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Effects of Fiber Length and Content on the Enhancement of Spray-Applied Substrate in Soil Spray Seeding

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Abstract: (1) Background: Soil stability is essential for hydroseeding applications, particularly in erosion-prone areas. This study examines the effects of coir fiber reinforcement on soil properties and optimizes fiber length and content for improved performance. (2) Methods: Triaxial tests, soil physical measurements, and cracking experiments were conducted on sandy and silty soils using five fiber lengths (1–5 cm) and three fiber contents (0.2–0.6%). Principal component analysis (PCA) and Response Surface Methodology (RSM) were applied for optimization. (3) Results: The results show that coir fiber increases soil cohesion, shear strength, porosity, and permeability while reducing bulk density. The best reinforcement occurred at a 3–4 cm fiber length and 0.4–0.6% content, enhancing both the shear strength and crack resistance. Correlation analysis indicated a positive relationship between porosity and shear strength and a negative correlation between crack ratio and shear strength, confirming fiber reinforcement benefits. RSM analysis identified 3.051 cm + 4.07% as optimal for sandy soil and 3.376 cm + 0.456% for silty soil. (4) Conclusions: The optimal coir fiber combination significantly improves soil stability, providing theoretical support for optimizing spray substrates.

Keywords: soil spray seeding; spray substrate; coir fiber; fiber reinforcement; shear strength



Academic Editor: José Miguel Molina Martínez

Received: 15 March 2025

Revised: 21 April 2025

Accepted: 30 April 2025

Published: 28 May 2025

Citation: Qu, Y.; Wang, P.; Zhao, W.; Wang, L.; Liu, Y.; Yang, G.; Song, G. Effects of Fiber Length and Content on the Enhancement of Spray-Applied Substrate in Soil Spray Seeding. *Appl. Sci.* **2025**, *15*, 6075. <https://doi.org/10.3390/app15116075>

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1. Introduction

In recent years, the ecological restoration of slopes has become a research hotspot in resource conservation and soil and water conservation. Among various restoration techniques, hydroseeding has been widely applied in the rehabilitation of slopes along highways, railways, and mining areas due to its high construction efficiency and broad material applicability [1]. The core of hydroseeding lies in the establishment of a suitable substrate that facilitates seed germination under poor or even harsh environmental conditions while ensuring long-term slope stability. However, under the influence of rainfall erosion, wet–dry cycles, and wind erosion, conventional spray substrates often suffer from structural looseness, low erosion resistance, and severe shrinkage cracking, which significantly restrict the survival and long-term growth stability of vegetation on slopes [2].

To enhance the stability of spray substrates, researchers have proposed the concept of fiber reinforcement [3–5]. Compared to early synthetic fibers, such as polypropylene, natural plant fibers offer greater environmental benefits and renewability, while their degradation products can improve soil organic matter content [6,7]. Coir fiber, in particular, has attracted significant attention due to its high tensile strength, elastic modulus, and hygroscopicity, enabling it to form an effective three-dimensional network structure within

the soil [8,9]. This structure enhances interparticle friction and interlocking forces, significantly increasing soil cohesion and erosion resistance. Additionally, the anchoring effect of fibers mitigates the expansion and connectivity of shrinkage cracks, thereby delaying soil deterioration caused by moisture loss [10,11]. However, studies have indicated that an insufficient fiber content fails to establish an effective reinforcement network, while excessive or overly long fibers tend to agglomerate, resulting in localized weak zones in the soil [12,13]. Moreover, different soil textures, such as sandy soil, silty soil, and clayey soil, exhibit varied responses to fiber reinforcement. Sandy soil, due to its larger porosity, benefits from a more pronounced network effect, whereas silty and clayey soils rely more on fiber reinforcement to restrict crack expansion and improve the overall mechanical performance. Therefore, when determining the optimal fiber content and length, multiple factors, such as soil texture, moisture content, and fiber characteristics, must be considered to achieve a balance between soil stability and improved physical structure [14,15].

Based on the abovementioned considerations, this study employs coir fiber as a reinforcement material and examines its effects on the stability and structural improvement of spray substrates in sandy and silty soils. A series of triaxial shear tests, physical property measurements, and cracking tests were conducted to evaluate the influence of fiber length and content on soil performance. Principal component analysis (PCA) and Response Surface Methodology (RSM) were applied to identify the optimal fiber parameter combinations. The findings aim to provide a scientific basis for the rational design of fiber-enhanced spray substrates and contribute to the development of more stable and effective slope restoration techniques.

2. Materials and Methods

The experimental materials primarily included fibers, soil, organic matter, and adhesive.

2.1. Experimental Materials
2.1.1. Fiber Material

Coir fiber was selected, and its performance parameters are shown in Table 1.

Table 1. Performance parameters of coir fiber.

Average Fineness (μm)	Density (kg/m ³)	Elastic Modulus (GPa)	Tensile Strength (Mpa)	Ultimate Elongation (%)	Moisture Absorption (%)
100–450	1390–1520	3–6	100–225	12–51.4	130–180

2.1.2. Test Soil

Two types of soil were used in this study. Soil A was collected near the Chongli Toll Station, Zhangjiakou City, Hebei Province (40°57' N, 115°17' E), and Soil B was obtained from Dongcaoying Folk Village, Zhangjiakou City, Hebei Province (40°56' N, 115°21' E). After air-drying, both soils were sieved through a 2 mm mesh. The soil texture was determined using the specific gravity method, following the Kachinsky classification system [16], and classification was conducted according to the World Reference Base for Soil Resources [17]. Soil A was classified as sandy soil, while Soil B was classified as silty soil. The distribution of soil particle sizes is presented in Table 2.

Table 2. Particle size distribution of the test soil.

Particle Size Range (mm)					
	1–0.05	0.05–0.01	<0.01	0.01–0.001	<0.001
Soil-type A	51.8%	28.2%	20%	14%	6%
Soil-type B	40.8%	42.4%	16.8%	13.8%	3%

2.1.3. Organic Fertilizer

The organic fertilizer was purchased from Shijiazhuang Fengdi Fertilizer Co., Ltd. (Shijiazhuang, China), and its chemical properties and nutrient composition are shown in Table 3. The test methods of each index refer to HJ/T 166-2004 [18].

Table 3. Chemical properties and nutrients of organic fertilizers.

pH	EC (kg/m ³)	Total Phosphorus (GPa)	Total Potassium (MPa)	Organic Matter (%)
7.74	8331	3.883	2.32	53.8

2.1.4. Adhesive

The adhesive material used was polyacrylamide (PAM) with a molecular weight of 12,000, purchased from Jinzhou Qingjun Building Materials Co., Ltd. (Jinzhou, China).

2.2. Experimental Design

The experiment was designed with three variables: soil type, fiber length, and fiber content. Soil type was classified into two groups: Soil Type A and Soil Type B. Fiber length was set at five levels: 1 cm, 2 cm, 3 cm, 4 cm, and 5 cm. Fiber content was tested at four levels: 0% (control group without fiber, CK), 0.2%, 0.4%, and 0.6% (*w/w*). Additionally, the polyacrylamide (PAM) content was uniformly set at 0.4%. The experiment included a total of 32 treatments, each with three replicates, and involved triaxial shear tests, physical property tests, soil cracking tests, and microstructure analysis.

2.3. Indicators and Methods

2.3.1. Physical Properties Experiment

Bulk Density: Measured using the ring knife method.

Porosity: Includes capillary porosity, aeration porosity, and total porosity, determined using the ring knife method.

Saturated Hydraulic Conductivity: Measured using the permeameter method [19], calculated using the following equation:

$$K = (10 \times Q_n \times L) / (t_n \times S \times (h + L)) \quad (1)$$

In Equation (1):

- K: Saturated hydraulic conductivity (permeability coefficient), mm/min.
- Q_n : Water outflow during the *n*-th measurement, mL (or cm³).
- L: Soil layer thickness, cm.
- t_n : Time interval for each permeability measurement, min.
- S: Cross-sectional area of the permeameter, cm².
- h: Water layer thickness, cm.
- V: Permeation velocity, mm/min.

2.3.2. Triaxial Test

Sample Preparation

Sample preparation was conducted according to the Standard for Soil Test Methods (GB/T 50123-2019) [20]. For each treatment, 3 kg of air-dried soil was weighed and placed in a mixing basin. Polyacrylamide was added and mixed evenly. The soil was then leveled, and coir fibers were incorporated before transferring the mixture into a sealed bag. A spray bottle was used to evenly distribute a predetermined amount of water.

Based on the compaction test, the optimum moisture content corresponding to the maximum dry density was determined, and a moisture content of 12% was set for this

experiment. According to the SL237-1999 Standard [21] for the soil test, the soil samples were moisturized for 36 h before testing. During sample preparation, compaction was applied uniformly, with each sample being compacted in three layers with 25 blows per layer. After preparation, the soil columns were weighed to ensure uniform mass across treatments.

Test Equipment and Methods

The test was conducted using a TSZ-6A strain-controlled triaxial apparatus (Nanjing Soil Instrument Co., Ltd., Nanjing, China). The triaxial apparatus applied confining pressure (where normal stresses in the x and y directions were equal) and axial pressure (in the z direction) to induce shear failure in the specimens. The cohesion and internal friction angle of the samples were determined based on the Mohr–Coulomb theory.

The test was conducted following the SL237-1999 Standard for Soil Tests, using the unconsolidated undrained (UU) shear method. The concept of the root-containing (reinforcement) effect coefficient was introduced [14] to evaluate the impact of fiber reinforcement on soil strength, expressed by the following equation:

$$R\sigma = \frac{(\sigma_1 - \sigma_3)_{fr}}{(\sigma_1 - \sigma_3)_{fs}} \quad (2)$$

In Equation (2):

$R\sigma$: Root-containing (reinforcement) effect coefficient.

$(\sigma_1 - \sigma_3)_{fr}$: Deviatoric stress at failure for fiber-reinforced or root-containing soil.

$(\sigma_1 - \sigma_3)_{fs}$: Deviatoric stress at failure for unreinforced soil.

Interface fiber-quantity characteristics were analyzed by cutting the failed triaxial test specimens into two halves, exposing failure surfaces A and B. The number of fibers on each surface was counted separately. The total fiber count on surfaces A and B, the difference in fiber quantity between the two surfaces, and the interface dispersion coefficient were recorded. By analyzing the fiber quantity in quarter sections of each specimen, the fiber dispersion coefficient, α , in the soil was calculated using the following equation:

$$\alpha = e^{\theta(x)} \quad (3)$$

$$\theta(x) = \frac{\sqrt{\sum (x_i - \mu)^2}}{n\mu} \quad (4)$$

In Equations (3) and (4):

α represents the fiber dispersion coefficient; μ represents the average number of fibers in the sample; n represents the number of divided sections (sample count); and x represents the number of fibers contained in the divided section ($i = 1, 2, 3, 4$).

The dispersion coefficient reflects the distribution state of fibers within the soil. A dispersion coefficient closer to 1 indicates a more uniform fiber distribution.

Microstructural observation: A scanning electron microscope (SEM), model S-3400N, was used for microstructural analysis. The failed triaxial test specimens were cut into small pieces using a scalpel, mounted onto sample holders, processed, and then placed in the SEM for observation at magnifications of 50 $\times$ and 100 $\times$.

2.3.3. Soil Cracking Test

The indoor test was conducted to measure the crack area.

Indoor test: 50 g of soil was weighed according to the experimental treatment, along with the designated amounts of fiber and adhesive. Then, 20 mL of water was added, and the mixture was thoroughly blended before being placed in a Petri dish. The samples were

left to air-dry naturally for approximately 20 days. After drying, photographs were taken using a mobile phone at a fixed distance of 15 cm, with a resolution of 4032×3024 pixels.

Image preprocessing: The images were imported into a computer and processed using WEGO 2.0 software to geometrically correct the ruler coordinates, ensuring the image was restored to an actual orthogonal coordinate system. The crack images were then cropped to a uniform format using Photoshop (PS) 2021, saved in a .JPG format, and binarized to distinguish between crack and non-crack regions.

Crack area measurement: ImageJ 1.53c software was used to set a threshold and select the crack regions, extracting and calculating the crack area.

2.4. Data Processing and Analysis

The data were organized using Microsoft Excel. Variance analysis and multiple comparison analysis using Duncan's method were performed with IBM SPSS Statistics 26. Principal component analysis and graph plotting were conducted using Origin Pro 2022, while response surface analysis and visualization were carried out using Design Expert 13.

3. Results

This section is divided by subheadings. It provides a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that are drawn.

3.1. Effects of Fiber Length and Content on Soil Properties Under Two Soil Conditions

3.1.1. Physical Properties

As shown in Tables 4 and 5, the addition of fibers significantly increased the total porosity and aeration porosity in both soil types. For Soil-type A, the optimal improvement was observed at a 3 cm fiber length with 0.2% and 0.4% content values, whereas for Soil-type B, the 4 cm fiber length exhibited the best performance. The aeration porosity initially increased and then decreased, reaching its highest values at 3 cm + 0.6% and 4 cm + 0.4% combinations. The capillary porosity showed a slight decrease, with the lowest value observed in the 5 cm + 0.6% combination. Fiber incorporation also led to a significant reduction in soil bulk density, with Soil-type A exhibiting the lowest bulk density at a 1–2 cm fiber length and 0.6% content, while Soil-type B showed the lowest value at a 5 cm fiber length and 0.2% content. The hydraulic conductivity increased significantly with higher fiber content, reaching its maximum at a 5 cm fiber length and 0.6% content, with values of 0.78 mm/min for Soil-type A and 0.69 mm/min for Soil-type B.

Table 4. Physical properties of Soil-type A.

Fiber Content	Fiber Length	Total Porosity (%)	Aeration Porosity (%)	Capillary Porosity (%)	Bulk Density (g/cm ³)	Hydraulic Conductivity (mm/min)
CK		38.63 ± 1.11 c	10.97 ± 1.14 c	27.66 ± 0.33 a	1.4347 ± 0.022 a	0.69 ± 0.01 b
	1 cm	41.8 ± 0.74 b	16.91 ± 0.17 b	24.89 ± 0.6 bc	1.2987 ± 0.003 b	0.74 ± 0.01 a
	2 cm	42.83 ± 0.49 b	17.43 ± 0.11 ab	25.41 ± 0.41 bc	1.2907 ± 0.004 b	0.75 ± 0.02 a
	3 cm	44.57 ± 0.49 ab	17.75 ± 0.12 ab	26.82 ± 0.42 ab	1.2773 ± 0.010 b	0.76 ± 0.01 a
	4 cm	44.07 ± 0.28 ab	18.03 ± 0.34 ab	26.04 ± 0.54 b	1.1637 ± 0.033 c	0.76 ± 0.01 a
0.2%	5 cm	42.63 ± 0.2 b	17.23 ± 0.04 ab	25.4 ± 0.23 bc	1.2873 ± 0.004 b	0.77 ± 0.02 a
	1 cm	42.83 ± 0.49 b	17.43 ± 0.11 ab	25.41 ± 0.41 bc	1.2907 ± 0.004 b	0.75 ± 0.02 a
	2 cm	44.1 ± 0.12 ab	17.66 ± 0.09 ab	26.44 ± 0.19 ab	1.2803 ± 0.005 b	0.75 ± 0.01 a
	3 cm	44.87 ± 0.22 a	18.1 ± 0.08 ab	26.77 ± 0.22 ab	1.2423 ± 0.009 b	0.75 ± 0.02 a
	4 cm	44.77 ± 0.37 ab	18.43 ± 0.28 a	26.34 ± 0.13 ab	1.1483 ± 0.067 c	0.76 ± 0.01 a
0.4%	5 cm	42.7 ± 0.32 b	17.23 ± 0.03 ab	25.47 ± 0.29 bc	1.2853 ± 0.004 b	0.77 ± 0.02 a
	1 cm	44.57 ± 0.3 ab	17.65 ± 0.07 ab	26.92 ± 0.24 ab	1.2883 ± 0.005 b	0.75 ± 0.01 a
	2 cm	44.07 ± 0.3 ab	17.93 ± 0.11 ab	26.14 ± 0.24 b	1.2693 ± 0.002 b	0.76 ± 0.01 a
	3 cm	44.23 ± 0.28 ab	18.33 ± 0.34 ab	25.9 ± 0.27 b	1.2740 ± 0.003 b	0.76 ± 0.02 a
	4 cm	44 ± 0.44 ab	17.85 ± 0.11 ab	26.15 ± 0.34 b	1.1010 ± 0.026 c	0.77 ± 0.01 a
0.6%	5 cm	41.4 ± 0.31 b	17.15 ± 0.07 ab	24.25 ± 0.24 c	1.3040 ± 0.007 b	0.78 ± 0.02 a

Different lowercase letters (a–c) within a column indicate significant differences at $p < 0.05$.

Table 5. Physical properties of Soil-type B.

Fiber Content	Fiber Length	Total Porosity (%)	Aeration Porosity (%)	Capillary Porosity (%)	Bulk Density (g/cm ³)	Hydraulic Conductivity (mm/min)
CK		44.4 ± 0.45 c	5.13 ± 0.05 d	39.27 ± 0.41 a	1.3137 + 0.00769 a	0.6 ± 0.01 b
0.2%	1 cm	46.27 ± 0.55 bc	10.87 ± 0.06 c	35.39 ± 0.62 b	1.1687 + 0.01943 b	0.65 ± 0.01 a
	2 cm	46.5 ± 0.74 bc	11.16 ± 0.12 bc	35.34 ± 0.82 b	1.1907 + 0.0111 b	0.65 ± 0.01 a
	3 cm	47.67 ± 0.61 b	11.72 ± 0.07 ab	35.95 ± 0.54 b	1.052 + 0.03424 c	0.67 ± 0.01 a
	4 cm	49.83 ± 0.47 ab	11.51 ± 0.11 b	38.33 ± 0.37 ab	1.1393 + 0.02043 b	0.67 ± 0.01 a
	5 cm	48.87 ± 0.26 ab	11.87 ± 0.19 ab	36.99 ± 0.44 ab	1.0673 + 0.01517 c	0.67 ± 0.02 a
0.4%	1 cm	46.4 ± 0.72 bc	11.11 ± 0.09 bc	35.29 ± 0.65 b	1.1267 + 0.01559 b	0.66 ± 0.02 a
	2 cm	47.3 ± 0.38 b	11.31 ± 0.09 b	35.99 ± 0.29 b	1.1503 + 0.02305 b	0.66 ± 0.01 a
	3 cm	48.93 ± 0.7 ab	12.01 ± 0.21 a	36.93 ± 0.8 ab	1.1483 + 0.06645 b	0.67 ± 0.01 a
	4 cm	50.7 ± 0.59 a	12.06 ± 0.06 a	38.64 ± 0.62 ab	1.0857 + 0.02422 c	0.67 ± 0.02 a
	5 cm	47.9 ± 0.15 b	11.73 ± 0.09 ab	36.17 ± 0.16 b	1.112 + 0.03291 b	0.68 ± 0.01 a
0.6%	1 cm	46.83 ± 1.17 bc	11.42 ± 0.07 b	35.41 ± 1.11 b	1.101 + 0.04219 b	0.65 ± 0.02 a
	2 cm	47.67 ± 0.61 b	11.72 ± 0.07 ab	35.95 ± 0.54 b	1.052 + 0.03424 c	0.67 ± 0.01 a
	3 cm	48.57 ± 0.37 ab	12.14 ± 0.14 a	36.43 ± 0.27 b	1.101 + 0.02608 b	0.68 ± 0.01 a
	4 cm	50.37 ± 0.47 ab	11.99 ± 0.09 a	38.37 ± 0.41 ab	1.0773 + 0.02422 c	0.68 ± 0.01 a
	5 cm	46.27 ± 0.48 bc	11.71 ± 0.08 ab	34.56 ± 0.41 b	1.0467 + 0.0227 c	0.69 ± 0.02 a

Different lowercase letters (a–c) within a column indicate significant differences at $p < 0.05$.

As shown in Figure 1, the addition of coir fiber significantly improved the shear strength parameters of both soil types. With increasing fiber length and content, the overall trend exhibited an initial increase followed by a decline. However, the optimal fiber length and content combinations differed between the two soil types. For cohesion, both Soil-type A and Soil-type B exhibited the highest values at a fiber length of 3 cm, particularly at 0.4% and 0.6% content values. For the internal friction angle, most combinations showed no significant differences ($p > 0.05$). In Soil-type A, the internal friction angle increased with fiber length before stabilizing, reaching its peak at 3 cm (28.73°), while in Soil-type B, the highest value was recorded at a 4 cm fiber length (27.03°). For the peak deviatoric stress, the optimal fiber length and content combinations were more complex and varied with increasing confining pressure. Regarding the reinforcement effect coefficient, Soil-type A achieved the best performance at a 3 cm fiber length and 0.4% content, with values ranging from 1.33 to 1.56. Soil-type B displayed a distinct “double-peak” pattern, with the 3 cm + 0.4% combination remaining the most effective (coefficient: 1.17–1.54), followed by 4 cm + 0.4%. For interface fiber quantity, both soil types showed a similar trend—fiber quantity increased with a higher fiber content but decreased with a longer fiber length. The highest interface fiber quantity was observed at a 1 cm fiber length with 0.6% content. For the dispersion coefficient, the most uniform fiber distribution was recorded under a 1 cm fiber length and 0.4% content, where the coefficient was closest to 1, indicating better fiber dispersion within the soil matrix.

3.1.2. Crack Resistance

As shown in Figure 2, the crack ratio of both soil types initially decreased and then increased after the incorporation of coir fiber, which aligns with the observed soil crack images (see Appendix A). The effects of different fiber lengths and contents on crack resistance varied. At a 0.2% fiber content, the 5 cm fiber length exhibited the best crack resistance. When the content increased to 0.4%, the 3–4 cm fiber length showed optimal performance. At a 0.6% content, the 1 cm fiber length was the most effective in mitigating cracking. Further analysis indicated that the optimal fiber content varied with fiber length: for 1–2 cm fibers, 0.6% content provided the best crack resistance; for 3–4 cm fibers, 0.4% content was the most effective; while for 5 cm fibers, the optimal content was 0.2%.

To further investigate the effects of coir fiber on soil properties in different soil types, a correlation analysis was conducted (Figure 3). The results indicate that an increase in fiber content enhances the porosity and shear strength without compromising reinforcement effectiveness. Instead, fiber incorporation improves the bonding between soil particles, contributing to strength enhancement. Longer fibers and a higher fiber content result in greater

improvements in the shear strength and reinforcement coefficient, particularly under high confining pressure, leading to increased soil stability. The peak deviatoric stress index showed a significant positive correlation with the reinforcement coefficient, further confirming the dual reinforcing effect of fibers. The crack ratio exhibited a negative correlation with other parameters, indicating that fiber incorporation improves soil structure, reduces crack formation, and enhances overall soil quality. In contrast, bulk density and hydraulic conductivity showed no significant correlation with other parameters, suggesting that fiber primarily optimizes the mechanical performance and stability of the soil, with minimal influence on these two factors.

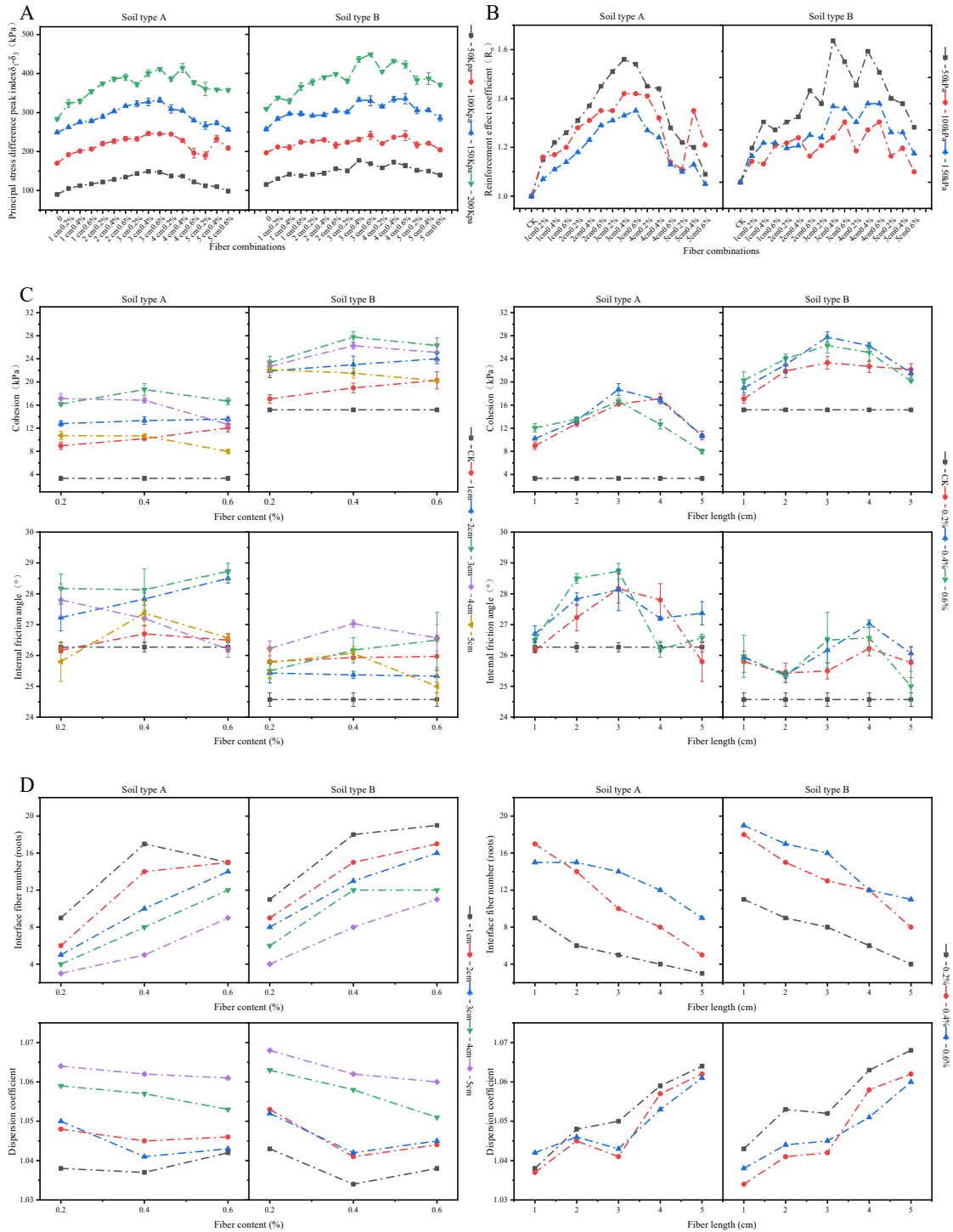


Figure 1. The effect of different fiber contents and fiber lengths on the soil shear strength under two soil types: (A) peak deviatoric strength; (B) reinforcement effect coefficient; (C) shear strength index; (D) interface dispersion coefficient.

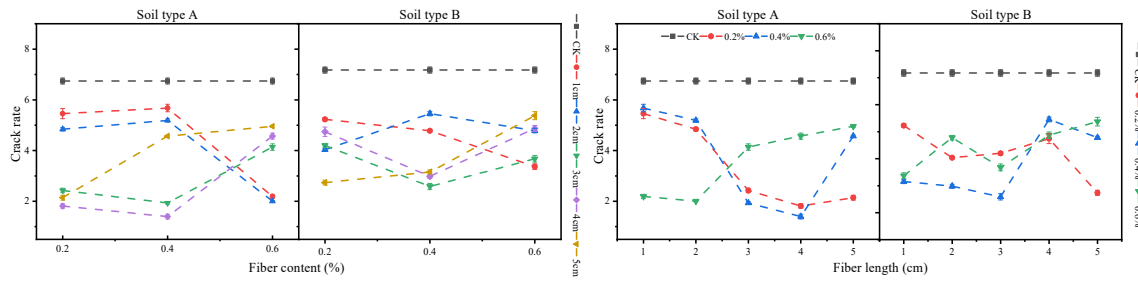


Figure 2. The effect of different fiber contents and fiber lengths on the soil crack rate under two soil types.

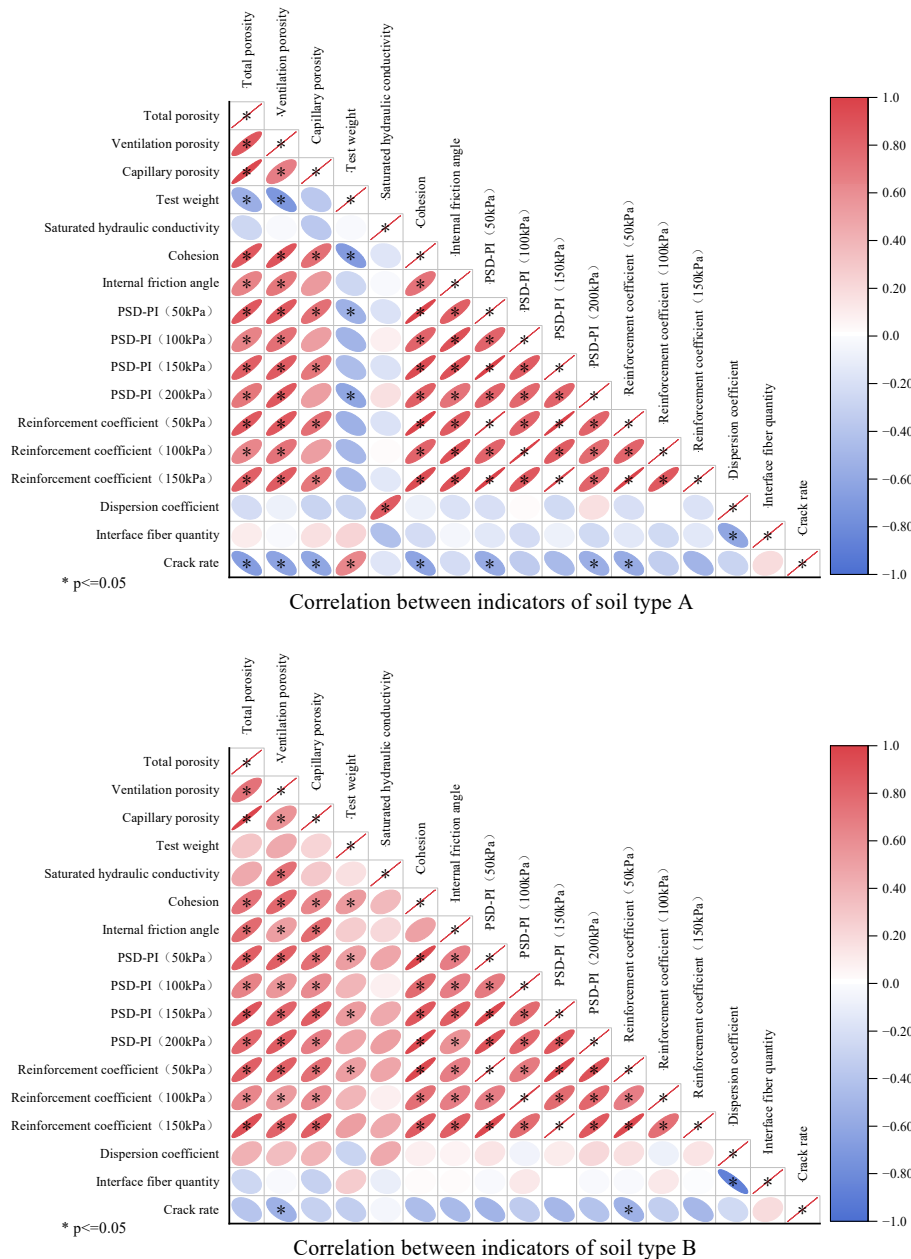


Figure 3. Correlation between indicators under two soil types.

3.2. Optimal Fiber Length and Content Combination Under Two Soil Conditions

This study used principal component analysis (PCA) to reduce the dimensions of multiple evaluation indicators, extract the main influencing factors, and construct a comprehensive score (Figure 4). Then, based on the PCA score, response surface analysis

(RSM) was used to design a Box–Behnken experimental scheme, fit a multivariate quadratic regression model, and analyze the interaction between factors. Finally, the optimal factor ratio combination was determined through model prediction and verification (Figure 5).

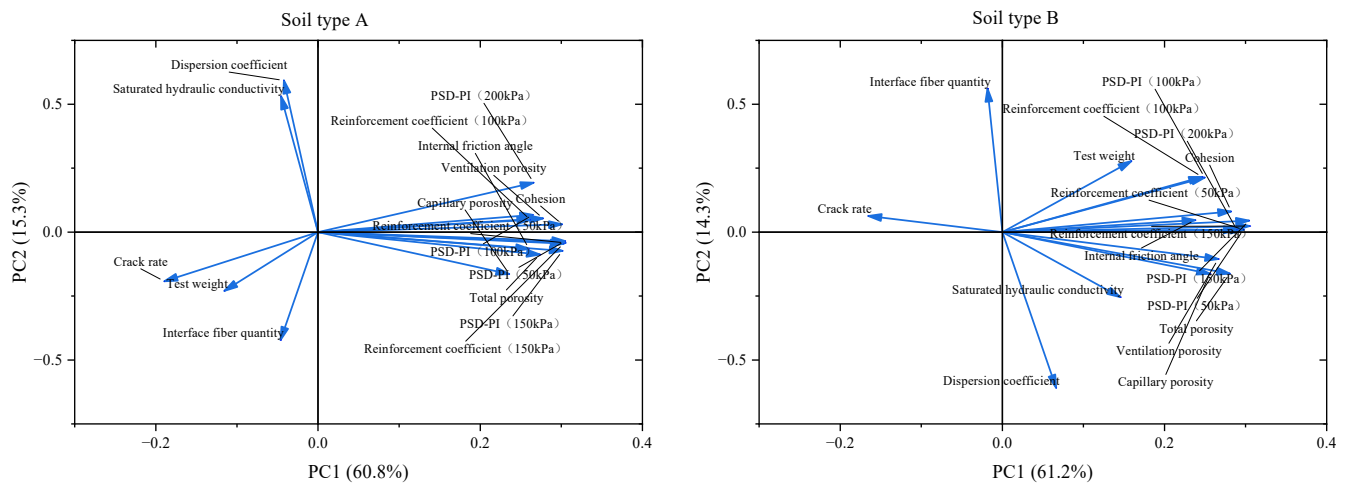


Figure 4. Two soil principal component analysis loading diagrams.

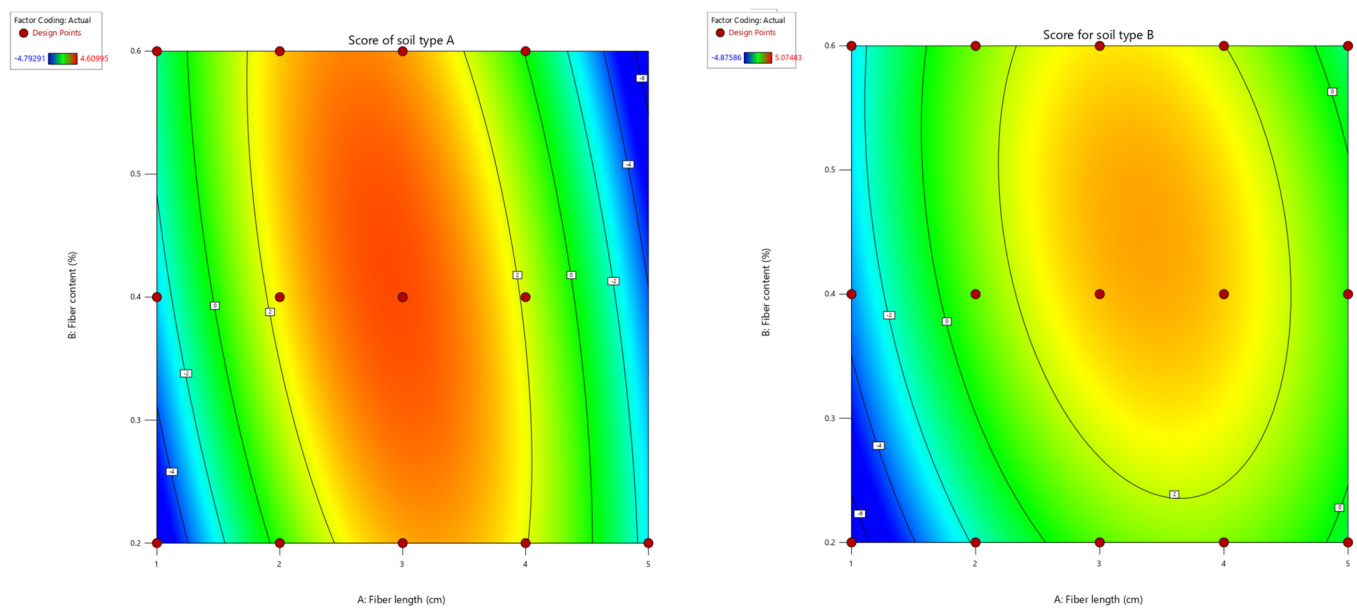


Figure 5. Two soil 2D response surface plots.

The findings indicate that for Soil-type A, the optimal fiber length and content combination are 3.051 cm and 4.07% ($R^2 = 0.8375$), while for Soil-type B, the best combination is 3.376 cm and 0.456% ($R^2 = 0.5889$). Under these optimal conditions, the overall soil performance reached its maximum. Additionally, response surface plots revealed significant variations in soil properties under different fiber length and content combinations, highlighting the strong interactive effects between these two factors on soil performance.

4. Discussion

This study investigated the interactions between coir fiber and soil properties, including physical characteristics, mechanical performance, and crack resistance, in sandy and silty soils with varying fiber lengths and contents. The results demonstrate that fiber incor-

poration effectively enhances overall soil stability, optimizes soil structure, and mitigates soil cracking.

From a mechanical perspective, fibers formed a three-dimensional network within the soil, strengthening interparticle cohesion and friction, thereby increasing soil cohesion and shear strength [22]. The optimal reinforcement was observed at fiber lengths in the range of 3–4 cm and a content in the range of 0.4–0.6%, where fibers were well-dispersed without excessive aggregation, significantly reducing lateral particle displacement during shear failure. This effect was more pronounced in sandy soil due to its larger porosity and weaker structural framework. However, sandy soil was also more sensitive to fiber content, as excessive or overly long fibers tended to accumulate locally, weakening reinforcement efficiency. Similar phenomena have been reported in studies on other natural fibers, such as straw and jute [23].

Regarding crack formation and propagation, soil cracking typically results from severe volume shrinkage due to water loss, leading to concentrated stress. Coir fiber, with its high tensile strength and elongation, acted as a constraint network within the soil, distributing localized tensile stress during moisture evaporation and preventing crack connectivity [24]. However, when fiber length or content was excessive, dispersion became less uniform, forming large aggregated structures. These fiber clusters created stress concentration zones at their peripheries, ultimately promoting cracking rather than preventing it [25]. Thus, the precise control of fiber length and content is essential to minimize soil cracking while maintaining adequate aeration and moisture retention.

The addition of fibers also altered soil physical properties, increasing porosity while decreasing bulk density. Previous studies indicate that natural fibers not only increase soil pore volume, but also contribute organic matter upon degradation [26], benefiting plant growth and soil aggregation. In this study, fibers of 3–4 cm length with a moderate-to-high content resulted in the most significant porosity improvements, particularly enhancing soil aeration and permeability. However, capillary porosity showed a slight decline, suggesting that excessive fiber content disrupted continuous capillary pores. In hydroseeding applications, this presents a trade-off: improved aeration and faster infiltration prevent surface runoff, but excessive permeability may limit water retention, potentially affecting plant root development. Therefore, fiber composition should be optimized based on local rainfall conditions and vegetation requirements.

Finally, the laboratory experiments inherently do not account for complex field conditions, including wet–dry cycles, rainfall erosion, and vegetation root reinforcement. Additionally, the long-term effects of fiber degradation on soil porosity and mechanical properties remain unexplored. Some studies suggest that fiber degradation can enhance soil organic matter while dynamically altering soil stability [27,28]. Future research should include long-term field monitoring to examine fiber–root interactions and assess their comprehensive effects on soil stabilization and ecological restoration.

In conclusion, coir fiber effectively improved soil properties in both sandy and silty soils. The appropriate fiber length and content combination balanced soil mechanical strength and crack resistance. To maximize effectiveness, fiber parameters should be tailored to specific soil conditions and engineering applications. Additionally, integrating long-term monitoring of vegetation and environmental factors can help optimize fiber-based soil reinforcement strategies for sustained stability and ecological benefits.

This research offers a promising reference for the practical application of natural fiber-reinforced ecological restoration materials in highway slopes for protection. The findings are expected to support the development of green and efficient slope engineering strategies adaptable to diverse site conditions.

5. Conclusions

This study investigated the application of coir fiber in different soil types by analyzing its effects on soil physical properties, mechanical properties, and crack resistance. The key conclusions are as follows:

1. The incorporation of coir fiber significantly increased soil porosity and aeration, with the most pronounced improvement observed at fiber lengths in the range of 3–4 cm and content in the range of 0.4–0.6%, leading to enhanced water permeability and aeration performance.
2. Fiber reinforcement notably improved soil cohesion and shear strength, with the optimal combinations being 3 cm fiber length and 0.4% content for Soil-type A, and 4 cm fiber length and 0.4% content for Soil-type B.
3. Fiber length and content had a significant effect on crack resistance, with 3–4 cm fibers at 0.4% content exhibiting the best performance.
4. Correlation analysis revealed a strong positive relationship between soil porosity and shear strength, confirming that fiber reinforcement not only improves pore structure but also enhances overall mechanical performance. Additionally, the crack ratio showed a negative correlation with shear strength and reinforcement coefficient, indicating that fiber incorporation effectively mitigates the adverse impact of cracks on soil stability.
5. Response surface analysis identified the optimal fiber combinations for Soil-type A as a 3.051 cm fiber length and 4.07% content, and for Soil-type B as a 3.376 cm fiber length and 0.456% content.

Overall, coir fiber significantly improved both the physical and mechanical properties of the soil, particularly in enhancing shear strength and crack resistance. The findings provide a theoretical basis for selecting appropriate fiber length and content combinations in engineering applications and clarify the interrelationships between key parameters, offering valuable insights for future research and practical implementation. This research offers a promising reference for the practical application of natural fiber-reinforced ecological restoration materials in highway slopes for protection.

Author Contributions: Conceptualization, W.Z.; Methodology, Y.Q. and W.Z.; Software, Y.Q.; Validation, Y.Q. and Y.L.; Formal analysis, Y.Q.; Investigation, P.W., W.Z., L.W. and G.Y.; Resources, G.S.; Data curation, Y.Q., W.Z. and Y.L.; Writing—original draft, Y.Q. and W.Z.; Writing—review & editing, Y.L. and G.S.; Supervision, G.S.; Project administration, Y.Q. and G.S.; Funding acquisition, P.W., L.W. and G.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Shanxi Luqiao Construction Group, Horticulture Greening Engineering Co., Ltd., under the Major Scientific Research Project Cooperation Agreement (grant number 200-662504058). The APC was also funded by this project.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: Authors Pengfei Wang, Long Wang and Gang Yang were employed by the company Shanxi Luqiao Construction Group, Horticulture Greening Engineering Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The sponsors had no role in the design, execution, interpretation, or writing of the study.

Appendix A

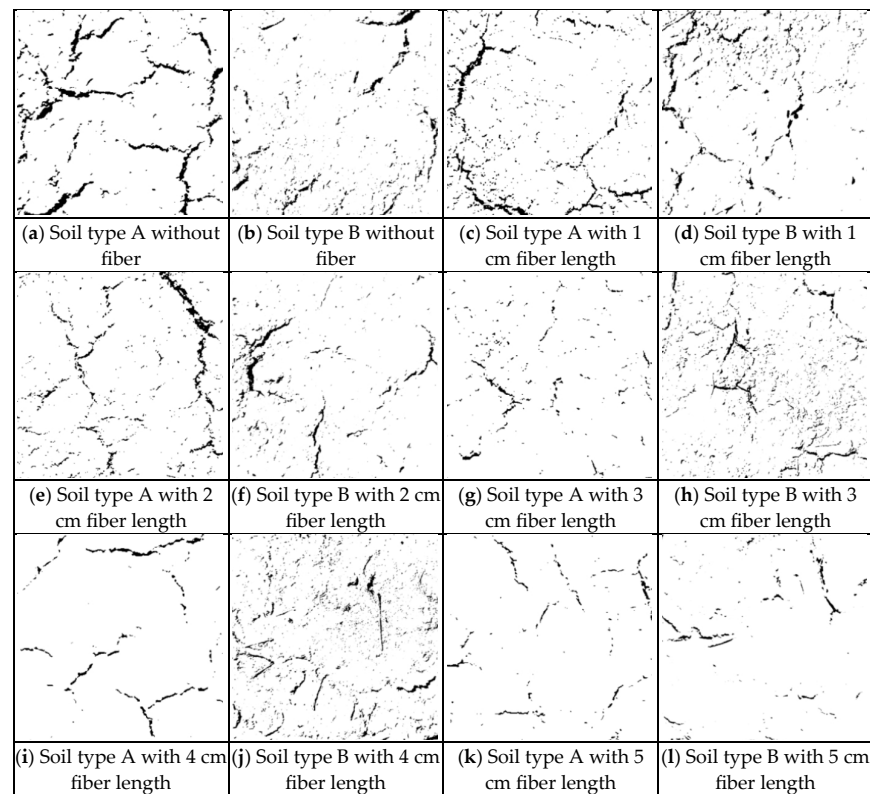


Figure A1. Image of fracture of soil with 0.2% fiber contents. * Due to space limitations, only one photo is provided for each treatment.

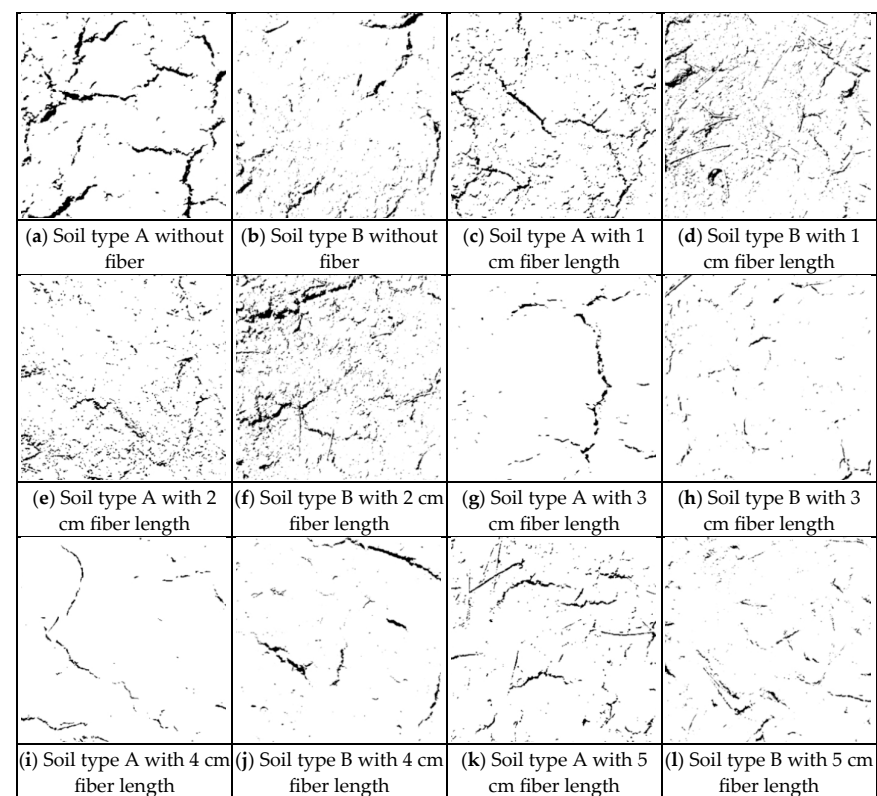


Figure A2. Soil fracture image with 0.4% fiber contents. * Due to space limitations, only one photo is provided for each treatment.

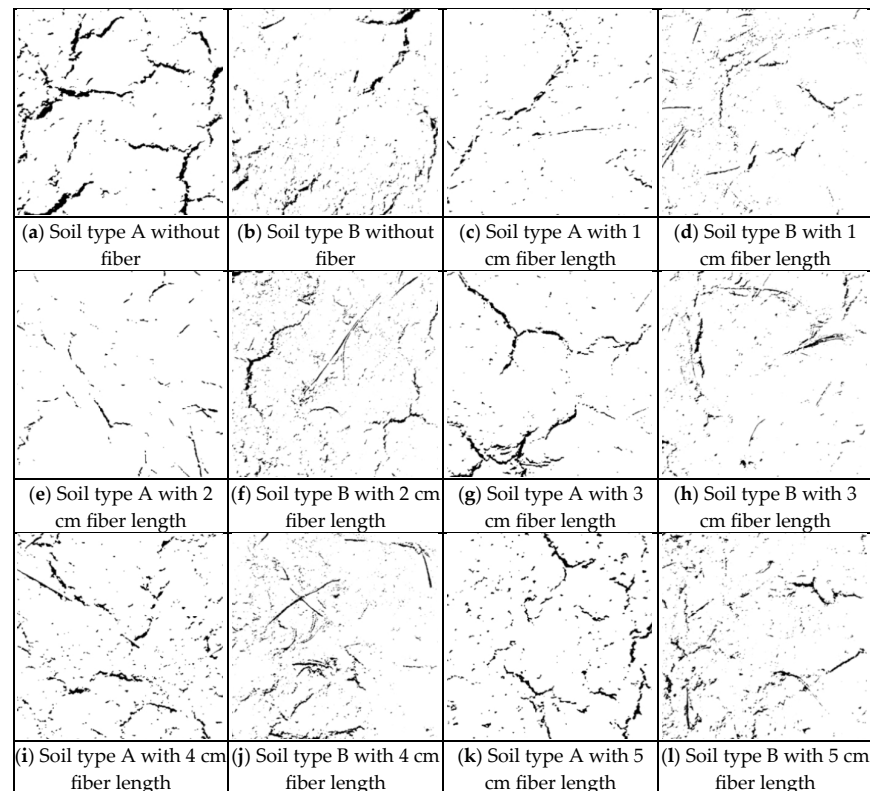


Figure A3. Image of fracture in soil with 0.6% fiber contents. * Due to space limitations, only one photo is provided for each treatment.

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