

Article

Effect of RTPF on Fracture Properties of Cement-Stabilized Soil

Chang Sun ^{1,2}, Fengchi Wang ^{3,*} and Tianbei Kang ¹

¹ School of Civil Engineering, Shenyang Jianzhu University, Shenyang 110168, China; sc0805@stu.sjzu.edu.cn (C.S.); kangtianbei@sjzu.edu.cn (T.K.)

² School of Civil Engineering, University of Science and Technology Liaoning, Anshan 114051, China

³ School of Transportation and Geomatics Engineering, Shenyang Jianzhu University, Shenyang 110168, China

* Correspondence: cefcwang@sjzu.edu.cn

Abstract

Recycled tire polymeric fiber (RTPF) is a type of nylon fiber recovered from end-of-life tires. Depending on the processing stages, RTPF exists in two forms, fibrils (FS) and fiber bundles (FB). Although fiber reinforcement has been widely investigated for cement-stabilized soils, the fracture behavior and reinforcing mechanisms of RTPF remain insufficiently understood. Three-point bending tests using DIC, CT, and SEM analyses were conducted. The results indicate that RTPF delays crack initiation, increasing both the time interval from initiation to fracture and the ultimate crack width. Flexural strength increases with RTPF content and exhibits a power-law relationship. Both FS and FB significantly improve unstable fracture toughness, increasing it from 0.19 MPa·m^{1/2} in the control specimen to 0.37 MPa·m^{1/2} and 0.78 MPa·m^{1/2}, respectively. Fracture energy increases by 49% and 228%, respectively. The peak reinforcing efficiency was achieved at the RTPF content of 0.2–0.4% for FS and 1–2% for FB. The higher distribution coefficients and lower orientation reflect an isotropic fiber distribution, which is beneficial for inhibiting multi-directional crack propagation. A calculation method was developed to estimate fracture toughness from the fiber reinforcing parameter, with the findings showing good agreement with experimental results. These findings demonstrate the feasibility of utilizing RTPF as a sustainable reinforcement material for improving the fracture resistance of cement-stabilized soils in geotechnical engineering applications.

Keywords: cement-stabilized soil; recycled tire polymer fiber; fracture parameter; fiber distribution

1. Introduction

Inorganic binder stabilization is a conventional treatment method for subgrade and pavement structures in problematic soils [1,2]. The hydration products generated by the cementitious reactions between the combined components provide binding effects, enhancing the soil strength and stiffness and thereby alleviating engineering issues such as uneven deformation, swelling, and pumping in problematic soil foundations and embankments [3]. For soils exhibiting more severe geotechnical deficiencies, an increased cement dosage is necessitated, which consequently imparts pronounced brittle characteristics to the stabilized soil matrix [4]. Although cement stabilization significantly improves strength and stiffness, excessive cement content often increases brittleness, making fracture behavior a governing failure mechanism under repeated traffic loading [5]. Therefore, fracture parameters such as fracture toughness and fracture energy, which describe crack propagation resistance and total energy dissipation, are more appropriate indicators of long-term pavement performance than are conventional strength indices.



Academic Editor: Claudio Mazzotti

Received: 11 June 2026

Revised: 20 July 2026

Accepted: 24 July 2026

Published: 30 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Geotechnical scholars have conducted extensive research on soil fracture properties, with a primary focus on evaluating the enhancement of fracture parameters through various stabilizing materials. Arto [6], Barani [7], and Erarslan [5] investigated the impact of additives, including lime, biopolymer, and cement, on the fracture characteristics of soils. Zhang [8] further predicted the fatigue behavior and ultimate failure of stabilized soils using fracture parameters derived from an inelastic cohesive zone model. Fiber has been recognized as an effective method of enhancing the fracture resistance of stabilized soils. Previous studies have consistently reported that both synthetic fibers, e.g., PET, polypropylene, and sisal [9–11], and natural fibers, e.g., rice straw, rice husk, and barley [12–14], can effectively improve the strength, ductility, and crack resistance of stabilized soils. However, the reported reinforcing efficiency strongly depends on fiber type, morphology, dosage, and fiber–matrix interaction mechanisms.

In the current context of promoting green building materials and the utilization of solid waste resources, recycled tire polymer fiber (RTPF) has emerged as a novel recycled material with both environmental benefits and engineering potential for improving the fracture performance of stabilized soils. RTPF is a by-product obtained through industrial processing from waste tires. Approximately one billion waste tires are generated annually worldwide, with RTPF accounting for 9–16% of tire recycling products. In the European Union alone, approximately 25,000 tons of RTPF are recovered from waste tires each year [15], the majority of which are disposed of by incineration, representing a potential source of environmental pollution. The main component of RTPF is nylon 66. Depending on the processing stages, RTPF can be divided into two forms: fibrils (FS) and fiber bundles (FB). FS consist of individual micron fibers with a length of approximately 8 mm. FB are comprised of a hybrid fiber system consisting of approximately 20 mm long stripy fibers and FS. The research conducted by Chen [16] and Onuaguluchi et al. [17,18] indicates that FS exhibit an equivalent reinforcing effect on conventional polypropylene fibers in concrete. Abbaspour [19] and Valipour [20] used FB to enhance the strength and ductility parameters of sandy soil and clay, achieving an enhancement effect similar to that of glass fibers. Sun [21] found both FS and FB, at appropriate contents, can improve the shear strength and frost durability of stabilized soil. However, these studies primarily focused on strength-related properties, while the fracture toughness, crack propagation mechanisms, and fiber orientation effects of RTPF-reinforced cement-stabilized soils remain poorly understood.

The macroscopic properties of fiber-reinforced composites are the result of the synergistic effect of the non-fiber matrix, fiber reinforcement, and the fiber–matrix interface [22,23]. The spatial distribution characteristics of the fibers in the soil matrix directly determine the bridging effect and reinforcement efficiency [24]. Studies have shown that the length, content, dispersion state, and spatial orientation collectively control the bridging behavior of the fibers, thereby determining the fracture strength, critical crack size, and multiple crack evolution [25,26]. When the fibers are distributed parallel to the principal tensile stress direction, they can maximize the reinforcing effect. However, when the fibers change from an ideal one-dimensional uniform distribution to a three-dimensional random distribution, their bridging efficiency significantly decreases, and some fiber clusters may even aggregate, forming local defects [27]. Due to the influence of multiple factors, such as matrix properties, molding processes, and fiber characteristics, it is difficult for fibers to achieve an ideal uniform distribution in the soil [28]. Digital image correlation technology (DIC) has been applied in studying fracture crack propagation and damage evolution in fiber-reinforced and self-compacting concrete [29,30]. Unlike conventional displacement measurements, DIC enables full-field strain monitoring and direct visualization of crack evolution, making it particularly suitable for investigating fracture processes in heterogeneous fiber-reinforced geomaterials. Existing studies remain largely confined to macroscopic mechanical re-

sponses, lacking detailed microscopic observations of the evolution mechanism of crack initiation and propagation during the fracture process. In particular, as a novel type of fiber, the improvement effect of RTPF on the fracture performance of soil and its underlying mechanism, especially the intrinsic correlation between the distribution characteristics of the fiber within the soil matrix and the macroscopic mechanical behavior, still require further clarification.

This paper investigates the fracture behavior and fiber distribution characteristics of cement-stabilized soil reinforced with RTPF. Through three-point bending tests integrated with DIC non-contact deformation measurement, the flexural strength, fracture toughness, and fracture energy of the stabilized soil under varying RTPF contents and forms were obtained, and the fracture process and energy absorption mechanisms were analyzed. Using CT nondestructive testing and SEM analysis, a three-dimensional spatial distribution model of RTPF was established to elucidate the reinforcement mechanism. The distribution coefficient was used to reflect the spatial uniformity of fibers within the matrix, and the orientation index was adopted to characterize the degree of fiber alignment along the principal stress direction. Accordingly, the relationship between the fiber-reinforcing parameters and the fracture parameters was established. To the authors' knowledge, this study is the first to systematically correlate RTPF morphology (FS and FB), three-dimensional fiber distribution characteristics obtained from CT analysis, and fracture parameters measured through DIC-assisted fracture testing. The findings are expected to provide a reference for the optimized design of fiber-reinforced soils.

2. Materials and Methods

2.1. Raw Materials

Test soil was obtained from Shenyang, Liaoning, China, at a depth of 0.7 m. The soil is classified as a low-plasticity inorganic clay, according to the plasticity chart in Standard Practice for Classification of Soils for Engineering Purposes ASTM D2487-17 [31]. Since the salt content in the soil is higher than 0.3%, it is further classified as carbonate saline soil. The soil was dried, crushed, and screened with a 5 mm strainer for future use. Basic properties of the soil are listed in Table 1, and the grain distribution is shown in Table 2.

Table 1. Basic physical properties of test soil.

Index	Natural Water Content	Liquid Limit	Plastic Limit	Plasticity Index	Specific Gravity	Maximum Dry Density/g·cm ⁻³	Optimal Water Content	Saline Content
Value	17.0%	29.47%	16.21%	13.26%	2.72	1.82	14.3%	2%

Table 2. Soil particle gradation.

Sieve Size/mm	0.075	0.15	0.3	0.6	1.18	2.36	4.75
Passing ratio (by mass)/%	0	2.6	6.8	12.0	18.9	71.1	100

P.O. 42.5 ordinary Portland cement was selected as the stabilized material. The cement content was determined as 15%, and the water/cement ratio was 0.85, based on preliminary unconfined compressive strength tests and engineering practice [32]. This proportion was selected to alleviate the long-term attack of carbonates on Portland cement, while maintaining proper workability and mechanical properties of the stabilized mixture.

RTPF is derived from the shredding of waste rubber tires. Depending on production objectives and processing levels, RTPF can be separated into two morphological types: FB and FS. FB is a hybrid fiber system separated during rough processing for steel fiber

production, which contains spiral stripy fibers and difficult-to-remove FS, with a mass proportion of 1.7–18%. FS are comprised of individual crimped micron fibers formed by further crushing the FB during the fine processing used for producing rubber particles. The performance parameters of individual FS and stripy fibers in FB are shown in Table 3. Fiber lengths were measured from 50 randomly selected fibers. The mean lengths of the FS and FB are 8.2 mm and 21.7 mm, with standard deviations of 1.8 and 4.7, respectively. Untreated RTPF was selected as the research object. Due to the differing amounts of rubber particles attached to their surfaces, FS and FB exhibit distinct apparent densities and specific surface areas. Thus, different mass fractions were adopted based on previous studies and relevant references: 0.5%, 1%, 2%, 3%, and 4% for FB and 0.1%, 0.2%, 0.4%, 0.8%, and 1.2% for FS.

Table 3. RTPF performance parameters.

RTPF Type	Length/mm	Diameter/ μm	Tensile Strength/MPa	Elastic Modulus/GPa	Moisture Absorption Rate	Elongation/%
FS	4.6–12.8	18.6–23.6	475–620	3.2–4.5	>0.4	17.7–23.5
Stripy fiber	10–30	30–1500	300–2000	2.0–7.5	0.05–0.13	18.0–25.0

2.2. Specimen Preparation

The mix proportion design was created in accordance with the Specification for Mix Design of Cement Soil JGJ/T 233-2011 [33]. The soil, cement and RTPF were weighed and mixed according to the setting mix proportion, and the RTPF was dispersed manually to ensure uniform dispersion. RTPF was added gradually in three portions, with thorough mixing after each addition until no visible fiber agglomeration was observed. The mixture was initially combined with 10% of the mixing water to pre-wet the fibers, enhancing the bond between RTPF and the soil particles. The remaining water was added in two increments, with each stirring time lasting not less than 120 s. The specimen for CT scanning was cylindrical, with a diameter of 50 mm and a height of 100 mm. The mixture was added to the mold in four layers. Each layer was compacted using a 500 g hammer with a drop height of 250 mm, with 25 blows applied per layer. Specimens were demolded after 2 h. The dimensions of the beam specimens were 100 × 100 × 400 mm. The specimen was prepared in three layers. After each layer was compacted, a pressure of 100 kN was applied using a hydraulic jack and maintained for 20 min to complete compaction. Specimens were demolded after 48 h. For each mixture, three parallel specimens were tested, and the average value was taken as the final result. The coefficient of variation for all measured properties was less than 15%. Data with a deviation greater than 15% among parallel specimens were excluded. All specimens were cured in a humidity-controlled curing chamber at 20 ± 2 °C and $\geq 95\%$ RH for 28 days. A pre-notch with a depth of 20 mm and a width of 2 mm was set at the middle of the beam's bottom face. The ratio of the cut height to the specimen height is 0.2. The specimen surface was polished and coated with a matte black paint speckle pattern for DIC analysis. The beam preparation process and dimensions are illustrated in Figure 1.

2.3. Test Methods

2.3.1. Three-Point Bending Test

The three-point bending test device consists of two parts: the loading system and the DIC system, as shown in Figure 2. Following the Test Method for Metallic Fiber Concrete—Measuring the Flexural Tensile Strength BS EN 14651 [34], loading was applied at the beam midspan, with bottom support positioned 50 mm from the beam edges. Steel sheets were placed 5 mm adjacent to the pre-notched area for mounting the extensometer, which

measured the crack mouth opening displacement (CMOD). The calculation methods for the fracture parameters are presented in Equations (1) and (5)–(9).

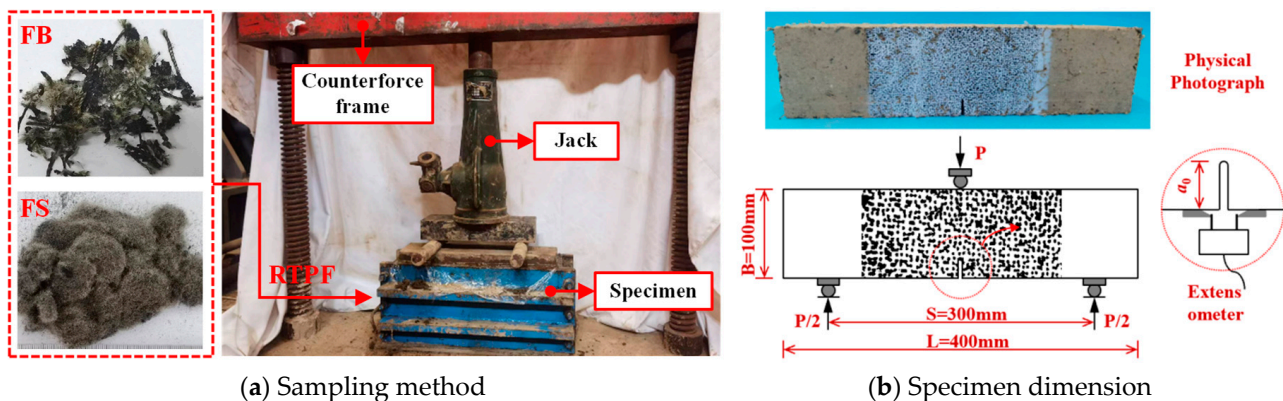


Figure 1. Preparation and dimensions of the test beam.

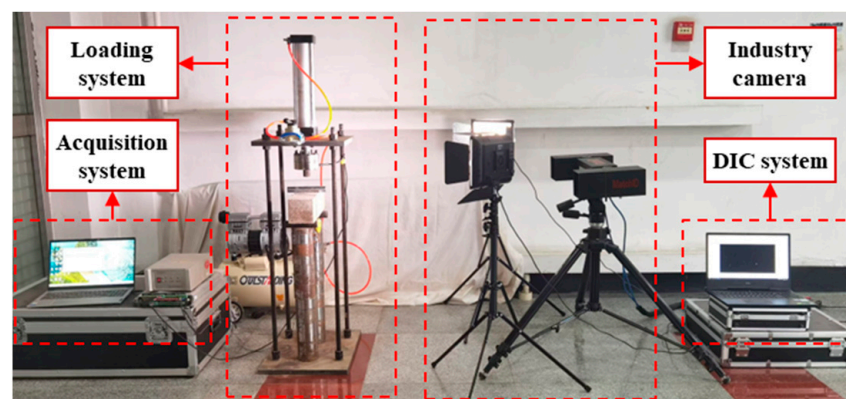


Figure 2. Three-point bending test system.

2.3.2. DIC Analysis

Synchronized data collection was initiated upon activating the load system, utilizing a high-speed static strain DIC system. To mitigate environmental light interference, two external light sources were set up to obtain images with stable gray values. A 5-megapixel industrial camera with a 50 mm focal length lens was used to continuously collect speckle images at 10 Hz. Before the test, the DIC system was calibrated, and the optical consistency of the system was checked. The DIC parameters were automatically optimized, with a subset size of 21 pixels and a step size of 5 pixels adopted for the present speckle pattern. The zero-mean normalized sum of squared difference was used as the correlation criterion. Based on system calibration, the measurement uncertainty was approximately 0.01 pixels. Full-field displacement and strain data were derived through Match-ID (2021.1) software analysis.

2.3.3. CT Analysis

To quantitatively characterize the three-dimensional random distribution of RTPF in the soil matrix while avoiding fiber dislocation caused by traditional sectioning methods, this study employed a NanoVoxel 4000 X-ray 3D microscope (Sanying Precision Instruments Co., Ltd., Tianjin, China) for the non-destructive CT scan of RTPF cement-stabilized soil. The scan was conducted at a voltage of 200 kV and a current of 350 μ A, with a spatial resolution of 21.31 μ m. CT images were processed for enhancement and segmentation using Avizo 3D (2022.2) software, employing the bilateral filtering and IsoData algorithm.

The process enabled FB to be distinguished from the soil matrix and a three-dimensional structural model to be reconstructed. CT scanning and image extraction are illustrated in Figure 3.

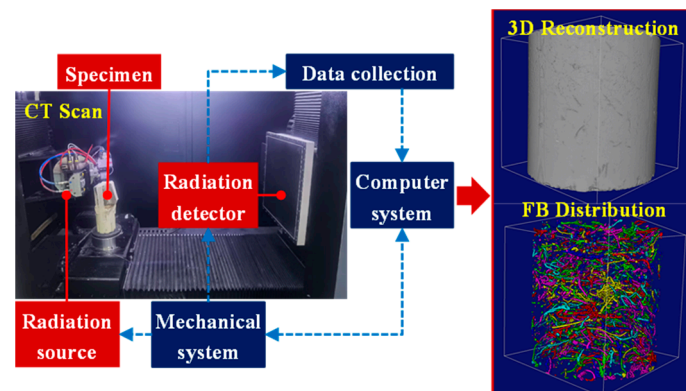


Figure 3. CT scan and 3D reconstruction.

2.3.4. SEM Analysis

The CT resolution is comparable to the diameter of the FS, which limits the reliable identification of single FS. Therefore, scanning electron microscopy (SEM) was utilized to examine the morphology of FS. SEM observations were performed at an accelerating voltage of 15 kV, with a working distance of 8.1 mm and a magnification of $50\times$ in backscattered electron mode. Specimens were taken from the tested beams, dried, and sputter-coated with gold prior to observation. Three regions were randomly chosen from each specimen for SEM analysis. Image J (1.54g) software was applied for image analysis to obtain fiber counts and dimensions across sections. The distribution coefficient and orientation index were then calculated using the equations presented in Equations (11)–(13).

3. Results and Discussion

3.1. Fracture Process Analysis

3.1.1. Load–CMOD Relationship

As shown in Figure 4, the load–CMOD curve characteristics of cement-stabilized soil under different RTPF contents exhibit consistent characteristics. RTPF-reinforced specimens exhibited a notable load increase after crack initiation, demonstrating good post-cracking load-carrying capacity. Increased RTPF content enhances the nonlinear growth phase of the load–CMOD curves and substantially elevates the crack initiation load, P_{ini} , and peak load, P_{max} , of the cement-stabilized soils. FS and FB increase P_{ini} by 47.92–175.00% and 93.75–475.00%, respectively, compared to the results for the non-fiber specimens, and P_{max} rises by 11.93–63.30% and 29.36–292.66%. Based on Li’s pull-out theory [35], RTPF transfers the external load from the matrix to the fibers through bonding effects and frictional energy dissipation during the delamination sliding stage. This mechanism facilitates stress redistribution to the non-fracture area and inhibits crack propagation [21]. SEM observations (see Figure 5) reveal that FS form a dense three-dimensional microcrack-blocking network through spatial distribution, which optimizes the meso-structure of the cement-stabilized soil. Moreover, the high specific surface area of FS allows them to be coated with abundant hydration products, as clearly shown in the SEM images. This coating likely inhibits microcrack initiation through interfacial chemical bonding between the fibers and hydration products. FB inhibit the early cracking by FS in the hybrid system, while significantly increasing the fracture load through the high-modulus stripy fibers. Macroscopic stripy fiber can cross the inherent pores in the matrix, directly bear loads

and bridge large-scale cracks. The rough texture on the fiber surface activates a stronger interlocking effect in the fiber–matrix interfacial transition zone [36]. The groove surface of the FB increases the fiber–matrix interface friction. During FB pull-out, the surface textures cause deflection of the crack propagation path, generating a mechanical anchoring effect.

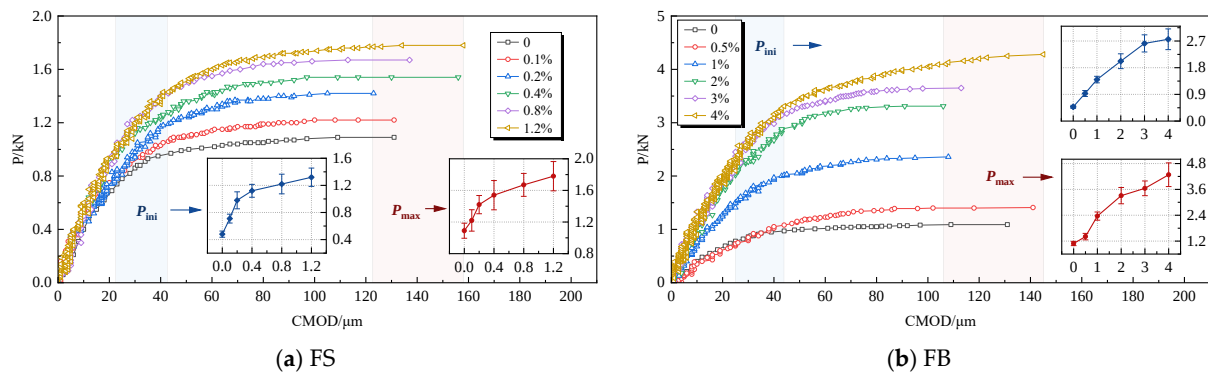


Figure 4. Load–CMOD curves.

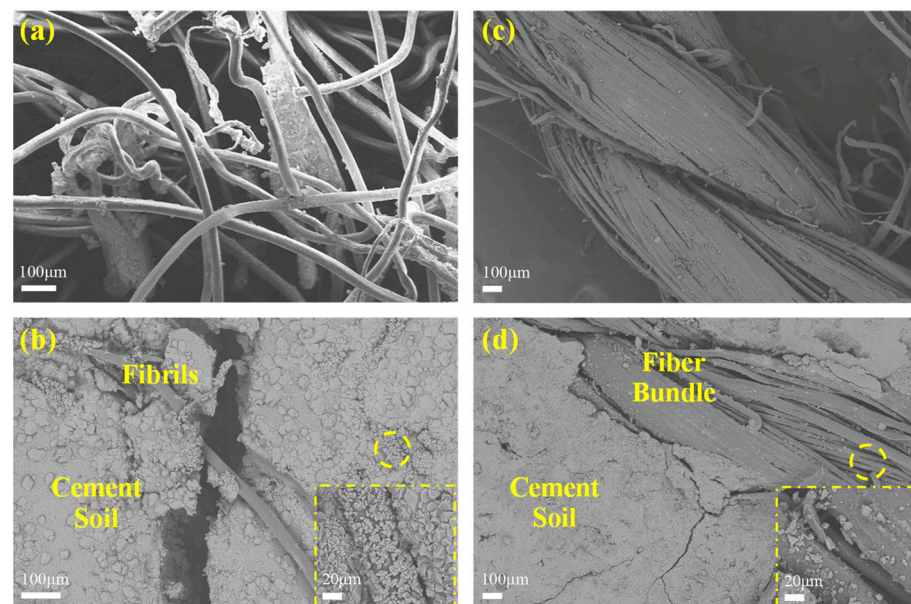


Figure 5. SEM morphology and mechanism of RTPF. (a) FS; (b) FS cement soil; (c) FB; (d) FB cement soil.

3.1.2. Crack Propagation Process

The horizontal displacement cloud image of RTPF cement-stabilized soil during the fracture evolution process is shown in Figure 6. Crack widths were quantified using the built-in Virtual Extensometer tool in Match-ID, with two gauge points placed on opposite sides of the crack to extract the normal displacement discontinuity as the crack opening displacement. In the initial loading stage, microcracks underwent stress redistribution with diffuse distribution characteristics. The specimen exhibits compression in the upper zone and tension in the lower zone, and the horizontal displacement remains at a relatively low level. The positive and negative displacement zones move upward from the beam base with the increase in the load. The appearance of displacement mutation at the pre-notched tip marks the generation of the crack initiation load and the formation of macroscopic cracks. Increasing load causes the cracks to extend vertically while opening horizontally. The displacement mutation zone expands upward, followed by rapid crack penetration through the full beam height, resulting in structural failure.

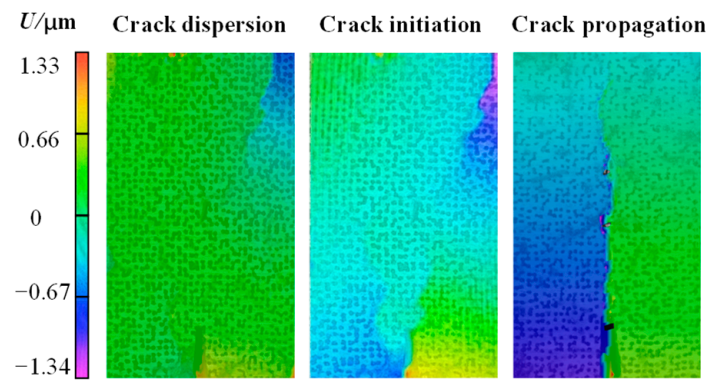


Figure 6. Displacement cloud images under different loads.

Comparative analysis of fracture strain cloud images (Figure 7) and crack parameters (Figure 8) under different RTPF contents indicates that non-fiber specimens exhibit typical brittle fracture characteristics. Cement soil is a brittle material; the specimens without fiber reinforcement experience instantaneous fracture immediately after crack initiation. Limited by the low frame rate of the DIC system, only 1–2 frames successfully recorded the critical crack propagation stage. RTPF achieves crack blocking and energy dissipation effects through fiber–matrix de-bonding and the pull-out mechanism, which greatly delays the crack initiation time. Moreover, the regulative effect of the fiber reinforcement mechanism on the fracture behavior intensifies at higher fiber contents. When RTPF contents exceed 0.4% for FS and 1% for FB, both the time interval from initiation to fracture and the ultimate crack width significantly increase. FS and FB extend the fracture time to 4.75 s and 11.15 s, respectively. Morphological analysis of fracture cracks reveals that 1.2% FS induces tortuous deflection of the crack path, prolongs the crack propagation path, and forms multi-level branch cracks. Conversely, 4% FB significantly amplifies the maximum crack width from 0.40 mm of FS to 2.74 mm. These observations collectively demonstrate that FS affect the microcrack development by regulating the microstructure of cement-stabilized soil, while the FB system has a more significant regulatory effect on the macroscopic properties after damage.

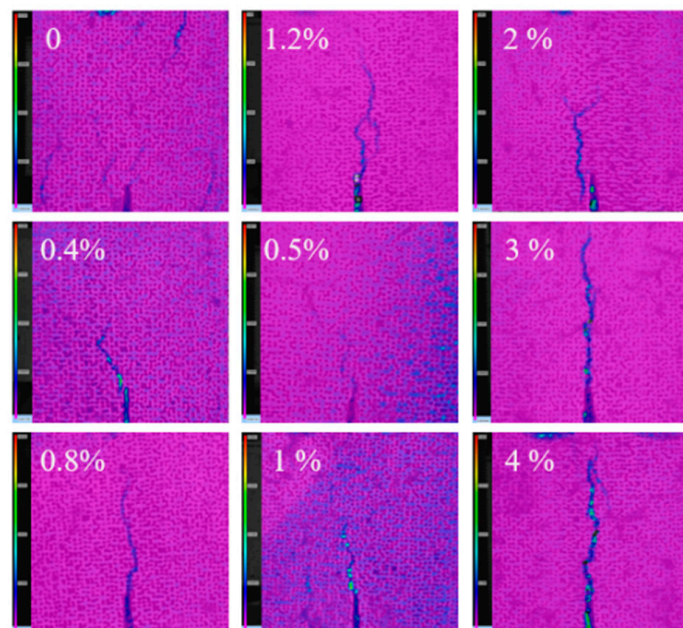


Figure 7. Strain cloud images at different RTPF contents.

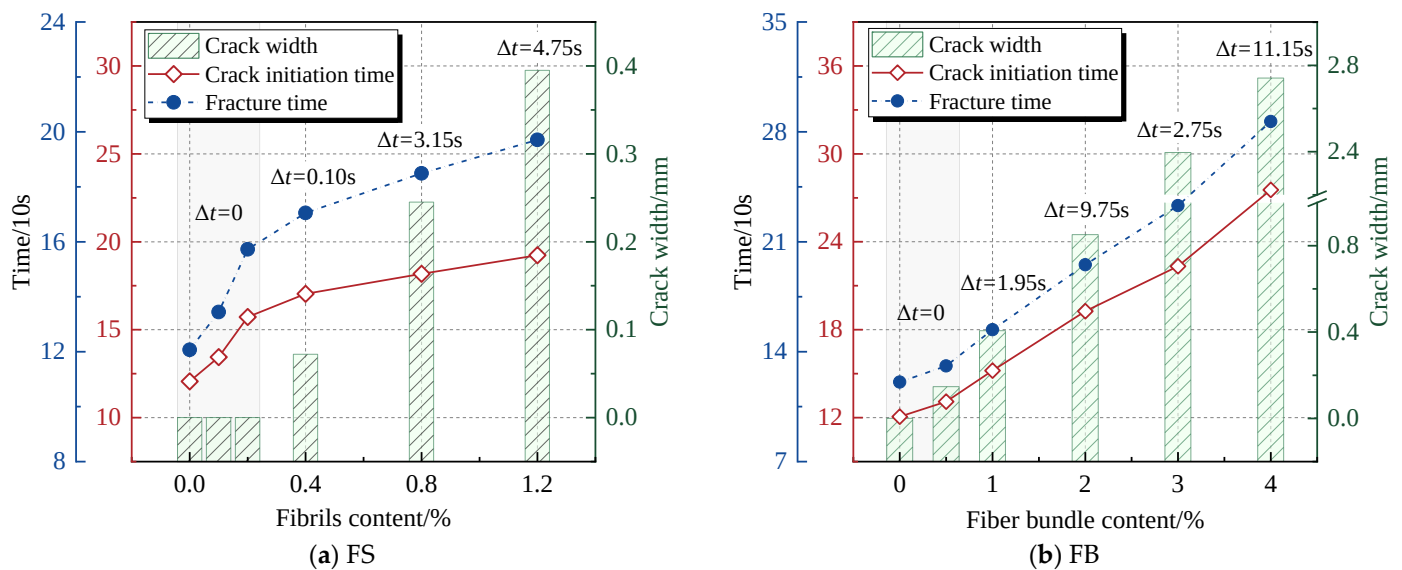


Figure 8. Fracture time and crack width.

3.2. Fracture Parameters Analysis

3.2.1. Flexural Strength

Fracture parameters are quantitative analysis indicators of fracture performance. The flexural strength, f_f , represents the maximum stress of the material before fracture under bending load, reflecting the strength limit of RTPF cement-stabilized soil under uniform force, which can be calculated according to BS EN 14651 [34]:

$$f_f = \frac{3SP_{\max}}{2B(H - a_0)^2} \quad (1)$$

where S is the span length between two supports (mm), $P_{\max}$ is the peak load in load–CMOD curves (kN), B is the specimen width (mm), H is the specimen height (mm), and a_0 is the prefabricated crack height (mm).

The strength gain ratio, δ (Equation (2)), was adopted to represent the flexural strength gain rate caused by the increase in RTPF content.

$$\delta = \frac{f_{f(i+1)} - f_{f(i)}}{f_{f(i)}} \times 100\% \quad (2)$$

It can be seen from Figure 9 that RTPF significantly enhances the flexural strength of cement-stabilized soils. FS and FB increase the flexural strength from 0.77 MPa to 1.25 MPa and 3.01 MPa, respectively. Previous studies have reported that PET, carbon, jute, and PVA fibers increase the flexural strength of stabilized soils by 80%, 31.5%, 187%, and 181%, respectively [9,37,38]. The enhancement achieved by FS is comparable to that of PET fiber, while the increase resulting from FB substantially exceeds most reported values, demonstrating the notable reinforcing efficiency of RTPF. RTPF inhibits the initiation and development of micro-cracks inside cement-stabilized soil through the fiber–matrix interface bonding effect and the three-dimensional network bridging effect. The enhancing effect is positively correlated with RTPF content, ω . The variation trend of flexural strength with the increase in RTPF content is described by the power function, as shown in Equations (3) and (4). The solid lines in Figure 9 represent the fitted curves, and the dashed lines indicate the 95% confidence bands. The f_f – ω fitting function index 0.875 and the coefficient 0.699 of FB are both higher than the 0.464 and 0.758 of FS, indicating that the content of FB has a stronger correlation with flexural strength. The strength gain rate of

RTPF initially increases and then decreases. The improvement effect of the increase in FS on the flexural strength gradually tends to saturation after ω_{FS} higher than 0.4% are reached, with δ_{FS} ranging from 8.45% to 6.59%. However, δ_{FB} decreases when the content of FB exceeds 1%, but is still higher than 10%. The stripy fibers in FB form a skeletal framework for cement-stabilized soil. The multi-scale stress transmission mechanism enabled FB to maintain a relatively superior performance regulation effect, even at a high content.

$$f_{f(FB)} = 0.875\omega_{FB}^{0.717} + 0.699 \quad (R^2 = 0.954) \quad (3)$$

$$f_{f(FS)} = 0.464\omega_{FS}^{0.484} + 0.758 \quad (R^2 = 0.957) \quad (4)$$

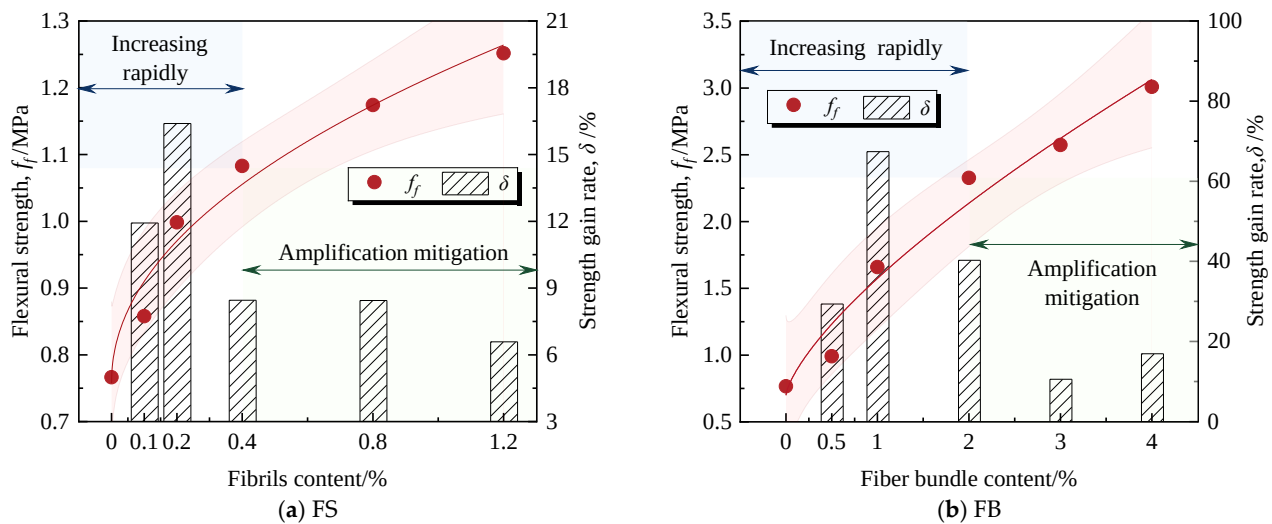


Figure 9. Influence of RTPF on flexural strength.

3.2.2. Double-K Fracture Toughness

Fracture toughness, K , is used to evaluate the failure threshold of RTPF cement-stabilized soil under cracked defect conditions. The unstable fracture toughness, K_{IC}^{un} , is composed of the inherent initiation fracture toughness of the material in the pre-notched tip region, K_{IC}^{ini} , and the cohesive fracture toughness determined by the cohesive force along the fracture process zone, K_{IC}^c [39]. The fracture toughness can be calculated according to the Norm for Fracture Test of Hydraulic Concrete DL/T 5332-2005 [40] and the methods of references [41,42], as shown in Equations (5)–(8):

$$K_{IC}^{un} = K_{IC}^{ini} + K_{IC}^c \quad (5)$$

$$K_{IC} = \frac{3PS \times 10^{-3}}{2BH^2} \sqrt{H} k_{(\beta)}(\alpha) \quad (6)$$

$$K_{IC}^{ini} = \frac{3P_{ini}S \times 10^{-3}}{2BH^2} \sqrt{H} k_{(\beta)}(\alpha_0) \quad (7)$$

$$K_{IC}^{un} = \frac{3P_{max}S \times 10^{-3}}{2BH^2} \sqrt{H} k_{(\beta)}(\alpha_c) \quad (8)$$

where α is the crack–height ratio, $\alpha = a/H$, $\alpha_0 = a_0/H$, $\alpha_c = a_c/H$, a is the crack height at the midspan of the specimen, a_c is the effective crack height, β is the span–depth ratio, $\beta = S/H$, and $k_{\beta}(\alpha)$ represents the functional relationship between α and β .

Figure 10 reveals a nonlinear strengthening effect of RTPF on the fracture toughness of cement-stabilized soils, where the double-K fracture parameters increase with the increase in RTPF content but exhibit progressively diminishing growth rates. At a 0.2% FS content,

K_{Ic}^{ini} surges from $0.05 \text{ MPa}\cdot\text{m}^{1/2}$ to $0.11 \text{ MPa}\cdot\text{m}^{1/2}$, with a growth rate of 100%. However, increasing FS content elevation leads to marginal diminution of fiber-reinforcement efficiency. K_{Ic}^{ini} increases linearly with the increase in FB content up to 3%, but shows a diminishing increase at higher fiber contents, with K_{Ic}^{ini} stabilizing at $0.28\text{--}0.30 \text{ MPa}\cdot\text{m}^{1/2}$. Owing to the relatively small deformation prior to specimen cracking, the strength of the cement-stabilized matrix and particle interlocking are the primary factors governing crack initiation. This contrasting behavior arises from their distinct controlling mechanisms. Crack initiation is governed by pre-existing defects within the cementitious matrix, which are not substantially altered by fiber addition; thus, the crack initiation load reaches a saturation plateau. In contrast, unstable fracturing is controlled by the fiber bridging capacity. This capacity continues to improve with increasing fiber content via frictional fiber pull-out and energy dissipation, resulting in a sustained rise in fracture resistance.

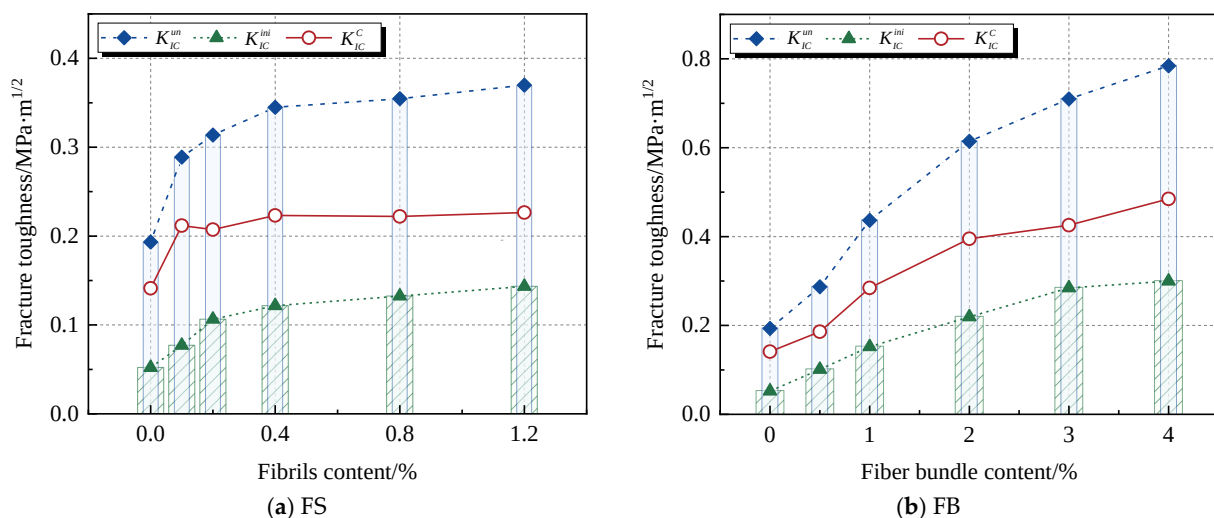


Figure 10. Influence of RTPF on double-K fracture toughness.

FS and FB increase K_{Ic}^{un} from $0.19 \text{ MPa}\cdot\text{m}^{1/2}$ to $0.37 \text{ MPa}\cdot\text{m}^{1/2}$ and $0.78 \text{ MPa}\cdot\text{m}^{1/2}$, respectively. K_{Ic}^{un} increases significantly with a FS content of 0.1–0.4%, reaching 93.25% of the maximum value. Adding FB with a content of 0.5–4% leads to a continuous increase in K_{Ic}^{un} at a rate of $0.07\text{--}0.15 \text{ MPa}\cdot\text{m}^{1/2}$. The trend of K_{Ic}^C varying with FB content is consistent with that of K_{Ic}^{un} , linearly increasing from $0.14 \text{ MPa}\cdot\text{m}^{1/2}$ to $0.49 \text{ MPa}\cdot\text{m}^{1/2}$ at a near-constant rate. The incorporation of FS increases K_{Ic}^C to $0.21\text{--}0.23 \text{ MPa}\cdot\text{m}^{1/2}$, and the variation range of K_{Ic}^C is relatively small, indicating that K_{Ic}^C exhibits low sensitivity to FS content. Previous studies reported that the initiation fracture toughness of PVA and jute-fiber-reinforced cement-stabilized soil is 0.421 and $0.372 \text{ MPa}\cdot\text{m}^{1/2}$ [38], respectively, and that of rice-straw-fiber-reinforced-lime-stabilized soil is $0.063 \text{ MPa}\cdot\text{m}^{1/2}$ [12]. This indicates that RTPF achieves fracture toughness enhancement comparable to, or even better than, that of conventional fibers. During the crack propagation and unstable fracture stages, RTPF anchors the matrix at both ends of the crack and absorbs energy through the bond–slip mechanism, thus enabling the fiber bridging effect to be fully exerted. Increased RTPF content heightened the fiber density along the crack paths. The stripy fibers in FB form a continuous reinforcement phase, enhancing the stress field intensity near the crack tip. Consequently, a greater external load is required for crack advancement, manifesting as an increase in unstable fracture toughness. Conversely, FS are constrained by size effects and fail to dissipate energy in millimeter-scale cracks. Moreover, when FS content reaches the critical threshold, the fiber spacing decreases, the interfacial stress overlaps, and the inhibitory effect on microcracks saturates.

3.2.3. Fracture Energy

Fracture energy, G_f , represents the energy consumed per unit area during the fracture process of RTPF cement-stabilized soil, reflecting the nonlinear energy absorption characteristics of ductile fracture and serving as the basis for the damage tolerance design of engineering structures. G_f is calculated through Equation (9) [43]:

$$G_f = \frac{W}{A_{lig}} = \frac{W_1 + W_2}{A_{lig}} = \frac{\int_0^{\delta_{max}} P(\delta) d\delta + mg\delta_{max}}{B(H - a_0)} \quad (9)$$

where W_1 is the total work done by the external load (N·mm), W_2 is the total work done by specimen self-weight (N·mm), A_{lig} is the fracture surface area (mm²), m is the specimen mass between support points (kg), g is gravitational acceleration (m/s²), δ is the specimen displacement during loading (mm), and CMOD = 100 μ m was taken as the fracture criterion.

Enhancement efficiency, η , is defined to represent the increase in fracture energy caused by each additional unit of RTPF, and is calculated by Equation (10):

$$\eta = \frac{(G_{f(i+1)} - G_{f(i)})/G_{f(i)}}{\omega_{i+1} - \omega_i} \times 100\% \quad (10)$$

Based on Figure 11, it can be stated that FS and FB increase the fracture energy of cement-stabilized soils from 11.51 N·m⁻¹ to 17.11 N·m⁻¹ and 37.76 N·m⁻¹, representing gains of 49% and 228%, respectively. The enhancement efficiency of RTPF decreases with the increase in FS content, while it first increases and then decreases with the increase in FB. When FS content rises from 0 to 0.2%, η_{FS} is 108.76–110.85%, while η_{FS} decreases to 6.72% as content increases from 0.8% to 1.2%. η_{FB} attains 155.03% at 1% content of FB, followed by a gradual decline to 5.43% as the content increases further. The resistance provided by the mechanical interlocking effect of FS enhances the energy dissipation during the micro-crack propagation process, thereby increasing the local toughness. In contrast, the dominant failure mode for stripy fibers in FB is fiber–matrix de-bonding and pull-out (Figure 12), where the frictional resistance governs the bridging mechanism. Simultaneously, SEM images in Figure 5 reveal that rubber particles are observed to adhere to the fiber surfaces. These particles induce micro-elastic deformation under applied stress [44], providing an additional energy dissipation mechanism that contributes to the retardation of subcritical crack growth.

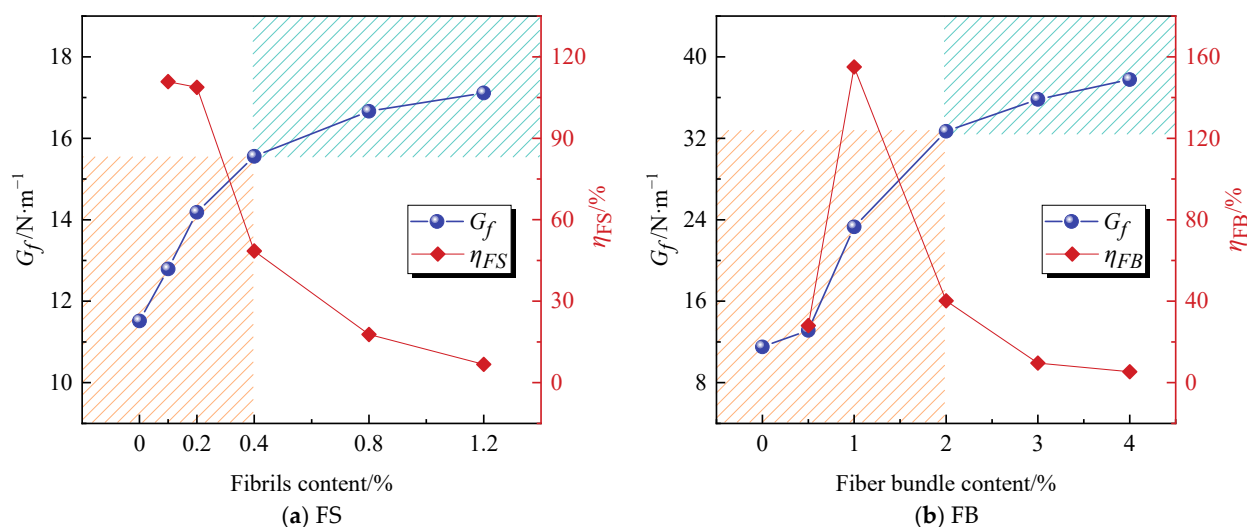


Figure 11. Influence of RTPF on fracture energy and fiber reinforcement efficiency.



Figure 12. Fiber pull-out morphology on fracture surfaces.

3.3. RTPF Distribution and Fracture Parameters Calculation Method

3.3.1. Distribution and Orientation Characteristics of RTPF

The distribution of FB and FS can be observed through CT and SEM images, respectively (Figure 13). RTPF is relatively uniformly distributed within the cement-stabilized soil. After the failure of the soil matrix, some RTPF were pulled out from the matrix, leaving voids, and the de-bonded fibers remained structurally intact. This indicates that the tensile strength of RTPF is significantly higher than that of the soil matrix, demonstrating the good toughness and load-bearing capacity of RTPF.

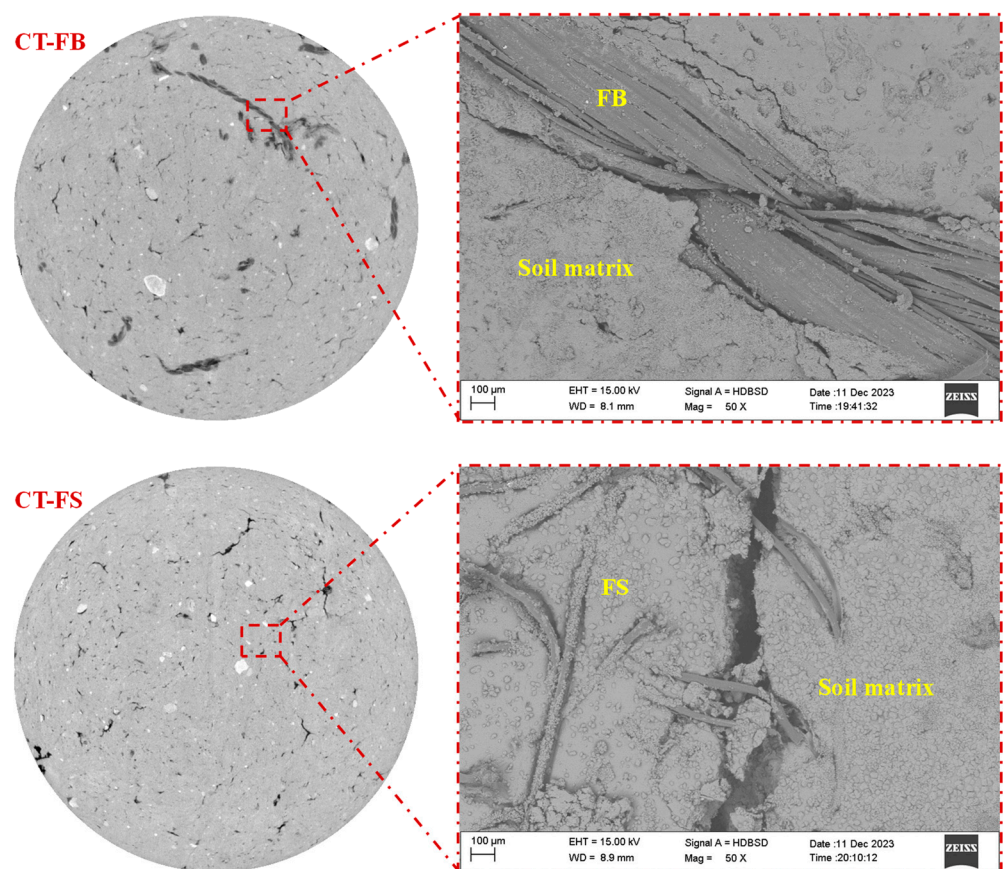


Figure 13. CT scan and SEM images.

Based on the Wilkinson stacked dot plot of FB length distribution (Figure 14), it can be observed that the increase in fiber content leads to a gradual increase in the dispersion of fiber length distribution. At a fiber content of 0.5%, the fiber lengths are primarily concentrated in the range of 7–12 mm, while at a 2% fiber content, the distribution range expands to 3–15 mm. With the fiber content increasing to 2%, the count of short fibers increases significantly, resulting in a corresponding reduction in fiber spacing. Notably, as the fiber content increases, the total count of fibers identified in the CT model decreases, from 192 at 0.5% to 169 at 2%, indicating the occurrence of fiber overlapping and bundling. This is confirmed by CT slice observations, which reveal more frequent fiber intersections within the same planes. The reduction in counted fibers can be attributed to the threshold segmentation algorithm, which cannot distinguish closely contacting or intersecting fibers in three-dimensional space and thus identifies them as single connected domains. The maximum measured length of 50 randomly selected FB is 29.6 mm. Therefore, fibers exceeding 30 mm in the CT-reconstructed model were classified as overlapping fibers. With the increase in fiber content, the count of longer fibers rises noticeably, and the proportion of overlapping fibers increases from 3.14% to 6.47%. These findings demonstrate that higher fiber content increases the spatial density of fibers, enhancing fiber–fiber interactions and promoting mechanical interlocking and contact.

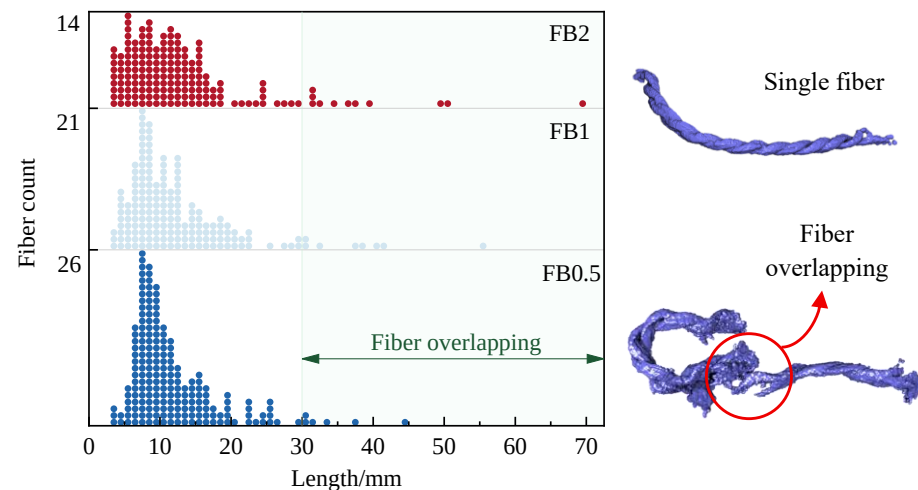


Figure 14. Length distribution of FB and diagram of fiber overlapping.

The distribution coefficient, α , and the orientation index, η_θ , were employed to quantitatively evaluate the uniform dispersion of RTPF and the average orientation on the cross-section, respectively, as described in Equations (11)–(13) [26,45]:

$$\alpha = \exp \left[-\sqrt{\frac{\sum (\frac{X_i}{X_{\text{average}}} - 1)^2}{n}} \right] \quad (11)$$

$$\eta_\theta = \frac{1}{X_i} \sum_{n=1}^{X_i} \cos \theta_n \quad (0 \leq \theta \leq 90^\circ) \quad (12)$$

$$\cos \theta = d_f / l \quad (13)$$

where X_i is the fiber count in the i image, X_{average} is the average fiber count over n images, and n is the total image count. The value of α ranges from 0 to 1, and a value closer to 1 indicates a more uniform fiber distribution across the cross-section. Additionally, θ_n is the angle between the axial direction of the n fiber and the direction normal to the cutting plane, d_f is fiber diameter, and l is the length of the fiber major axis in the image.

The distribution and orientation of FB in soil exhibit typical normal distribution characteristics, and the probability density distribution is shown in Figure 15. With an increase in fiber content, the fiber count on the cross-section significantly increases, and the fiber spacing decreases, thereby enhancing the tensile resistance provided by the fibers. When the fiber content is 0.5%, 1%, and 2%, α of FB is 0.72, 0.79, and 0.81, respectively, while the η_θ is 0.40, 0.34, and 0.33. Evidently, an increase in fiber content leads to a higher α and a reduction in η_θ . The parameter changes are more pronounced when the fiber content increases from 0.5% to 1%, whereas the changes become less significant when the content increases from 1% to 2%. This trend is consistent with the macroscopic mechanical behavior, where the increase in flexural strength diminishes at higher fiber contents, suggesting a gradual saturation of the fiber reinforcement effect under high-fiber-content conditions. Further measurements and calculations based on SEM images reveal that the α and η_θ of FS are 0.65 and 0.24, respectively. The cement-stabilized soil matrix is heterogeneous, leading to multi-directional crack growth. A reduction in η_θ indicates a more random fiber orientation, which allows fibers to bridge potential crack planes in multiple directions. It also facilitates a three-dimensional fiber network for multi-directional stress transfer, thereby improving overall fracture resistance. The crimped topological structure of FS results in a multi-axial orientation distribution, with a higher degree of orientation dispersion compared to that of FB, thereby providing superior inhibition of multi-directional propagating microcracks. In contrast, the FB, characterized as independent and less deformable single entities, exhibit better dispersion uniformity within the matrix than do the highly compliant FS.

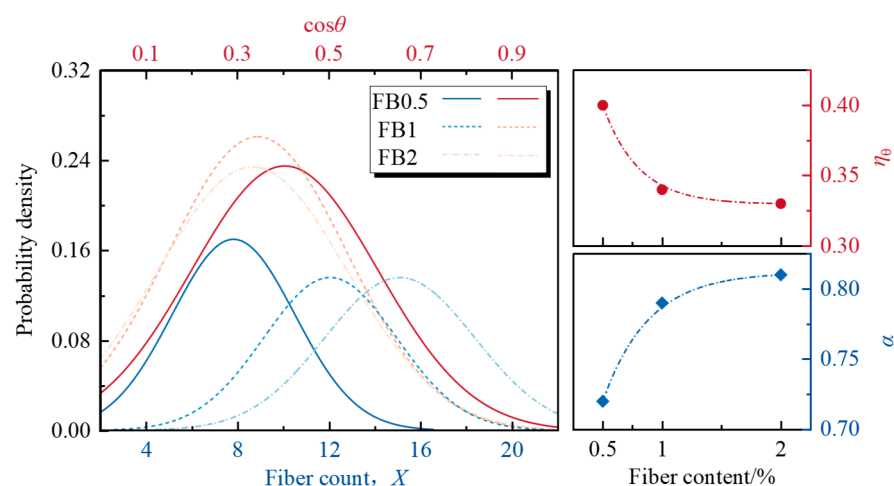


Figure 15. Distribution and orientation index of FB.

3.3.2. Calculation Method for Fracture Parameters

The reinforcing effect of RTPF is significantly influenced by its geometric dimensions, and its spatial distribution within the matrix is closely related to the fiber content. Therefore, to comprehensively characterize the combined influence of fiber content, ω , diameter, d , and length, l , the fiber reinforcing index, RI , was adopted to quantify the reinforcing efficiency of RTPF. Among these parameters, the length of FB is taken as the mean value measured from CT images, which is 18.54 mm. Other dimensions are determined from SEM images. The diameter of FB is 1.07 mm, and the diameter and length of FS are 0.03 mm and 8.12 mm, respectively.

$$RI = \omega \times l/d \quad (14)$$

Regression analysis was conducted on the test results under the conditions of 0, 0.1%, 0.2%, 0.4% and 1.2% for FS and 0, 0.5%, 1%, 2%, and 4% for FB. On this basis, a

calculation method for the fracture parameters of RTPF cement-stabilized soil, considering the influence of RI , was established. The results are shown in Equations (15)–(18).

$$K_{IC(FS)}^{ini} = 0.06 + 0.08RI_{FS} - 0.02RI_{FS}^2 \quad (R^2 = 0.947) \quad (15)$$

$$K_{IC(FS)}^{un} = 0.22 + 0.17RI_{FS} - 0.04RI_{FS}^2 \quad (R^2 = 0.907) \quad (16)$$

$$K_{IC(FB)}^{ini} = 0.05 + 0.61RI_{FB} - 0.38RI_{FB}^2 \quad (R^2 = 0.998) \quad (17)$$

$$K_{IC(FB)}^{un} = 0.18 + 1.61RI_{FB} - 1.06RI_{FB}^2 \quad (R^2 = 0.992) \quad (18)$$

To verify the applicability of the above model, test data under the conditions of 0.8% FS and 3% FB were selected as the validation set, and these were not included in the regression analysis. The relative error between the theoretical values and the measured values is less than 12.66%. As shown in Figure 16, the theoretical values are closely distributed along the 45° reference line, indicating good agreement with the experimental measurements. The error analysis indicates that the ratio of the predicted values to the measured values of all data points ranges from 0.92 to 1.07, with the mean absolute error controlled within 2.6%, and the normalized root mean square error is lower than 0.125. All error metrics remain at a low level, indicating that the proposed RI -based calculation method reliably estimates fracture performance within the tested range (0–1.2% FS or 0–4% FB). This empirical relationship is intended for trend description within this range and should not be extrapolated beyond the current experimental conditions.

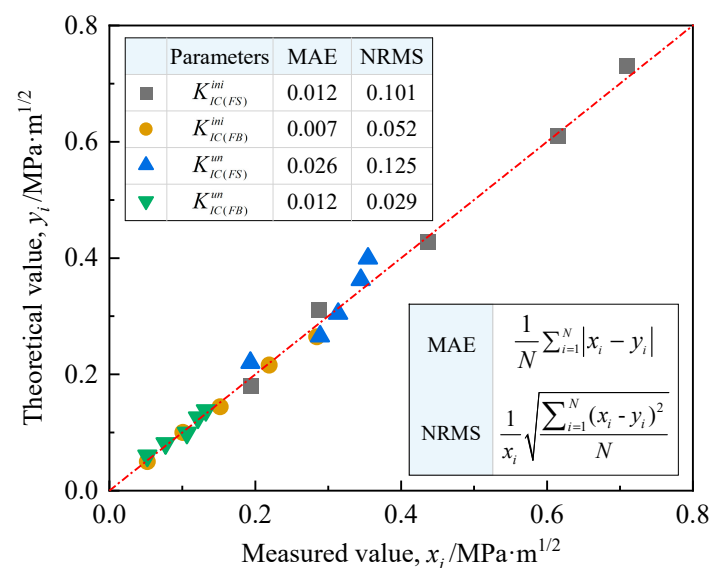


Figure 16. Comparison between theoretical values and measured values.

4. Conclusions

Based on three-point bending tests integrated with the DIC system, this study investigates the fracture behavior of RTPF cement-stabilized soil. The distribution and orientation of RTPF within the soil matrix were further analyzed through CT scan and SEM analysis. The conclusions are as follows:

(1) RTPF effectively delays crack initiation and promotes a more ductile fracture process, indicating its potential to mitigate brittle failure in cement-stabilized soils. FS primarily enhance resistance to microcrack initiation through microstructural refinement, whereas FB provide superior post-cracking reinforcement through crack bridging and pull-out mechanisms.

(2) RTPF increases the flexural strength and has a nonlinear strengthening effect on the fracture toughness and fracture energy of cement-stabilized soils. Optimal reinforcing efficiency is obtained at 0.2–0.4% FS and 1–2% FB.

(3) Fiber distribution exhibits a higher distribution coefficient and a lower orientation index, which saturate with increasing fiber content. Improved fiber dispersion and multi-directional orientation enhance the effectiveness of crack-bridging mechanisms and contribute to improved fracture performance.

(4) Under the experimental conditions of 15% cement content, 28 day curing age, 0–1.2% FS, and 0–4% FB, fracture toughness can be reasonably estimated using the proposed fiber-reinforcing parameter.

RTPF provides an effective and sustainable reinforcement strategy for cement-stabilized soils by improving crack resistance, fracture toughness, and energy absorption capacity, thereby significantly enhancing the durability and crack resistance of cement-stabilized subgrade materials under repeated traffic loading. FB exhibit superior reinforcement efficiency compared with that of FS. CT-based distribution analysis demonstrates that fiber spatial characteristics play a key role in governing fracture behavior. For practical applications, the recommended RTPF contents are 0.4% FS and 1% FB, which can be achieved using conventional mixing equipment and are feasible for field implementation. As a recycled material, RTPF contributes to waste tire valorization while enhancing the mechanical performance of pavement and geotechnical structures.

However, the proposed calculation method for fracture parameters was developed for a specific saline soil and cement content; therefore, further validation under different soil types, curing conditions, and field environments is necessary. Future studies should investigate the long-term durability, cyclic loading performance, and field applicability of RTPF-reinforced cement-stabilized soils.

Author Contributions: C.S. wrote the original manuscript and visualized the data. F.W. acquired the funding and reviewed and supervised the study. T.K. conceptualized the methodology. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Central Guidance on Local Science and Technology Development Fund of Liaoning Province, China, under grant No. 2023JH6/100100018; the open research fund of Shenyang Key Laboratory of Low-Carbon Transportation Construction, Maintenance and Operation under grant No. LJ232410153005; and the Liaoning Provincial Department of Education Fund under grant no. JYTMS2023157.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data supporting the findings of this study are available within the paper.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

CMOD	Crack mouth opening displacement
FB	Fiber bundles
FS	Fibrils
RTPF	Recycled tire polymeric fiber

References

- Barman, D.; Dash, S.K. Stabilization of expansive soils using chemical additives: A review. *J. Rock. Mech. Geotech. Eng.* **2022**, *14*, 1319–1342. [\[CrossRef\]](#)
- Ghader, P.; Ranjbar, N. Clayey soil stabilization using geopolymer and portland cement. *Constr. Build. Mater.* **2018**, *188*, 361–371. [\[CrossRef\]](#)
- Wei, L.; Chai, S.; Guo, Q.L.; Wang, P.; Li, F. Mechanical properties and stabilizing mechanism of stabilized saline soils with four stabilizers. *Bull. Eng. Geol. Environ.* **2020**, *79*, 5341–5354. [\[CrossRef\]](#)
- Lei, S.; Jia, X.; Zhao, C.; Shao, M. A review of saline-alkali soil improvements in China: Efforts and their impacts on soil properties. *Agric. Water Manag.* **2025**, *317*, 109617. [\[CrossRef\]](#)
- Erarslan, N.; Aliha, M.R.M. Fracture and damage analysis of cement-stabilized fine and coarse grain soils under static and cyclic loading using chevron-notched scb specimen. *Fatigue Fract. Eng. Mater. Struct.* **2025**, *48*, 2708–2724. [\[CrossRef\]](#)
- Arto, I.; Gallego, R.; Cifuentes, H.; Puertas, E.; Gutiérrez-Carrillo, M.L. Fracture behavior of rammed earth in historic buildings. *Constr. Build. Mater.* **2021**, *289*, 123167. [\[CrossRef\]](#)
- Barani, O.R.; Barfar, P. Effect of xanthan gum biopolymer on fracture properties of clay. *J. Mater. Civ. Eng.* **2021**, *33*, 04020426. [\[CrossRef\]](#)
- Zhang, J.; Teixeira, J.E.S.L.; Little, D.N.; Kim, Y.-R. Prediction of fatigue crack growth behavior of chemically stabilized materials using simple monotonic fracture test integrated with computational cohesive zone modeling. *Compos. Part B Eng.* **2020**, *200*, 108367. [\[CrossRef\]](#)
- Hernández, C.; Botero, E.; Beltrán, G. The study of fracture mechanics of PET fiber-reinforced soils based on flexural tests and imaging techniques. *Transp. Geotech.* **2025**, *51*, 101486. [\[CrossRef\]](#)
- Wei, L.; Chai, S.; Xue, M.; Wang, P.; Li, F. Structural damage and shear performance degradation of fiber-lime-soil under freeze-thaw cycling. *Geotext. Geomembr.* **2022**, *50*, 845–857. [\[CrossRef\]](#)
- Wang, Y.; Hu, X.; Pei, Q.; Cui, X.; Qi, P.; Xue, Z. Improvement of mechanical behavior of cemented soil reinforced with waste sisal fibers: An optimal selection and modification research. *Case Stud. Constr. Mater.* **2024**, *21*, e03515. [\[CrossRef\]](#)
- Liu, S.; Wang, Y.; Tian, H.; Sun, S.; Zhang, L.; Zhou, R.; Han, C. Mechanical properties and toughening effect of rice straw fiber-reinforced soil. *Case Stud. Constr. Mater.* **2024**, *21*, e03511. [\[CrossRef\]](#)
- Xiao, Y.; Tong, L.; Che, H.; Guo, Q.; Pan, H. Experimental studies on compressive and tensile strength of cement-stabilized soil reinforced with rice husks and polypropylene fibers. *Constr. Build. Mater.* **2022**, *344*, 128242. [\[CrossRef\]](#)
- Zafar, T.; Ansari, M.A.; Husain, A. Soil stabilization by reinforcing natural and synthetic fibers—A state of the art review. *Mater. Today Proc.* **2023**. [\[CrossRef\]](#)
- Baričević, A.; Jelčić Rukavina, M.; Pezer, M.; Štirmer, N. Influence of recycled tire polymer fibers on concrete properties. *Cem. Concr. Compos.* **2018**, *91*, 29–41. [\[CrossRef\]](#)
- Chen, M.; Jiang, R.; Zhang, T.; Zhong, H.; Zhang, M. Development of green engineered cementitious composites with acceptable dynamic split resistance utilising recycled polymer fibres. *Constr. Build. Mater.* **2024**, *415*, 134979. [\[CrossRef\]](#)
- Serdar, M.; Baričević, A.; Jelčić Rukavina, M.; Pezer, M.; Bjegović, D.; Štirmer, N. Shrinkage behaviour of fibre reinforced concrete with recycled tyre polymer fibres. *Int. J. Polym. Sci.* **2015**, *2015*, 145918. [\[CrossRef\]](#)
- Onuaguluchi, O.; Banthia, N. Scrap tire steel fiber as a substitute for commercial steel fiber in cement mortar: Engineering properties and cost-benefit analyses. *Resour. Conserv. Recycl.* **2018**, *134*, 248–256. [\[CrossRef\]](#)
- Abbaspour, M.; Aflaki, E.; Nejad, F.M. Reuse of waste tire textile fibers as soil reinforcement. *J. Clean. Prod.* **2019**, *207*, 1059–1071. [\[CrossRef\]](#)
- Valipour, M.; Shourijeh, P.T.; Mohammadinia, A. Application of recycled tire polymer fibers and glass fibers for clay reinforcement. *Transp. Geotech.* **2021**, *27*, 100474. [\[CrossRef\]](#)
- Sun, C.; Wang, F.; Zhao, H.; Chen, H. Shear performance of recycled tire polymer fiber reinforced cement stabilized carbonate saline soil. *J. Build. Mater.* **2025**, *28*, 799–807.
- Wu, Z.; Khayat, K.H.; Shi, C. Effect of nano-sio₂ particles and curing time on development of fiber-matrix bond properties and microstructure of ultra-high strength concrete. *Cem. Concr. Res.* **2017**, *95*, 247–256. [\[CrossRef\]](#)
- Ren, G.; Yao, B.; Huang, H.; Gao, X. Influence of sisal fibers on the mechanical performance of ultra-high performance concretes. *Constr. Build. Mater.* **2021**, *286*, 122958. [\[CrossRef\]](#)
- Ding, C.; Guo, L.; Chen, B. Orientation distribution of polyvinyl alcohol fibers and its influence on bridging capacity and mechanical performances for high ductility cementitious composites. *Constr. Build. Mater.* **2020**, *247*, 118491. [\[CrossRef\]](#)
- Huang, H.; Gao, X.; Teng, L. Fiber alignment and its effect on mechanical properties of UHPC: An overview. *Constr. Build. Mater.* **2021**, *296*, 123741. [\[CrossRef\]](#)
- Abrishambaf, A.; Pimentel, M.; Nunes, S. Influence of fibre orientation on the tensile behaviour of ultra-high performance fibre reinforced cementitious composites. *Cem. Concr. Res.* **2017**, *97*, 28–40. [\[CrossRef\]](#)

27. Qing, L.; Li, Y.; Wang, X.; Yu, K.; Mu, R. Investigation of mixed-mode fracture of aligned steel fibre reinforced cementitious composites. *Int. J. Fract.* **2021**, *228*, 159–178. [\[CrossRef\]](#)
28. Ding, C.; Guo, L.; Chen, B. An optimum polyvinyl alcohol fiber length for reinforced high ductility cementitious composites based on theoretical and experimental analyses. *Constr. Build. Mater.* **2020**, *259*, 119824. [\[CrossRef\]](#)
29. Liu, H.; Duan, G.; Wang, F.; Zhang, J.; Zhou, Y.; Feng, Y.; Zhang, K. Investigation on mechanical behaviors of self-compacting concrete containing reclaimed asphalt pavement. *Constr. Build. Mater.* **2022**, *346*, 128421. [\[CrossRef\]](#)
30. Skarżyński, Ł.; Suchorzewski, J. Mechanical and fracture properties of concrete reinforced with recycled and industrial steel fibers using digital image correlation technique and X-ray micro computed tomography. *Constr. Build. Mater.* **2018**, *183*, 283–299. [\[CrossRef\]](#)
31. ASTM D2487-17; Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International: West Conshohocken, PA, USA, 2011.
32. Wang, F.; Sun, C.; Zhao, H.; Liu, Y. Effect of waste tire rubber crumb on impermeability of cement-stabilized soil. *Environ. Technol.* **2024**, *45*, 4243–4254. [\[PubMed\]](#)
33. JGJ/T 233-2011; Specification for Mix Proportion Design of Cement Soil. China Architecture & Building Press: Beijing, China, 2011.
34. EN 14651:2005; Test Method for Metallic Fibre Concrete-Measuring the Flexural Tensile Strength (Limit of Proportionality (LOP), Residual). British Standards Institution: London, UK, 2008.
35. Li, V.C.; Wang, Y.; Backer, S. A micromechanical model of tension-softening and bridging toughening of short random fiber reinforced brittle matrix composites. *J. Mech. Phys. Solids* **1991**, *39*, 607–625. [\[CrossRef\]](#)
36. Xue, G.; Wu, J.; Xu, S.; Liu, J.; Dong, W. Study on the fracture mechanical properties of steel slag fine aggregate concrete. *Mater. Rep.* **2025**, *39*, 126–132.
37. Wang, L.; Shao, G. Test research on flexural strength of soil-cement reinforced with carbon fibers. *Case Stud. Constr. Mater.* **2023**, *19*, e02280. [\[CrossRef\]](#)
38. Yao, X.; Liu, K.; Huang, G.; Wang, M.; Dong, X. Mechanical properties and durability of deep soil–cement column reinforced by jute and pva fiber. *J. Mater. Civ. Eng.* **2021**, *33*, 4333–4338. [\[CrossRef\]](#)
39. Xu, S.; Reinhardt, H.W. Determination of double-K criterion for crack propagation in quasi-brittle fracture, Part II: Analytical evaluating and practical measuring methods for three-point bending notched beams. *Int. J. Fract.* **1999**, *98*, 151–177. [\[CrossRef\]](#)
40. DL/T 5332-2005; Norm for Fracture Test of Hydraulic Concrete. China Electric Power Press: Beijing, China, 2005.
41. Xiao, J.; Xu, J.; Luo, S.; Zhang, K.J.; Zhang, Q.T. Effect of sisal fiber on fracture performance of recycled aggregate concrete. *J. Build. Mater.* **2023**, *26*, 587–595. [\[CrossRef\]](#)
42. Wu, K.; Luo, S.; Zheng, J. Fracture propertie analysis of recycled aggregate concrete based on digital image correlation technique. *Eng. Mech.* **2022**, *39*, 147–157.
43. Xu, S.; Xiong, S.; Li, H.; Lu, Y. Quantitative characterization and mechanism analysis on thickness-dependent size effect of concrete fracture. *China Civ. Eng. J.* **2017**, *50*, 57–71.
44. Wang, F.; Ping, X.; Zhou, J.; Kang, T. Effects of crumb rubber on the frost resistance of cement-soil. *Constr. Build. Mater.* **2019**, *223*, 120–132. [\[CrossRef\]](#)
45. Xu, S.; Feng, Y.; Liu, J.; Zeng, Q. Micro indentation fracture of cement paste assessed by energy-based method: The method improvement and affecting factors. *Constr. Build. Mater.* **2020**, *231*, 117136. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.