationship by forcing a crack to initiate and propagate at a predetermined location.

Dog-bone-shaped specimens, similar in geometry to standard tensile specimens but with a pre-fabricated notch around four sides in the central working section, were used. The notches were cut using an ultra-thin saw blade (0.4 mm thickness) to ensure a notch width less than 0.6 mm. This design reduced the cross-sectional area at the notch to approximately 61% of the original, thereby concentrating tensile stress at this point and promoting stable initiation and propagation of a single crack, preventing the random formation of multiple cracks.

Tests were conducted on an electro-hydraulic servo testing machine under displacement control. To accurately measure the crack opening displacement, two extensometers with a gauge length of 5 mm were attached across the notch. Load and COD data were simultaneously collected. Analysis of the load–COD curve allows for the calculation of key micromechanical parameters such as fiber bridging complementary energy (J'_b), providing data support for evaluating the material's toughening mechanisms.

2.3.7. Fiber Dispersion Test

Starting 2.5 mm from the primary crack in each failed specimen, a 5 mm-thick slice was carefully extracted from the cross-section using a precision cutting machine. The sliced surface underwent a sequential polishing process to achieve a smooth and reflective finish, essential for high-resolution microscopic examination. Initially, the surface was polished with P800 abrasive paper, followed by P1200 to eliminate surface irregularities and enhance fiber visibility. The polished surface was systematically divided into 20 equally sized regions to facilitate comprehensive analysis across the entire specimen. Each region was observed under an optical microscope, and high-resolution (100×) images were captured to document the fiber distribution patterns.

The acquired images, containing point cloud distributions of the polyvinyl alcohol (PVA) fibers, were converted to grayscale to improve contrast between the fibers and the cementitious matrix. Subsequently, a global grayscale threshold was applied to binarize the images, effectively distinguishing fiber regions from the background, as shown in Figure 5. Otsu's algorithm was used as the basis for selecting the image binarization threshold.

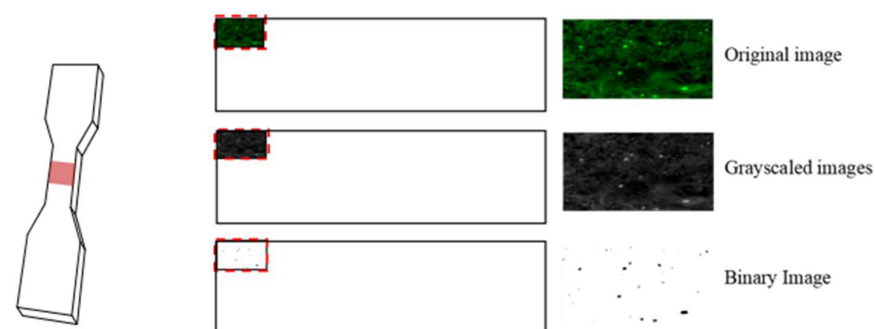


Figure 5. Flowchart of Fiber Dispersion Testing and Processing.

The processed image data were analyzed to derive quantitative metrics of the fiber dispersion coefficient as follows:

$$\alpha = \exp\left(-\sqrt{\frac{\sum\left(\frac{X_i}{X_{average}} - 1\right)^2}{n}}\right) \quad (1)$$

Here, α denotes the fiber dispersion coefficient, ranging from 0 to 1. A value of α closer to 1 indicates superior fiber dispersion performance. The variable n represents the total number of images analyzed. X_i refers to the number of fiber ends detected in the i -th image, while $X_{average}$ signifies the average number of fiber ends per image.

2.3.8. Mercury Intrusion Porosimetry (MIP)

To evaluate the pore structure and density of the cementitious matrix, AutoPre IV9500 Mercury Intrusion Porosimetry (MIP) was conducted on representative fractured samples. The samples were collected from the core of the specimens after mechanical testing, immersed in anhydrous ethanol to arrest hydration, and dried in a vacuum oven prior to testing.

3. Results

3.1. Rheology

In the rheological assessments, a linear relationship was observed between shear rate ($\dot{\gamma}$) and shear stress (τ), demonstrating a strong fit with the Bingham model ($\tau = \tau_0 + \mu\dot{\gamma}$). From each shear stress–shear rate plot, the yield stress (YS) and plastic viscosity (PV) were determined as the intercept and slope of the linear regression, respectively. This approach effectively minimized the influence of shear history on the results. The confidence level of the model fit exceeded 99% for all test results, ensuring high reliability; any tests falling below this threshold were excluded from further analysis. A total of 50 superplasticizer (SP) to binder (SP/B) combinations were evaluated across various viscosity modifying agent (VMA) dosages.

3.1.1. Yield Stress (YS) of Mortar Incorporating GT Replacement

Figure 6 (left) shows the effect of GT content on plastic viscosity. For Fine GT, its replacement level does not significantly affect the yield stress. The yield stress was nearly 85 Pa. The influence of gold tailings sand on mortar yield stress can primarily be attributed to two factors. First, compared with quartz sand, gold tailings sand has a larger particle size, known as the “particle-size effect.” When quartz sand is replaced by gold tailings sand, the coarser aggregate results in a reduced specific surface area and lower water demand. Consequently, the amount of free water in the matrix increases, improving fluidity and thereby reducing the yield stress [20]. However, because gold tailings sand has a rougher surface compared with quartz sand [21,22], its higher water absorption leads to increased water demand—i.e., the water-absorption effect—thus raising the yield stress [12]. For F-GT, these two opposing effects appear to balance each other; hence, varying the amount of finer GT does not notably affect the yield stress.

In contrast, for M-GT and C-GT, when the replacement level is below 50%, the yield stress decreases. This is because the particle-size effect dominates over the water-absorption effect, resulting in a net reduction in yield stress. Once the replacement level exceeds 50%, its influence on yield stress becomes negligible.

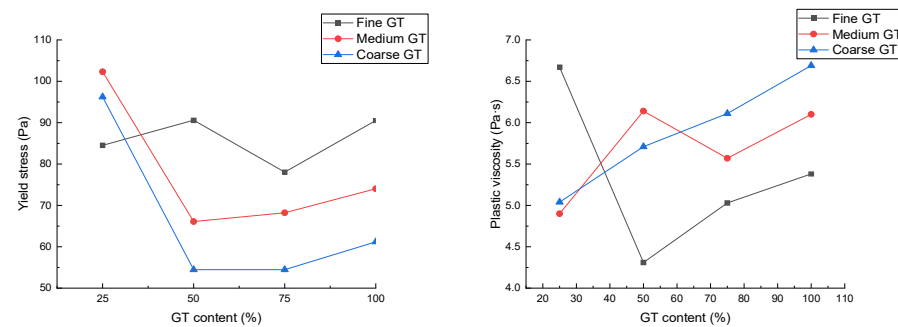


Figure 6. Effect of GT content on the rheology parameters.

3.1.2. Plastic Viscosity (PV) of Mortar Incorporating GT Replacement

Figure 6 (right) shows the effect of GT content on plastic viscosity. When the replacement level of F-GT is below 50%, increasing the content reduces plastic viscosity. However, when the replacement level of F-GT exceeds 50%, or when M-GT and C-GT are used, further increases in the replacement content raise plastic viscosity. This may be because plastic viscosity is primarily governed by the water absorption of the fine aggregate. Compared with quartz sand, GT has a rougher surface and higher water absorption, as well as better water-retention capability, resulting in a higher plastic viscosity. A higher plastic viscosity promotes the uniform dispersion of fibers in the matrix [23].

3.2. Fiber Dispersion Coefficient

Figure 7 illustrates the influence of GT content and fineness on the fiber dispersion coefficient. A value closer to 1 indicates better fiber dispersion. As shown in Figure 7, all mixtures exhibit fiber dispersion coefficients above 0.80. Theoretically, higher plastic viscosity promotes fiber dispersion within the matrix [23]. Although Figure 6 shows that plastic viscosity increases with GT content, Figure 7 reveals no pronounced changes in the fiber dispersion coefficient with varying GT content. This is because, in the present study, each mixture was adjusted using different dosages of water-reducer and thickener to regulate the plastic viscosity, ensuring that each mix achieves a relatively high fiber dispersion coefficient. This observation suggests that discrepancies in flowability and fiber dispersion—caused by differences in surface roughness between gold tailing sand and quartz sand—can be mitigated by tuning the dosages of water-reducer and thickener.

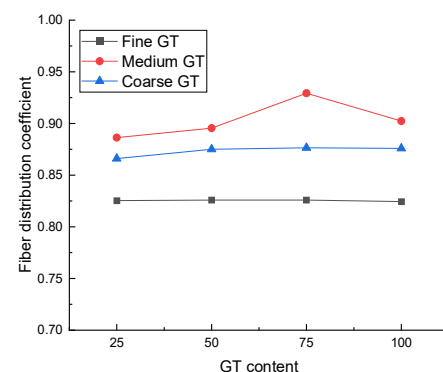


Figure 7. Fiber distribution coefficient of ECC mixtures.

Additionally, Figure 7 indicates that F-GT yields the lowest fiber dispersion coefficient, while M-GT achieves the highest, with C-GT falling in between. This finding implies that regardless of how the water-reducer and thickener are adjusted, the effect of GT fineness on fiber dispersion cannot be overlooked. Due to its higher fineness, F-GT has a larger specific surface area and thus a higher water demand, leading to lower overall flowability

and uneven fiber distribution, which reduces the dispersion coefficient [2]. By contrast, the coarser particle size of M-GT lowers the specific surface area and water demand, resulting in increased free water in the matrix, enhanced flowability, and more uniform fiber dispersion. However, because C-GT has the largest particle size and hence the lowest water demand, it is prone to bleeding, impairing the matrix's water-retention capacity and reducing its plastic viscosity. Consequently, the fiber dispersion coefficient declines to some extent [20].

3.3. Compressive Strength

Figure 8 shows the compressive strength of ECC incorporating different contents of GT. As depicted in the figures above, for all three fineness levels of GT sand, the compressive strength of ECC mixtures initially increases with GT substitution and subsequently decreases as the substitution level continues to rise. For instance, the compressive strength of ECC incorporating 75% of F-GT was about 90% higher than that with 25% of F-GT. However, when the substitution level of F-GT increased from 75% to 100%, the compressive strength declined by about 12.7%. This is because the larger particle size of GT sand relative to silica sand increases the matrix porosity [24].

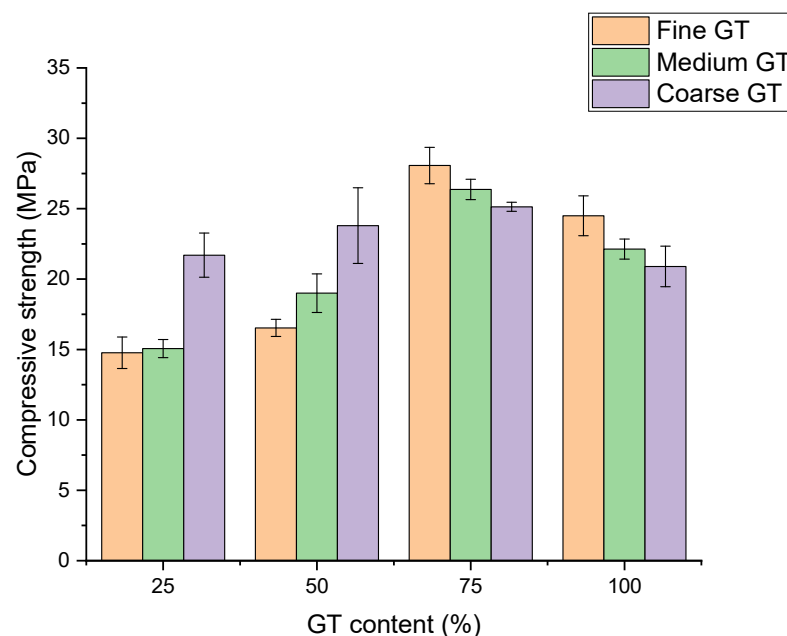


Figure 8. Compressive strength of ECC mortars.

When the GT substitution level is held constant and does not exceed 50%, increasing the particle size of GT sand leads to an improvement in compressive strength. Conversely, when the GT substitution level surpasses 50%, further increases in GT particle size result in a decrease in compressive strength. This reduction is caused by the incorporation of overly coarse aggregates, which increases the matrix porosity and subsequently lowers the compressive strength.

In cases where GT sand is co-substituted with silica sand, the presence of smaller aggregates fills the voids between larger aggregates, resulting in a denser structure and enhanced compressive strength. However, when GT sand of a single particle size is used exclusively, the uniform particle size leads to significant voids and thus a reduction in strength. This explains why, at 100% GT substitution, the compressive strength of the matrix decreases. This phenomenon can be attributed to the principle of tight packing. Based on particle tight packing theory and utilizing the modified Andreasen–Andersen (A&A) model, the proportions of each solid component were determined, and residuals

(RRS) were calculated using the least squares method [25]. The relationship between RRS and compressive strength for each mix ratio is illustrated in Figure 9. It is evident that, excluding the first data point, all other points exhibit decreasing residuals with increasing compressive strength. This indicates that as the ratio of GT to silica sand approaches the ideal tight packing curve, the overall slurry porosity decreases and the compressive strength increases. The first data point on each curve represents mortar with 100% GT, which contains only GT sand without silica sand. Consequently, there are no fine particles to fill the voids between coarse particles, resulting in increased porosity and decreased compressive strength.

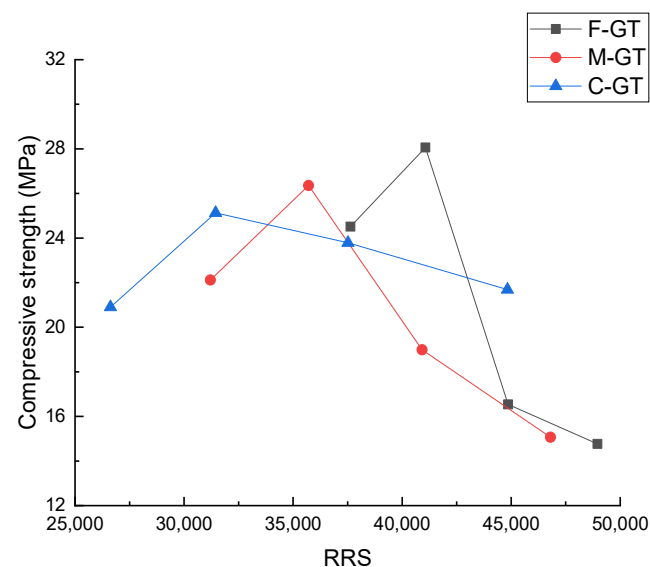


Figure 9. RRS of mortar mixtures.

3.4. Fracture Toughness

Figure 10 illustrates the effects of varying gold tailings (GT) sand substitution levels and particle fineness on the fracture toughness (FT) of the matrix. Coarse-GT (C-GT) mixtures exhibit a near-continuous increase in FT with rising GT content: at 25% substitution, fracture toughness is about $0.67 \text{ MPa} \cdot \text{m}^{0.5}$, climbing to approximately $1.03 \text{ MPa} \cdot \text{m}^{0.5}$ at 100% GT.

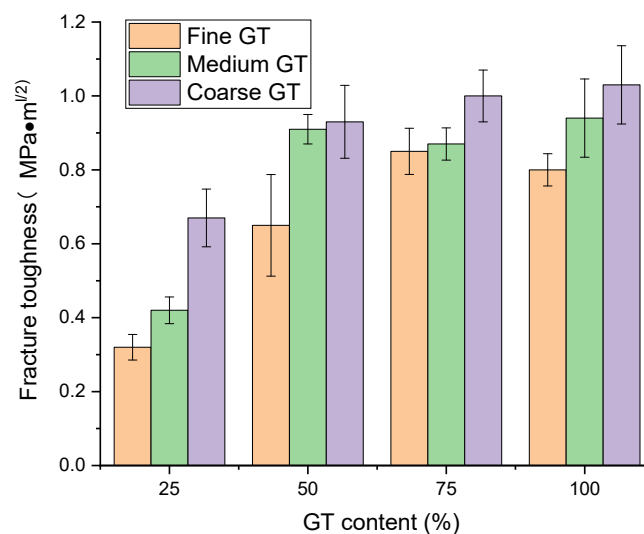


Figure 10. Fracture of ECC mortars.

A similar trend emerges for Fine-GT (F-GT) and Medium-GT (M-GT) mixtures up to 75% substitution, where FT improves alongside increasing GT content. For instance, F-GT mixtures show an FT of around $0.32 \text{ MPa}\cdot\text{m}^{0.5}$ at 25% substitution, rising to roughly $0.85 \text{ MPa}\cdot\text{m}^{0.5}$ at 75%. However, when F-GT completely replaces silica sand (i.e., 100% substitution), fracture toughness drops to about $0.8 \text{ MPa}\cdot\text{m}^{0.5}$.

When the GT substitution level remains fixed, fracture toughness also increases with larger GT particle size. For example, at 100% substitution, FT can vary from about $0.8 \text{ MPa}\cdot\text{m}^{0.5}$ in F-GT mixtures to approximately $1.03 \text{ MPa}\cdot\text{m}^{0.5}$ in C-GT mixtures. The stronger particle skeleton formed by coarser particles enhances bridging action, providing a more effective resistance to crack propagation and thus improving the matrix's fracture toughness. These findings highlight the integral role of particle size distribution and surface texture in dictating the fracture performance of ECC matrices under partial or full replacement of silica sand by GT.

Figure 11 shows the relationship between fracture toughness and compressive strength in ECC matrices. A positive correlation is evident: mixtures exhibiting higher compressive strength typically display lower porosity and a denser matrix structure, facilitating more effective bridging and, consequently, higher fracture toughness. Notably, the ratio of fracture toughness to compressive strength varies according to GT sand fineness, suggesting that differences in GT particle size play a critical role in governing the interplay between these two properties.

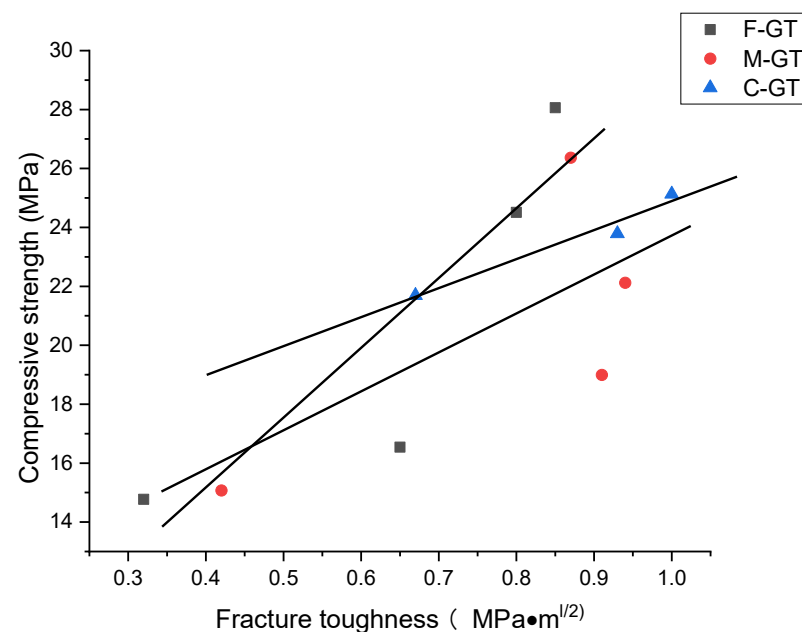


Figure 11. Relationship between Compressive Strength and Fracture Toughness of the ECC Matrix.

A critical microstructural correlation must be addressed regarding the 100% coarse GT mixture (A12), which exhibits the highest matrix fracture toughness ($J_{\text{tip}} = 49.37 \text{ J/m}^2$) despite possessing the highest porosity (30.9%) and a severely compromised compressive strength. This apparent contradiction is fundamentally governed by the distinct failure mechanisms under compression versus fracture. While compressive strength is highly defect-sensitive and drastically weakened by the massive voids formed by the lack of fine fillers [24], the matrix fracture toughness is primarily dictated by the crack propagation path. In the A12 mixture, the 100% coarse GT ($>600 \mu\text{m}$) particles are highly rigid with rough surface textures. As the crack tip advances through the porous matrix, it is hindered from penetrating these robust coarse particles, forcing the crack to deflect and bypass them.

This crack tortuosity and deflection mechanism significantly prolongs the actual crack propagation path, demanding substantial fracture surface energy [26,27]. Consequently, the macroscopic J_{tip} is anomalously elevated. However, this excessively high matrix fracture energy makes it difficult for the fiber bridging capacity (J_b') to stabilize the rapidly widening cracks, leading to the aforementioned fiber rupture and a corresponding loss in tensile ductility.

3.5. Axial Tensile Test

3.5.1. First Cracking Strength

Figure 12 presents the representative tensile stress–strain curves for the GT-blended ECC mixtures. To demonstrate the stability and experimental repeatability of the pseudo-strain hardening behavior, the stress–strain curves of three independent replicate specimens from a representative mixture (Mix A4) are plotted in Figure 12. All replicates exhibited consistent multiple-cracking patterns and sustained strain capacities. The curves clearly illustrate the transition from the linear elastic stage to the multi-cracking strain-hardening stage. Key parameters, including the first cracking strength (the onset of nonlinearity) and the ultimate tensile strength (peak stress prior to failure), are explicitly annotated on the curves to demonstrate the data extraction methodology. It is important to note that the distinct ‘jagged’ fluctuations or load drops observed in the stress–strain curves (Figure 12) are not data recording errors, but rather the actual physical manifestation of the pseudo-strain hardening behavior inherent to ECC. Each sudden drop in stress corresponds to the initiation of a new micro-crack within the cementitious matrix. Immediately following crack formation, the PVA fibers successfully bridge the crack surfaces, transferring the tensile stress back to the uncracked matrix, which causes the load-bearing capacity to rise again until the subsequent crack initiates. This continuous cycle generates the steady-state multiple cracking patterns. For context, conventional concrete typically exhibits highly brittle behavior under tension, with an ultimate tensile strain capacity of only about 0.01%. By contrast, the fine GT-blended ECC in this study achieves an ultimate tensile strain of up to 3.0%, representing a 300-fold increase over conventional concrete. This extreme enhancement in ductility is not a random anomaly, but the fundamental hallmark of ECC. The main reason for this significant increase lies in the tailored micromechanics of the composite: rather than failing via a single localized fracture, the PVA fibers provide steady-state bridging across the matrix. This continuous crack-bridging mechanism transfers the tensile stress back to the uncracked matrix, initiating multiple micro-cracks and effectively transforming the material’s failure mode from brittle fracture to ductile pseudo-strain hardening. To explicitly clarify this significant disparity, the typical tensile response curve of conventional concrete has been superimposed onto Figure 12. The macroscopic failure modes of the specimens further corroborate the ductility measurements. As shown in Figure 13, the failed dog-bone specimens exhibit a dense, saturated multiple-cracking pattern within the gauge length.

Figure 14 illustrates the first cracking strength (FCS) of ECC under various GT substitution levels and fineness conditions. As the F-GT content increases from 0% to 75%, the FCS rises from approximately 2.12 MPa to around 3.05 MPa, then declines at 100% GT substitution to about 2.5 MPa. However, at 100% substitution, the matrix contains only coarser single-graded GT particles, leading to higher matrix porosity and consequently reducing the FCS.

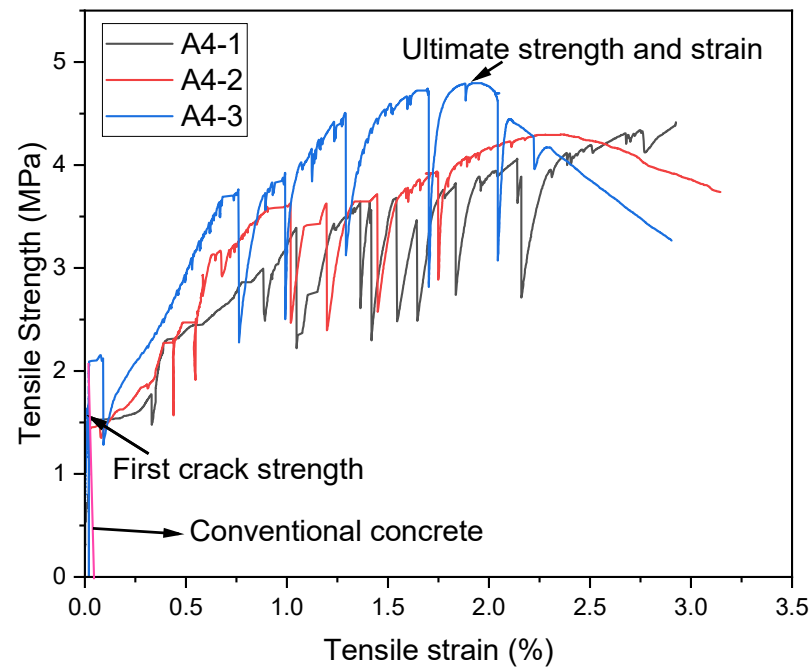


Figure 12. Representative stress–strain curves for three replicate specimens of the A4 mixture under uniaxial tension, demonstrating the pseudo-strain hardening behavior and experimental repeatability. A typical tensile response curve of conventional concrete is superimposed for comparison.



Figure 13. The photograph of the failed dog-bone specimens.

Under identical substitution levels, GT fineness does not significantly affect the FCS—an observation consistent with prior results on ECC compressive strength and fracture toughness. As depicted in Figures 15 and 16, the FCS strongly correlates with compressive strength and fracture toughness, with the former exhibiting a linear relationship and the latter showing an exponential one. This prominent interdependence arises because, at the moment of first cracking, fibers have not yet contributed substantially to crack bridging. Hence, the FCS is predominantly governed by the matrix strength [28]. By linking the

roughness of GT particles, matrix porosity, and the measured FCS values, these results underscore the critical role of aggregate texture and gradation in tailoring the early cracking behavior of ECC.

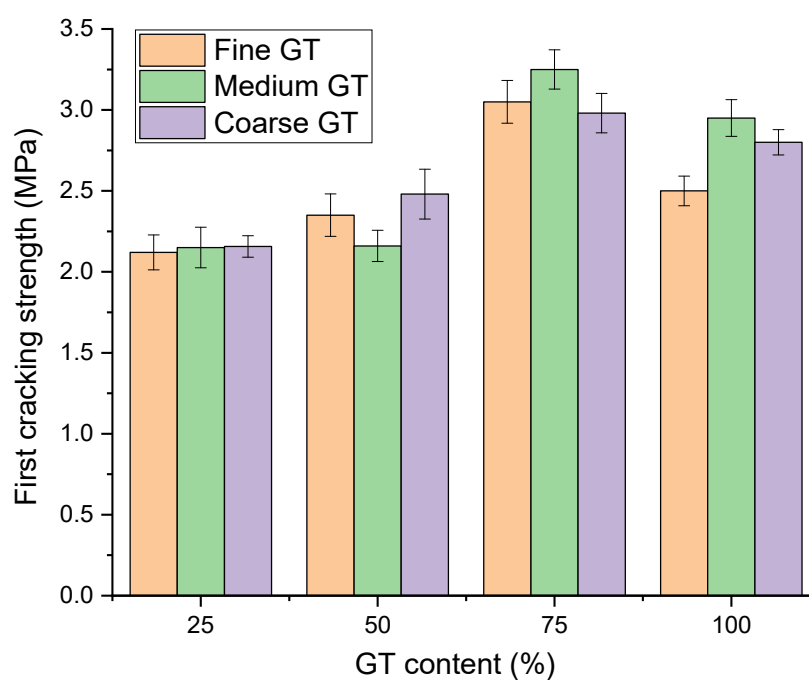


Figure 14. Influence of GT Fineness and Content on ECC First Cracking Strength.

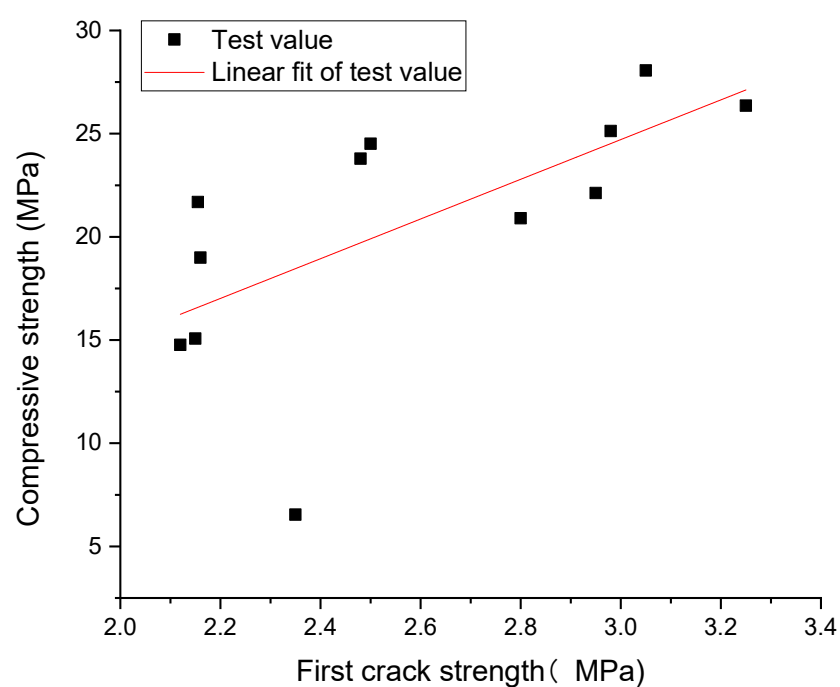


Figure 15. Relationship between First Cracking Strength and Compressive Strength.

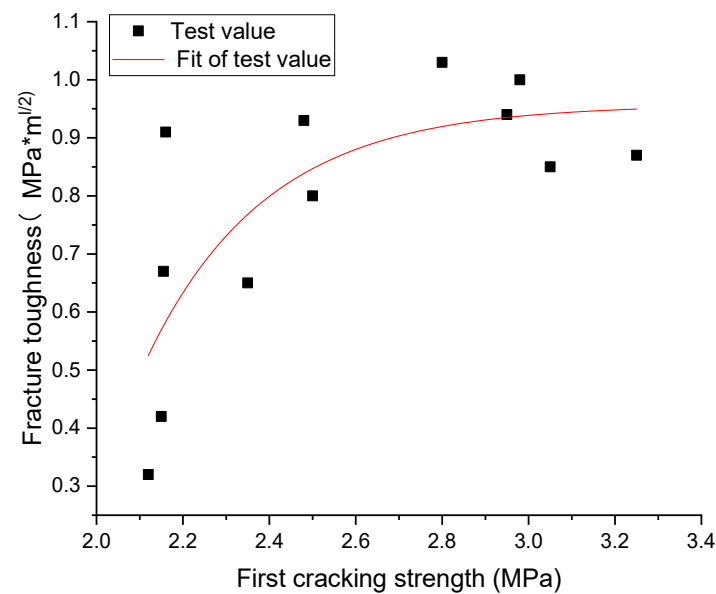


Figure 16. Relationship between First Cracking Strength and Fracture Toughness.

3.5.2. Ultimate Tensile Strain

Figure 17 presents the ultimate tensile strain results of ECC specimens incorporating GT. As shown in the figure, the ultimate tensile strain of the ECC specimens gradually increases with higher GT content. The matrix, fibers, and the bond between them jointly affect the tensile strain of ECC specimens. Generally, a higher matrix fracture toughness leads to a higher first-crack strength of ECC specimens, reducing the likelihood of multiple cracking and thus lowering ductility [29]. Moreover, tighter bonding between the matrix and fibers restricts fiber sliding and pullout, which further reduces ECC ductility.

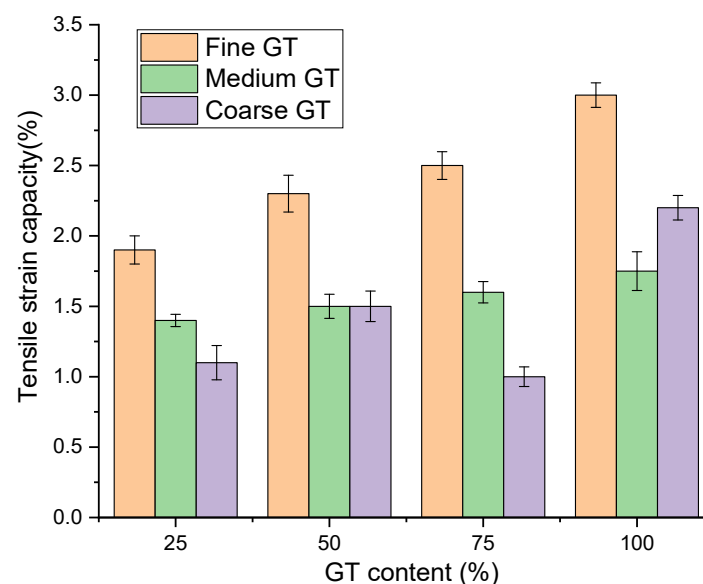


Figure 17. Influence of GT Fineness and Content on the Ultimate Tensile Strain of ECC.

When substituting conventional silica sand with GT sand, the rougher surface and higher water absorption capacity of GT [21,22] reduce the free water available for early hydration. This reduction limits the excessive precipitation of hydration products around the PVA fibers, weakening the chemical bonding and thereby facilitating stable fiber pull-out, which ultimately enhances ductility [30].

Conversely, within the GT mixtures, increasing the particle size from fine (F-GT) to coarse (C-GT) reduces the specific surface area and water absorption capacity. Consequently, more free water is retained in the matrix, promoting vigorous hydration. The dense accumulation of hydration products creates an excessively strong interfacial bond (over-strong anchorage). Under tensile loading, this restricts fiber slippage and triggers premature fiber rupture [27], which accounts for the significantly reduced ultimate tensile strain observed in the coarser GT mixtures.

Under the same replacement level, a larger GT particle size results in a lower ultimate tensile strain. Two factors contribute to this outcome. First, larger GT particles more readily form a coarse particle skeleton, enhancing the matrix strength and reducing ductility. Second, as the GT particle size increases, the specific surface area and water absorption decrease, which promotes hydration reactions and leads to increased hydration products. This rise in hydration products strengthens the matrix bond, further diminishing ductility.

3.5.3. Ultimate Tensile Strength

Figure 18 illustrates the ultimate cracking strength of ECC under various GT substitution levels and fineness conditions. As GT content increases, the ultimate cracking strength generally rises, given that both the first cracking strength and tensile strain tend to increase with higher GT content. This improvement in ductility translates into a higher ultimate cracking strength. Meanwhile, the impact of GT particle size on ultimate cracking strength is comparatively modest: although coarser GT particles reduce the ultimate tensile strain, the change in first cracking strength with GT fineness remains limited, resulting in no pronounced overall trend.

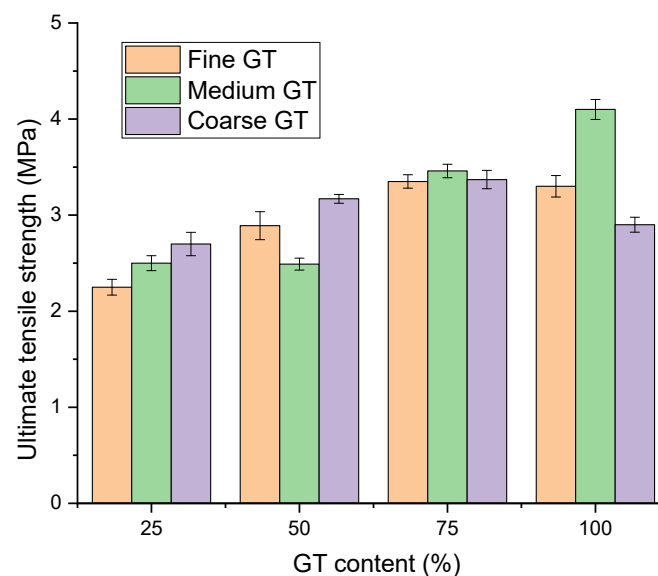


Figure 18. Influence of GT Content and Fineness on Ultimate Cracking Strength.

Figure 19 shows a fitted correlation between the first cracking strength and ultimate cracking strength, revealing a clear positive association. In other words, as the first cracking strength increases, the ultimate cracking strength likewise grows. This finding underscores how enhancements in the matrix's initial cracking resistance can elevate the composite's capacity to withstand greater loads at failure.

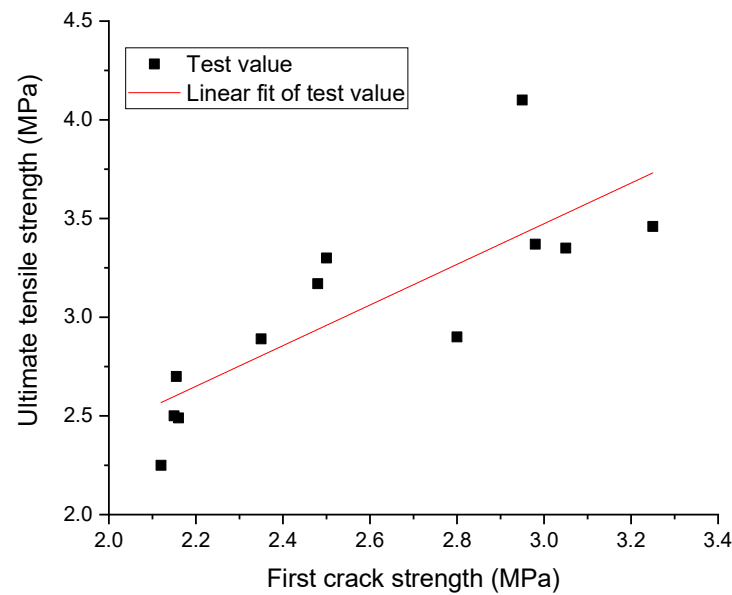


Figure 19. Relationship between First Cracking Strength and Ultimate Cracking Strength.

3.6. Single-Crack Tensile Test Result

Table 5 shows the results of the single-crack tension test. The pseudo-strain hardening (PSH) index can be calculated based on the data in Table 5. And the PSH is summarized in Table 6. The PSH, a pivotal micromechanical parameter (J_b / J_{tip}), quantifies the material's inherent capacity for stable multiple cracking, which is directly linked to its macroscopic tensile ductility. The analysis of Table 6 clearly indicates that the fineness and substitution level of gold tailings (GT) exert a significant influence on this critical index. Generally, as the particle size of GT increases (from F-GT to M-GT to C-GT) and its substitution level rises, the PSH index consistently decreases. This trend is largely attributable to the intricate interplay between GT characteristics and the composite's micromechanical components. Finer GT, particularly at moderate substitution levels, tends to optimize particle packing within the matrix, thereby contributing to a lower matrix fracture energy (J_{tip}) and a more robust fiber–matrix interface for effective fiber bridging complementary energy (J_b). For instance, F-GT mixtures at 20% and 40% substitution (A1: 55.18%, A2: 48.79%) exhibit the highest PSH indices. Conversely, coarser GT or higher GT substitution levels (e.g., C-GT mixtures A7, A8, A9, or F-GT at 100% in A3) often lead to an increase in J_{tip} due to enhanced aggregate interlock or potential alterations in the interfacial transition zone. While a tougher matrix can increase compressive strength, a higher J_{tip} often outpaces any concurrent gains in J_b , making it more challenging for fibers to trigger multiple cracking and thus significantly reducing the PSH index. This balance between matrix properties and fiber bridging is crucial, highlighting that the optimal PSH is achieved when GT's characteristics facilitate a low J_{tip} and a high J_b .

A value of $J_b' / J_{tip} > 1$ is a necessary condition for strain-hardening behavior, with higher ratios generally indicating more robust multiple cracking and greater tensile strain capacity. However, the analysis of Table 5 reveals a nuanced and seemingly contradictory trend: as the gold tailings (GT) substitution level increases, particularly for F-GT, the PSH index (J_b' / J_{tip}) consistently decreases (e.g., from 55.18 for A1-F25 to 12.47 for A10-F100), yet the ultimate tensile strain ($\epsilon_{t,max}$) simultaneously increases (e.g., from 1.9% for A1 to 3.0% for A10). This observation suggests that while the PSH index remains a fundamental criterion, the ultimate ductility of GT-blended ECCs is governed by a more complex interplay of factors, predominantly involving GT's dual influence on matrix properties and the fiber–matrix interface.

Table 5. Test results of single-crack tension test.

Mixture ID	σ_{oc} (MPa)		δ_B (mm)	
	Average	Variance	Average	Variance
A1	0.297	0.003	1.735	1.563
A2	0.377	0.000	2.032	1.098
A3	0.926	0.092	1.158	0.005
A4	0.839	0.092	1.714	1.028
A5	1.185	0.848	1.281	0.116
A6	1.157	0.198	2.042	3.504
A7	1.474	0.091	0.840	0.098
A8	0.902	0.085	1.065	0.003
A9	1.079	0.049	1.099	0.107
A10	1.128	0.064	1.376	0.034
A11	0.675	0.084	1.163	0.475
A12	1.101	0.599	1.191	0.000

Table 6. Comparisons on PSH index.

Mixture ID	J_b' (J/m ²)	J_{tip} (J/m ²)	J_b'/J_{tip}	$\epsilon_{t,max}$ (%)	$J_b'/J_{tip}/\epsilon_{t,max}$
A1	312.86	5.67	55.18	1.9	29.04
A2	471.86	9.67	48.79	1.4	34.85
A3	202.09	20.51	9.85	1.1	8.95
A4	338.93	22.13	15.31	2.3	6.66
A5	225.51	40.43	5.58	1.5	3.72
A6	378.96	37.74	10.04	1.5	6.69
A7	378.61	29.02	13.05	2.5	5.22
A8	134.51	31.37	4.29	1.6	2.68
A9	265.67	42.44	6.26	1.0	6.26
A10	342.98	27.50	12.47	3.0	4.16
A11	117.14	39.98	2.93	1.75	1.67
A12	203.60	49.37	4.13	2.2	1.88

The primary reason for the observed decrease in the PSH index with increasing GT content lies in the significant increase in matrix fracture toughness (J_{tip}). As detailed in Sections 3.3 and 3.4, GT, particularly with its rougher surface texture and ability to form a more robust particle framework, enhances aggregate interlock and matrix density (especially when co-substituted with silica sand, aligning with tight packing principles). This leads to a substantial increase in compressive strength and, consequently, matrix fracture toughness (J_{tip}). While the fiber bridging complementary energy (J_b') may also increase with GT content due to improved matrix–fiber bonding at initial stages, its increment is often insufficient to offset the more pronounced rise in J_{tip} . This imbalance results in a net reduction in the J_b'/J_{tip} ratio, indicating that the energy required to propagate a crack in the matrix is rising faster than the energy provided by fiber bridging to sustain multiple cracking.

Furthermore, an apparent paradox emerges in Table 6: while the PSH index for the 100% F-GT mixture (A10) drops to 12.47 compared to lower substitution groups, it paradoxically achieves the highest ultimate tensile strain of 3.0%. This phenomenon can be elucidated by coupling the energy criteria with the microstructural flaw distribution. Although the PSH index decreases, a value of 12.47 still robustly satisfies the fundamental energy requirement for steady-state multiple cracking [5]. Once this energy criterion is met, the ultimate ductility becomes highly sensitive to the distribution of pre-existing matrix flaws and fiber slippage behavior. According to the MIP results (Section 3.7), the moderately increased porosity in A10 (15.5%) acts as uniformly distributed natural micro-

flaws. These micro-flaws lower the cracking initiation threshold and promote the steady development of multiple microcracks [25]. Furthermore, the single-crack tensile results and the maintained bridging complementary energy suggest that fine GT particles may foster an optimal interfacial transition zone (ITZ). This optimized ITZ likely facilitates stable frictional sliding and a continuous fiber pull-out mode rather than premature rupture. This stable pull-out mechanism maximizes energy dissipation, overriding the lower theoretical energy margin and translating into superior macroscopic ductility.

3.7. MIP

The pore structure of the ECC matrix provides critical microstructural evidence that explains the variations in macroscopic mechanical properties. Table 7 and Figure 20 present the porosity and pore size distribution of selected ECC mixtures. The data demonstrate a strong dependence of matrix porosity on both the substitution level and the fineness of the gold tailings (GT) sand. Notably, mixture A3 (25% C-GT) exhibited the lowest porosity at 11.5%. This confirms the tight packing theory discussed in Section 3.3, where the synergistic co-substitution of coarse GT and finer silica sand allows smaller particles to effectively fill the interstitial voids between the larger aggregates, resulting in a highly dense matrix. In contrast, when silica sand is fully replaced by GT sand (100% substitution), the lack of aggregate gradation leads to a significant increase in porosity. For instance, the porosity increases progressively from 15.5% in A10 (100% F-GT) to 24.2% in A11 (100% M-GT), and peaks at 30.9% in A12 (100% C-GT). This microstructural data directly correlates with the compressive strength and first cracking strength trends. The highly porous structure of A12, driven by the uniform, coarse particle size of C-GT creating massive voids without fine fillers, explains its substantial drop in compressive strength compared to optimally blended mixtures. Furthermore, the elevated porosity in 100% substitution groups directly contributes to the reduction in matrix fracture toughness and first cracking strength, as a highly porous matrix is more susceptible to early crack initiation.

Table 7. Porosity of ECC matrix (%).

A3	A9	A10	A11	A12
11.5	21.5	15.5	24.2	30.9

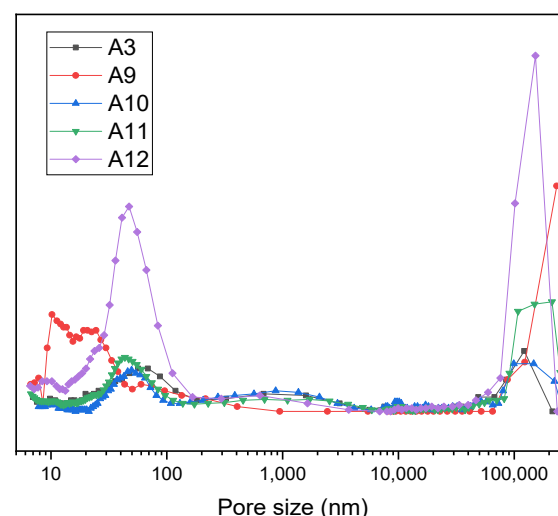


Figure 20. Pore size distribution of ECC matrix.

3.8. Mechanistic Interplay of Rheology, Microstructure, and Mechanical Performance

To avoid isolated analyses of individual indicators, the macroscopic mechanical properties of the GT-blended ECC must be understood through a unified logical chain. The physical characteristics of the raw materials directly dictate the fresh state rheology, which subsequently governs microstructural formation and ultimate mechanical failure modes. Firstly, the raw material properties—specifically the rougher surface texture and varying specific surface areas of GT compared to silica sand—alter the initial water demand. As demonstrated in Section 3.1, finer GT particles accelerate free water consumption, modifying the plastic viscosity. Secondly, these rheological shifts directly influence the microstructural network. An optimized plastic viscosity, achieved at moderate GT substitution levels, stabilizes the suspension and prevents fiber agglomeration, maintaining a high fiber dispersion coefficient (Section 3.2). Simultaneously, conforming to the tight packing theory, the co-substitution of multi-graded aggregates minimizes interstitial voids, yielding the lowest matrix porosity (e.g., 11.5% in the A3 mixture, Section 3.7). Finally, this established microstructure dictates the macroscopic mechanical response. A denser matrix intrinsically elevates compressive strength and first cracking strength. However, extreme microstructural variations induce distinct failure mechanisms. For instance, the 100% C-GT mixture forms a highly porous matrix with a robust coarse particle skeleton. While this skeleton induces severe crack tortuosity and artificially inflates matrix fracture toughness, the altered hydration dynamics create an overly strong interfacial bond. This restricts fiber slippage and triggers premature fiber rupture, severely degrading tensile ductility. In contrast, the 100% F-GT mixture balances a moderate porosity (which acts as uniformly distributed micro-flaws to lower the crack initiation threshold) with an optimal fiber–matrix interfacial transition zone. This structural synergy ensures stable, continuous fiber pull-out rather than rupture, thereby overriding the reduced pseudo-strain hardening (PSH) index and maximizing the ultimate tensile strain up to 3.0%.

4. Environmental and Cost Evaluation

Table 8 shows the cost and environmental effect of raw materials. The CO₂ emissions, energy consumption, and cost per cubic meter of GT-blended ECC were calculated as shown in Table 9 by aggregating the impacts of each raw material based on the mixture proportions provided in Table 7 [31]. The raw material costs were based on current local market prices. While transportation-related impacts were not considered due to limited data, the results reveal that GT-blended ECC mixtures exhibit lower carbon emissions (326–331 kg/m³) compared to typical M45-ECC (555 kg/m³) [32], primarily due to the replacement of cement with a high amount of fly ash and the incorporation of gold tailings. Similarly, energy consumption (4.04–4.29 GJ/m³) and cost (448–476 \$/m³) are substantially reduced compared to typical ECC (6.14 GJ/m³ and 557 \$/m³). The carbon intensity, defined as carbon emissions per unit tensile strain capacity, further highlights the efficiency of GT-blended ECC, with values ranging from 108.8 to 174.4 kg/m³/%, lower than the 185 kg/m³/% of typical ECC. This improvement can be attributed to the synergistic effects of fly ash and gold tailings, which reduce cement demand while maintaining mechanical performance. Additionally, the use of PVA fibers, despite their high individual environmental and cost impacts, does not outweigh the benefits of reduced cement content. The optimized mixture A-10, with the highest gold tailings content (416 kg/m³), demonstrates the lowest carbon emissions, energy consumption, and cost, suggesting that further increases in industrial byproduct utilization could enhance sustainability. Moreover, the tensile strain capacity of A10 was comparable to that of typical ECC, indicating potential durability benefits through crack control. Future research could explore the use of alternative fibers or hybrid systems to further reduce costs while maintaining performance.

Overall, GT-blended ECC presents a viable pathway to lower environmental and economic impacts in construction applications.

Table 8. CO₂ emission, energy consumption and cost of raw materials of ECC.

Constituent	CO ₂ Emission (kg/t)	Energy Consumption (GJ/t)	Cost (\$/t)
Cement	840	5.50	150
Fly ash	0	0	45
Water	0	0	0.675
Gold tailings	0	0	0
Silica sand	10.2	0.55	63
PVA	3430	101	15,000
Thickener	300	0.72	1402
SP	750	35	3300

Table 9. Environmental and cost impacts of typical M45- ECC and GT-blended ECC.

Name	Tensile Strain (%)	Carbon Emission (kg/m ³)	Energy Consumption (GJ/m ³)	Cost (\$/m ³)	Carbon Intensity (kg/m ³ /%)
A-1	1.9	331	4.29	476	174.4
A-4	2.3	330	4.16	467	143.3
A-7	2.5	327	4.10	454	130.8
A-10	3	326	4.04	448	108.8
M45-ECC	3	555	6.14	557	185.0

5. Conclusions

This study systematically investigated the feasibility and micromechanical mechanisms of utilizing gold tailings (GT) sand with varying fineness and substitution levels as fine aggregates in Engineered Cementitious Composites (ECC). Based on the comprehensive experimental and microstructural analyses, the following primary conclusions are drawn:

- (1) Substituting silica sand with GT up to a moderate level ($\leq 75\%$) significantly enhances both the compressive strength and fracture toughness of the composite. The rough surface texture of GT effectively strengthens the aggregate–matrix interlock. However, complete substitution (100% GT) increases matrix porosity, resulting in a degradation of compressive and first cracking strengths.
- (2) Blending different fractions of GT with silica sand successfully conforms to the tight packing theory. The intercalation of finer particles within the voids of coarser aggregates minimizes matrix porosity, consistently yielding superior compressive and fracture properties compared to mono-graded mixtures.
- (3) A distinct microstructural paradox was identified in the 100% coarse GT mixture. Despite possessing the highest porosity (30.9%) and compromised compressive strength, this mixture exhibited anomalously high fracture toughness. The rigid and highly tortuous coarse aggregates force propagating cracks to deflect, consuming substantial fracture energy. However, this overly aggressive mechanical anchorage triggers premature fiber rupture, severely restricting macroscopic ductility.
- (4) The 100% fine GT composite achieved an exceptional ultimate tensile strain of 3.0%, successfully overriding a notably reduced pseudo-strain hardening (PSH) index. By

adequately satisfying the fundamental energy criterion, the fine GT particles foster an optimal interfacial transition zone that facilitates stable, continuous fiber pull-out. Concurrently, uniformly distributed micro-flaws (moderate porosity) lower the crack initiation threshold, sustaining the multiple cracking process.

- (5) The environmental assessment confirms that GT-blended ECC presents a highly sustainable alternative for infrastructural applications. The optimized mixtures reduce CO₂ emissions by 41%, energy consumption by 34%, and overall material costs by up to 20% compared to conventional ECC, without compromising vital tensile and strain-hardening performance.
- (6) While this study systematically establishes the micromechanical and rheological frameworks for GT-blended ECC, long-term durability assessments fall outside the current scope. Future research will focus on the durability performance of these sustainable composites—particularly frost resistance and freeze–thaw durability in high-altitude environments, potentially coupled with the development of self-healing mechanisms—to ensure their viability in extreme engineering applications.

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References

- Lei, D.; Jia, H.; Yu, L.; Li, Y.; Wu, Z.; Wang, B.; Zhou, A.; Qin, L.; Sun, J.; Wang, W.; et al. Recent developments in Low-Carbon Engineered Cementitious Composites (ECC). *J. Build. Eng.* **2025**, *100*, 111734. [\[CrossRef\]](#)
- Li, J.; Qiu, J.; Weng, J.; Yang, E.-H. Micromechanics of engineered cementitious composites (ECC): A critical review and new insights. *Constr. Build. Mater.* **2023**, *362*, 129765. [\[CrossRef\]](#)
- Ji, J.; Zhang, Z.; Lin, M.; Li, L.; Jiang, L.; Ding, Y.; Yu, K. Structural application of engineered cementitious composites (ECC): A state-of-the-art review. *Constr. Build. Mater.* **2023**, *406*, 133289. [\[CrossRef\]](#)
- Yang, E.-H.; Li, V.C. Tailoring engineered cementitious composites for impact resistance. *Cem. Concr. Res.* **2012**, *42*, 1066–1071. [\[CrossRef\]](#)
- Kanda, T.; Li, V.C. New micromechanics design theory for pseudostrain hardening cementitious composite. *J. Eng. Mech.* **1999**, *125*, 373–381. [\[CrossRef\]](#)
- Li, V.C.; Mishra, D.K.; Wu, H.-C. Matrix design for pseudo-strain-hardening fibre reinforced cementitious composites. *Mater. Struct.* **1995**, *28*, 586–595. [\[CrossRef\]](#)
- Lu, C.; Shen, Q.; Zhang, Z. Sustainable design of high strength ECC using steel slag as fine aggregate: Toward waste valorization and environmental benefits. *Sustain. Chem. Pharm.* **2026**, *49*, 102288. [\[CrossRef\]](#)
- Li, Y.; Li, J.; Yang, E.-H.; Guan, X. Multiple cracking and strain-hardening criteria of Engineered Cementitious Composites (ECC) with river sand. *Cem. Concr. Res.* **2024**, *180*, 107511. [\[CrossRef\]](#)
- Tan, B.; Raza, A.; Zhang, G.; Yuan, C. Experimental Study on Interface Bonding Performance of Frost-Damaged Concrete Reinforced with Yellow River Sedimentary Sand Engineered Cementitious Composites. *Materials* **2025**, *18*, 3278. [\[CrossRef\]](#) [\[PubMed\]](#)

10. Song, Q.; Zou, Y.; Bao, J.; Zhang, P. Disposal of solid waste as building materials: A study on the mechanical and durability performance of concrete composed of gold tailings. *J. Mater. Res. Technol.* **2024**, *30*, 2111–2124. [\[CrossRef\]](#)
11. Mashifana, T.; Sithole, T. Clean production of sustainable backfill material from waste gold tailings and slag. *J. Clean. Prod.* **2021**, *308*, 127357. [\[CrossRef\]](#)
12. Ahmed, T.; Elchalakani, M.; Basarir, H.; Karrech, A.; Sadrossadat, E.; Yang, B. Development of ECO-UHPC utilizing gold mine tailings as quartz sand alternative. *Clean. Eng. Technol.* **2021**, *4*, 100176. [\[CrossRef\]](#)
13. Duan, Y.; Yuan, Q.; Yu, C.; Zheng, C. A large-scale study on solidification of gold tailings based on microbially induced carbonate precipitation (MICP). *Biogeotechnics* **2025**, *3*, 100164. [\[CrossRef\]](#)
14. Chandrasekhar, C.; Ransinchung, G. Assessment of interface characteristics and durability aspects of manufactured sand (M-sand) in engineered cementitious composites. *J. Build. Eng.* **2024**, *91*, 109705. [\[CrossRef\]](#)
15. Wu, H.-L.; Yu, J.; Zhang, D.; Zheng, J.-X.; Li, V.C. Effect of morphological parameters of natural sand on mechanical properties of engineered cementitious composites. *Cem. Concr. Compos.* **2019**, *100*, 108–119. [\[CrossRef\]](#)
16. Cheng, Z.; Wang, K.; Zhou, J.; Wu, H. Mechanical properties evaluation of sustainable engineered cementitious composites containing recycled fine powders. *J. Build. Eng.* **2023**, *71*, 106438. [\[CrossRef\]](#)
17. Şahmaran, M.; Lachemi, M.; Hossain, K.M.; Li, V.C. Internal curing of engineered cementitious composites for prevention of early age autogenous shrinkage cracking. *Cem. Concr. Res.* **2009**, *39*, 893–901. [\[CrossRef\]](#)
18. Xue, Y.; Wang, L.-C.; Liu, Y.; Ranjith, P.; Cao, Z.-Z.; Shi, X.-Y.; Gao, F.; Kong, H.-L. Brittleness evaluation of gas-bearing coal based on statistical damage constitution model and energy evolution mechanism. *J. Cent. South Univ.* **2025**, *32*, 566–581. [\[CrossRef\]](#)
19. Cao, Z.; Miao, C.; Du, F.; Zhu, D.; Teng, T.; Xue, Y. A bifurcation dynamical analysis of a non-darcy seepage system in post-failure rock based on a novel truncated spectral method. *Processes* **2026**, *14*, 1468. [\[CrossRef\]](#)
20. Safiddine, S.; Debieb, F.; Kadri, E.H.; Menadi, B.; Soualhi, H. Effect of Crushed Sand and Limestone Crushed Sand Dust on the Rheology of Cement Mortar. *Appl. Rheol.* **2017**, *27*, 12–20.
21. Li, J.; Zhang, H.; Li, Z.; Du, M.; Chen, J.; Xiong, Y.; Zhang, H.; Cheng, Y. Wetting characteristic and flow behavior of silicate binder at various sand particle-particle interfaces: Fine or coarse, circular or angular particles. *J. Mater. Res. Technol.* **2023**, *26*, 7166–7181. [\[CrossRef\]](#)
22. Behzadipour, H.; Sadrekarimi, A. Effects of microbially induced calcite precipitation on static liquefaction behavior of a gold tailings sand. *Biogeotechnics* **2024**, *2*, 100097. [\[CrossRef\]](#)
23. Yang, E.-H.; Sahmaran, M.; Yang, Y.; Li, V.C. Rheological control in production of engineered cementitious composites. *ACI Mater. J.* **2009**, *106*, 357. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Ćosić, K.; Korat, L.; Ducman, V.; Netinger, I. Influence of aggregate type and size on properties of pervious concrete. *Constr. Build. Mater.* **2015**, *78*, 69–76. [\[CrossRef\]](#)
25. Lei, D.-Y.; Li, M.-A.; Wang, P.-G.; Guo, L.-P.; Li, Y.; Liu, J.-P.; Zhang, P.; Li, S.-C.; Li, C.-C.; Li, Z.-H. Design of ultra-high strength, ultra-high ductility cementitious composites (UHS-UHDCC). *Constr. Build. Mater.* **2022**, *322*, 125914. [\[CrossRef\]](#)
26. Li, V.C.; Wang, S. Microstructure variability and macroscopic composite properties of high performance fiber reinforced cementitious composites. *Probabilistic Eng. Mech.* **2006**, *21*, 201–206. [\[CrossRef\]](#)
27. Paul, S.C.; van Zijl, G.P. Mechanically induced cracking behaviour in fine and coarse sand strain hardening cement based composites (SHCC) at different load levels. *J. Adv. Concr. Technol.* **2013**, *11*, 301–311. [\[CrossRef\]](#)
28. Zhang, Z.; Gao, Y.; Qin, F.; Sun, F.; Huang, Y. Mechanical properties of sustainable high strength ECC with substitution of cement by limestone powder. *Case Stud. Constr. Mater.* **2023**, *19*, e02434. [\[CrossRef\]](#)
29. Chandrasekhar, C.; Ransinchung, G. Engineered cementitious composites (ECC) with manufactured sand (M-sand) for pavement applications. *Compos. Commun.* **2023**, *41*, 101657. [\[CrossRef\]](#)
30. Kanda, T.; Li, V.C. Interface property and apparent strength of high-strength hydrophilic fiber in cement matrix. *J. Mater. Civ. Eng.* **1998**, *10*, 5–13. [\[CrossRef\]](#)
31. Zhang, H.; Wu, Z.; Hu, X.; Ouyang, X.; Zhang, Z.; Banthia, N.; Shi, C. Design, production, and properties of high-strength high-ductility cementitious composite (HSHDCC): A review. *Compos. Part B Eng.* **2022**, *247*, 110258. [\[CrossRef\]](#)
32. Li, V.C. Tailoring ECC for special attributes: A review. *Int. J. Concr. Struct. Mater.* **2012**, *6*, 135–144. [\[CrossRef\]](#)

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