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The Mechanical Properties and Micro-Mechanism of Xanthan Gum–Coconut Shell Fiber Composite Amended Soil

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Abstract: Targeting the engineering properties of poor strength and susceptibility to damage in roadbeds and slopes within clay regions, xanthan gum is employed as a soil enhancer, concurrently addressing the issue of the low utilization rate of plant coir fiber. The unconfined compressive strength test (UCS) is used to analyze the influence of different maintenance methods, maintenance duration, xanthan gum dosage, and coconut fiber dosage on the mechanical properties of the enhanced soil. Furthermore, based on scanning electron microscope (SEM) tests, the underlying mechanisms governing the mechanical properties of fiber-reinforced xanthan gum-improved soil are uncovered. The results indicated that the compressive strength of amended soil is significantly enhanced by the incorporation of xanthan gum and coir fiber. After 28 days of conditioning, the compressive strength of the amended soil under dry conditions (conditioned in air) was significantly higher (3 MPa) than that under moist conditions (conditioned in plastic wrap) (0.57 MPa). Xanthan gum influenced both the compressive strength of the specimens and the degree of strength enhancement, whereas coir fibers not only augmented the strength of the specimens but also converted them from brittle to ductile, thereby imparting residual strength post-destruction. Microscopic analysis indicates that the incorporation of xanthan gum and coconut shell fiber significantly diminishes the number of pores and cracks within the soil matrix, while enhancing the internal inter-particle cementation. This synergistic effect contributes to soil improvement, providing theoretical and technical guidance for roadbed enhancement and slope repair.

Keywords: xanthan gum; coconut shell fiber; mechanical properties; microscopic mechanism

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1. Introduction

The tensile strength of clay is rather low, and under arid conditions, it may readily become fragile. When exposed to external forces, it is susceptible to brittle failure, hence constraining the use of clay in projects with significant load-bearing demands. Consequently, it is imperative to strengthen the clay, augment its structure, and bolster its strength and stability to guarantee the project's safety and stability.

Qi et al. [1] investigated the reinforcement of mudstone slopes in tailings piles using xanthan gum, discovering that the incorporation of xanthan gum markedly diminishes the crack area following the shrinking and drying of mudstone, with the average enhancement efficiency exhibiting a positive correlation to the concentration, specifically within the range of 0.5% to 2% xanthan gum content. Upon surpassing 2%, a negative connection is observed, with the maximum average improvement efficiency being 45%. Zhang et al. [2] indicated that a low liquid limit powdery soil is typically unsuitable for direct application

as roadbed or slope soil. They conducted unconfined compressive strength tests to examine the impact of xanthan gum on the enhancement of low liquid limit powdery soil and discovered that a xanthan gum concentration of 2%, maintained for 7 days, results in a stabilization of the soil's strength. Anandha et al. [3] discovered that the incorporation of xanthan gum into the soil creates a gel covering on the surface and a gel plug within the soil matrix, which can markedly diminish the hydraulic conductivity of the soil. Zizzo et al. [4] performed an experimental investigation to enhance soil resistance to cracking by dry cracking tests on kaolin, discovering that xanthan gum and recycled carpet fibers can augment soil strength and diminish cracking. Zhang et al. [5] discovered that xanthan gum (XG) and junction cold gel (GG) significantly enhance the water retention capacity of sandy soils. These materials absorb water to create hydrogels and biofilms, which diminish the pore space between the soil particles, hence enhancing the water retention capacity of sandy soils. As the concentration of biopolymers rises, the water retention capacity of sandy soils correspondingly increases. The water retention capacity of sandy soils treated with knotted cold gel surpassed that of sandy soils treated with xanthan gum. Miao et al. [6] conducted indoor dry and wet cycle tests on xanthan gum-enhanced expansive soil, quantitatively analyzing the entire crack development process using digital image processing technology (PCAS). They examined the effects of xanthan gum incorporation on the crack morphology and characteristic indices of the expansive soil, discovering that xanthan gum mitigated cracking primarily through two mechanisms: it formed a "bridge-link" structure with soil particles via bonding and cementation, and it obstructed the water contact with the soil particles through filling and film formation, thereby reducing the thickness of the hydration film of the clay minerals. Xanthan gum mitigates the cracking of expanded soil through two mechanisms: firstly, it establishes a "bridging" structure with soil particles via bonding and cementation, thereby enhancing the overall tensile strength of the soil; secondly, it obstructs water contact with soil particles through filling and film formation, consequently diminishing the thickness of the hydration film surrounding clay minerals. Wang et al. [7] discovered that xanthan gum and guar gum interacted with soil minerals to create cement, thereby enhancing the bonding strength among soil particles, increasing soil cohesion, reducing the expansion and contraction of expansive soils, and improving both shear strength and unconfined compressive strength.

Jin et al. [8] examined the evaporation and cracking properties of straw and polypropylene fiber-reinforced soils, discovering that the incorporation of natural and polypropylene fibers diminishes water evaporation and mitigates cracking, thereby offering a method for soil enhancement in arid regions. Wang et al. [9] performed loose and undrained triaxial experiments, revealing that the incorporation of polypropylene fiber and fly ash into the roadbed soil enhances its ductility and stiffness, while also establishing a denser skeletal structure inside the soil. Zhao et al. [10] enhanced soil using coconut fiber, discovering that the fiber substantially increases the soil's shear strength by direct shear testing, hence promoting slope stability and presenting the extensive application potential. Estabragh et al. [11] incorporated nylon fibers into clay soil and discovered that this addition markedly enhances the shear strength and friction angle of the soil matrix. Li [12] consider fiber-reinforced soil functions as a composite material, with fibers imparting significant tensile strength. Randomly distributed fibers engage with the soil to enhance interfacial resistance and interlocking, hence augmenting soil strength. This research discusses the use of coir fibers into a xanthan gum and clay mixture to enhance the soil's strength and reduce brittleness.

Anusudha et al. [13] conducting indoor experiments on clay amended with coir fiber, discovering that the unconfined compressive strength of soil is significantly increased when coir fiber is added to it. The increase is directly proportional to the quantity of the fiber

used. The peak compressive strength of the fiber-reinforced soil with 1.5% fiber content is more than twice that of the unreinforced soil. Moreover, the stiffness and ductility of the soil are quite improved with the use of natural fiber. Cao et al. [14] used coir fiber to reinforce red clay, and the results showed that the incorporation of coir fiber can improve the strength and ductility of red clay.

Previous studies only reflected in the improvement of soil by fiber or xanthan gum alone, studying its mechanical properties and micro-mechanisms, or considering the study of improved soil under a single maintenance method; in this paper, we combine the two materials and consider the strength change, stress–strain trend, damage morphology, and micro-analysis of improved soil under different maintenance methods.

The double-helix structure of xanthan gum can form a three-dimensional network in solution, dispersing coir fibers, preventing aggregation, and enhancing the homogeneity and stability of composites. Its good fluidity improves the processing performance, reduces resistance, and facilitates the mixing and molding of fibers with other matrices. The hydroxyl and carboxyl groups of xanthan gum can form hydrogen bonds with the hydroxyl groups on the surface of coir fiber to enhance the bonding force; the negative side-chain charge interacts with the positive charge on the surface of coir fiber to produce electrostatic interactions, which further stabilizes the structure and enhances the performance of the composite material. The combination of the two materials synergistically enhances the mechanical properties of the clay and necessitates an in-depth study.

2. Model Test and Materials

2.1. Experimental Material

The soil sample was collected from the Jiangxia District of Wuhan, Huibei Province, China. exhibiting a yellow hue and possessing a firm, plastic consistency. The fundamental physical property indicators are shown in Table 1, and the clay is illustrated in Figure 1. The "Technical Specification for Highway Engineering Soil Test" (JTG3430-2020) [15] stipulates that the test soil was subjected to sieving via a 2 mm screen, and the resulting soil sample was thereafter dried in an oven at 105 °C for use.

Table 1. The base parameters of the soil sample.

Natural Moisture Content W/%	Plastic Limit W_P/%	Liquid Limit W_L%	Plasticity Index I_p	Maximum Dry Density $\rho_{d\ max}$	Optimal Moisture Content W_{op}/%
13.46	26.70	58.60	31.80	1.69	21.25



Figure 1. Clay used in the test.

The fiber used in the experiment were coconut shell fibers acquired from Tianjin Gaga Green Products Technology Col; the coconut shell fiber for reference is provided in Figure 2, and the base parameters of coconut coir fiber in Table 2. The coconut shell fibers exhibited a light yellow hue, measured 200–250 μm in diameter, and possessed a circular morphology. Coconut fiber consists of cellulose, hemicellulose, lignin, and pectin. Its primary advantage lies in its extraction from coconut shells, transforming trash into a valuable resource. It is easily obtainable, cost-effective, and environmentally benign. In recent years, it has been extensively utilized for soil enhancement. A combined photoelectric liquid–plastic limit tester was used to measure the liquid–plastic limit of the soil and calculate the plasticity index of the soil. The test was conducted in accordance with the geotechnical test specification. According to the Geotechnical Test Specification for Highway (JTG 3430-2020) [15], the optimum moisture content and optimum dry density were obtained by lightweight compaction method.



Figure 2. Coconut coir fiber used in the test.

Table 2. The base parameters of coconut coir fiber.

Fiber Diameter /μm	Fiber Density /(g/cm^3)	Tensile Strength /MPa	Elongation /%	Initial Modulus of Elasticity /GPa	Initial Fiber Length /cm
200–250	1.1–1.2	85.2–110.5	0.2–0.3	2.1–2.4	12–20

Xanthan gum is a high molecular weight polymer produced through the fermentation of Xanthomonas campestris, manifesting as a white to light yellow powder, as shown in Figure 3. The basic physical parameters of xanthan gum are shown in Table 3. It dissolves in water at ambient temperature, yielding a translucent, viscous liquid with superior thickening capabilities. It possesses benefits including safety, non-toxicity, and chemical stability. Following its discovery in 1954 and subsequent approval by the U.S. Food and Drug Administration in 1956, numerous countries worldwide have progressively initiated industrial production of xanthan gum, establishing it as one of the most esteemed biogums recognized globally today. China is presently the foremost producer of xanthan gum globally. Statistical study indicates that the price of xanthan gum has consistently decreased in a linear fashion over the past thirty years. The expense of using xanthan gum as a soil modifier is comparable to that of cement, suggesting that xanthan gum serves as a cost-effective and eco-friendly soil enhancement material.

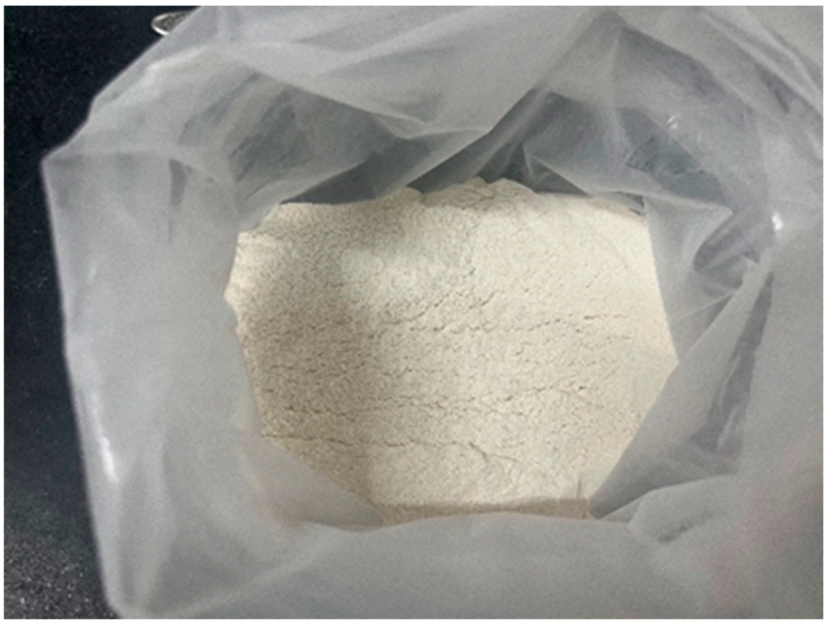


Figure 3. Powdered form of xanthan gum biopolymer.

Table 3. Basic physical parameters of xanthan gum.

Molecular Formula	Dry Weight Loss /%	Melting Point /°C	Boiling /°C	PH $\rho_{d\ max}$
$C_{35}H_{49}O_{29}$	8.4	64.43	145.2	7.2

2.2. Experimental Steps

In this experiment, xanthan gum concentrations were established at 0%, 1.0%, 1.5%, 2%, and 2.5%, while coconut shell fiber concentrations were set at 0%, 0.1%, 0.3%, 0.5%, and 1.0%. The curing duration was conducted under moist circumstances using cling film. An orthogonal test was conducted under dry conditions (air curing) for durations of 0 days, 7 days, and 28 days, with a fiber length of 30 mm. The dry mixing technique involved 200 g of a soil sample, which had been sieved through a 2 mm mesh and dried, combined with varying quantities of xanthan gum and coconut fiber. Following agitation, distilled water was incorporated into each soil sample in accordance with the optimal water content for varying xanthan gum concentrations, and the mixture was uniformly mixed with a spatula. The soil sample was subsequently positioned into a mold to produce a conventional cylindrical specimen with a bottom diameter of 39.1 mm and a height of 80 mm. Use a jack to compress and shape the sample, thereafter extract it, weigh it, verify the uniform quality, and assign a number. One hundred and twenty-five sets of samples were tested, comprising seventy-five sets cured in wet conditions (a temperature of 22 ± 2 °C and a humidity of 95 ± 5%) and fifty sets cured under dry conditions (a temperature of 22 °C and a humidity less than 70%). Table 4 presents the experimental conditions. The Figure 4 is test preparation process.

Table 4. Experimental conditions.

Type of Experiment	Maintenance Method	Fiber Content (%)	Xanthan Gum Content (%)	Maintenance Period (d)
Unconfined compressive strength	Wet curing Dry maintenance	0%, 0.1%, 0.3%, 0.5%, 1%	0%, 0.1%, 1.5% 2%, 2.5%	0 d, 7 d, 28 d 7 d, 28 d

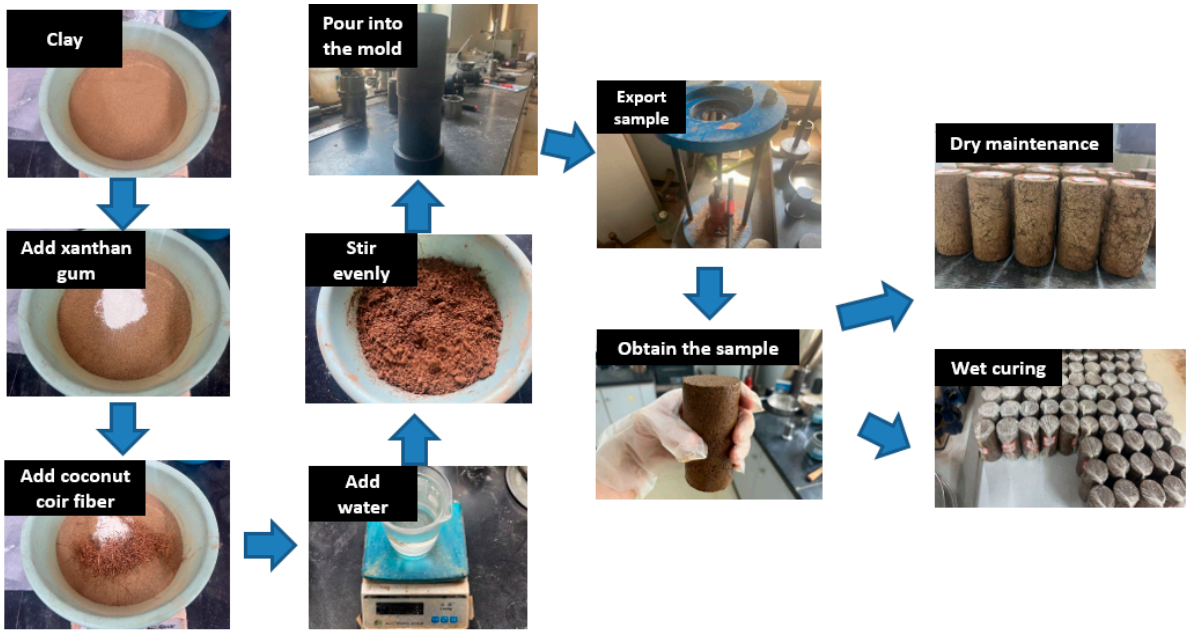


Figure 4. The figure of test preparation process.

2.3. Experimental Methods

2.3.1. Unconfined Compressive Strength

At the conclusion of the sample maintenance cycle, the specimen for the unconfined compressive strength test was subjected to the WDW-10E microcomputer-controlled electronic universal testing machine, which has a maximum load capacity of 17 kN and a loading rate of 1 mm/min. The test was terminated once the sample strength diminished to a point of no further change, and the morphology of the destroyed samples was analyzed for appearance characteristics.

2.3.2. SEM Electron Microscope Analysis

Following the compressive strength test, to elucidate the interaction among xanthan gum, coconut fiber, and clay, tiny specimens of the mixed modified soil were extracted, each measuring around 10 mm × 10 mm with a thickness of less than 2 mm. The samples were dehydrated in an oven at 50 °C for 12 h, subsequently lyophilized, coated with gold on their surfaces, and examined using an electron microscope.

3. Test Results and Discussion

3.1. Effect of Xanthan Gum and Coconut Fiber on Soil Strength

Table 5 enumerates the compressive strength of the samples subjected to various beginning circumstances at 7 days and 28 days. The table indicates that, under uncured conditions, the unconfined compressive strength of soil enhanced with xanthan gum or coconut fiber alone can attain 185 kPa and 259 kPa, respectively. The unconfined compressive strength of the composite-improved soil exceeds that of the soil enhanced only with fiber or xanthan gum. As the quantities of fiber and xanthan gum rise, the unconfined compressive strength of fiber-reinforced clay significantly surpasses that of xanthan gum. The cementitious substance generated between the xanthan gum and the soil has not yet completely reacted; however, the friction between the fiber and the soil, along with the network structure established by the adhesion between the fiber and the xanthan gum, produces a locking force within the soil, thereby augmenting the compressive strength of the sample [16]. Tang et al. [17,18], through the experimental study of this three-dimensional mesh structure, found that the fibers were interlinked with the soil to form a

mesh structure. The gel formed by xanthan gum with water and soil can well connect the fiber roots and form a three-dimensional mesh structure. This increases the strength of the soil. Consequently, during brief curing durations, the cementing efficacy of xanthan gum in the soil remains inadequately harnessed, whereas the fibers predominantly contribute to the augmentation of soil strength in samples subjected to a limited curing time.

Table 5. Compressive strength of specimens under different dosages, different curing methods, and curing ages.

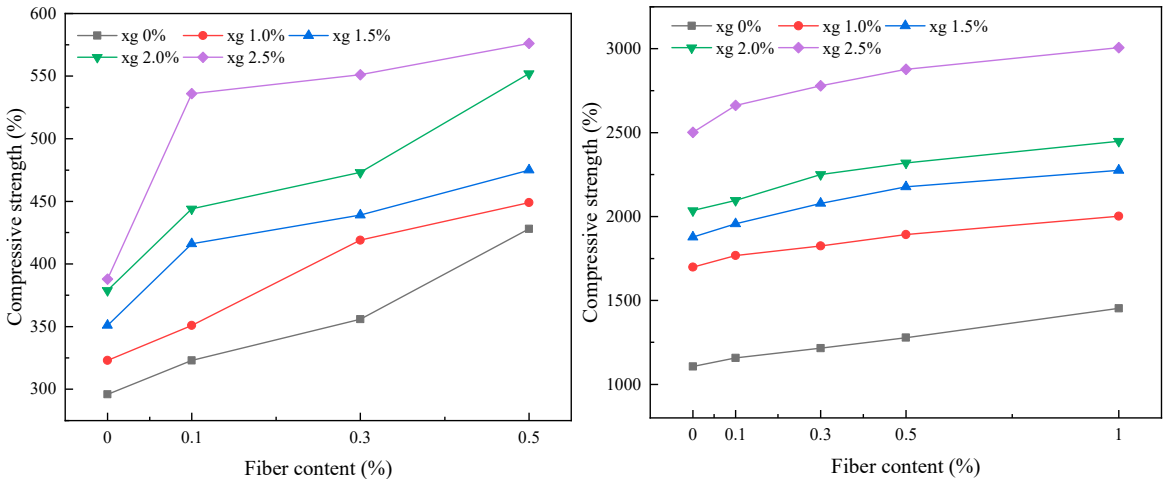
Material Dosage (%)		Compressive Strength Under Different Curing Methods and Curing Ages (kPa)				
Xanthan Gum Content	**Fiber Content**	**0 Days**	**7 Days of Wet Curing**	**28 Days of Wet Curing**	**7 Days of Dry Curing**	**28 Days of Dry Curing**
0	0	102	212	296	823	1106
	0.1	204	231	323	875	1158
	0.3	231	240	356	924	1216
	0.5	259	268	428	987	1279
	1.0	/	/	/	1117	1453
1.0	0	138	259	324	1432	1699
	0.1	241	268	352	1521	1768
	0.3	296	305	419	1577	1824
	0.5	314	324	475	1645	1892
	1.0	/	/	/	1795	2002
1.5	0	148	278	352	1873	1877
	0.1	286	296	416	1935	1956
	0.3	305	314	440	1967	2078
	0.5	333	333	475	2016	2177
	1.0	/	/	/	2189	2275
2.0	0	167	296	379	1997	2035
	0.1	296	305	444	2029	2096
	0.3	314	324	473	2240	2251
	0.5	338	342	552	2306	2320
	1.0	/	/	/	2392	2449
2.5	0	185	305	389	2423	2501
	0.1	305	331	537	2507	2662
	0.3	323	341	551	2618	2779
	0.5	356	360	576	2741	2877
	1.0	/	/	/	2960	3006

Note: "/" for the unmeasured strength, the specimen is gradually compressed, the strength is in the continuous smooth and slow to the right.

As the curing duration is established, the unconfined compressive strength of the specimen rises with the incorporation of fiber or xanthan gum. Following a 28-day curing period under arid conditions, with an XG concentration of 2.5%, the sample exhibits a compressive strength enhancement of 2316 kPa. Under dry curing circumstances, a 1% addition of XG resulted in an 11.31-fold increase in the unconfined compressive strength of the sample. A 2.5% addition led to a 12.52-fold increase. The augmentation of xanthan gum content correlates with the enhancement of the sample's compressive strength and the degree of strength improvement. Figure 5 illustrates that the compressive strength of the composite amended soil is higher than that of the soil amended with xanthan gum or coir fiber alone. So, composite materials have an enhancing effect on soil improvement.

Figure 6 illustrates that after a brief curing time, namely under wet conditions for seven days, the compressive strength of samples containing only fiber does not exhibit substantial enhancement. As the xanthan gum concentration rises, the compressive strength

of the samples exhibits a notable alteration, suggesting that the curing duration positively influences the interaction of xanthan gum with the soil.



(**a**) 28 days under wet conditions (**b**) 28 days under dry conditions

Figure 5. Variation of compressive strength with coconut husk fiber content.

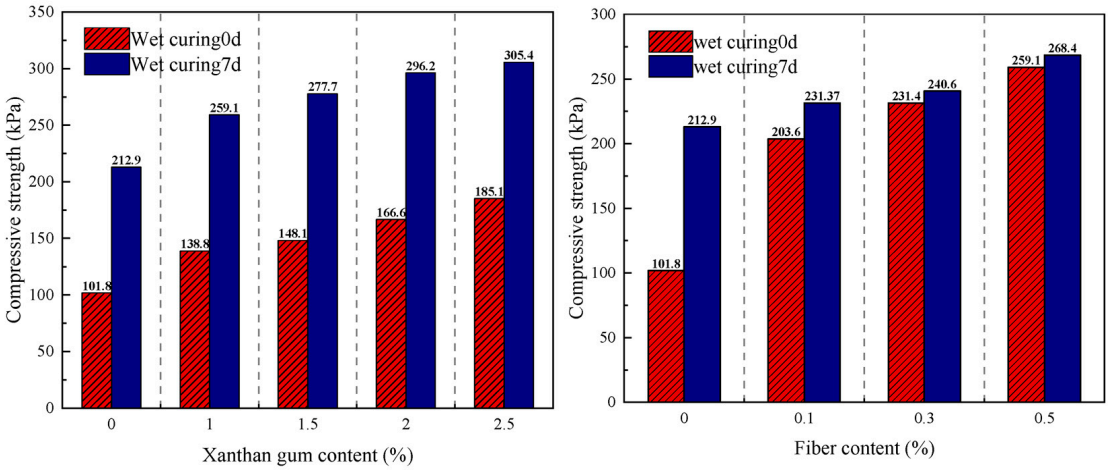


Figure 6. Effect of short curing age on the compressive strength of xanthan gum or coir fiber alone.

3.2. Analysis of the Efficiency of Strength Improvement in Materials

The following equation was used to evaluate the effect of xanthan gum and coconut fiber in increasing the strength of composite amended soils.

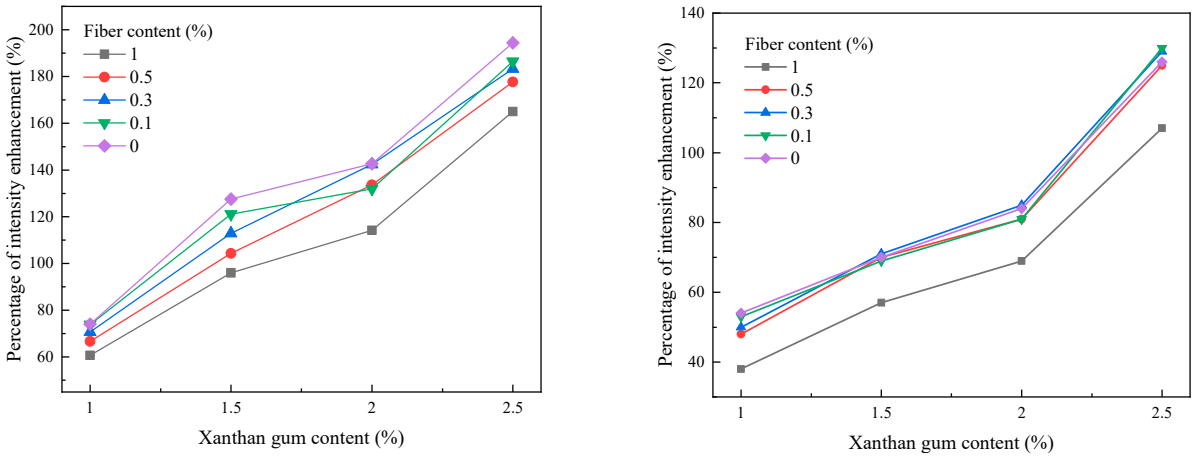
$$W_{xg} = \left[UCS_{f+xg} - UCS_f\right] / UCS_f \quad (1)$$

$$W_f = \left[UCS_{f+xg} - UCS_{xg}\right] / UCS_{xg} \quad (2)$$

where W_{xg}, W_f represent the improvement percentages of the sample UCS by xanthan gum and coconut shell fiber, respectively.

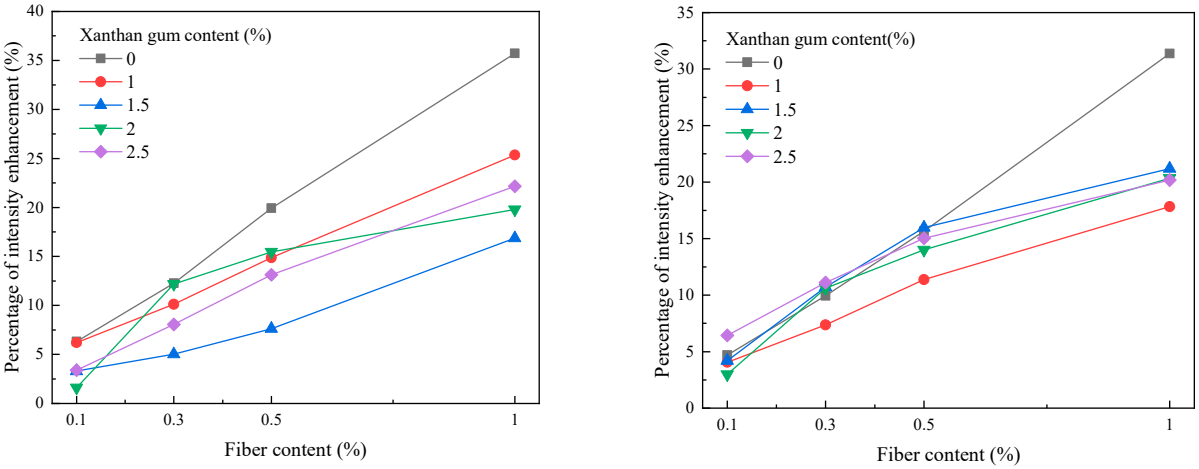
Figure 7 illustrates the impact of specimen strength increase efficiency using xanthan gum doping at a specified coir fiber doping level. Figure 8 illustrates the effect of using xanthan gum at a specific xanthan gum doping level on the efficiency of specimen strength improvement. The efficacy of xanthan gum in enhancing specimen strength (W_{xg}) is evidently proportional to its concentration, given a fixed fiber doping level. Similarly, at a specific xanthan gum concentration, the effectiveness of fiber in augmenting specimen strength (W_f) also rises with increased fiber doping levels. It is evident that an increase in

xanthan gum or fiber dosage enhances the interaction of the combined material with the soil matrix, hence improving the strength efficiency [19].



(**a**) 7 days under dry conditions (**b**) 28 days under dry conditions

Figure 7. Variation in the percentage improvement in specimen strength with xanthan gum content at different curing ages.



(**a**) 7 days under dry conditions (**b**) 28 days under dry conditions

Figure 8. Variation in the percentage improvement in specimen strength with fiber content at different curing ages.

The analysis of the strength enhancement efficiency graphs for 7 days and 28 days reveals a decline in the interaction efficiency at 28 days relative to 7 days. It is evident that the cementation between xanthan gum and soil particles is largely achieved within 7 days for specimens cured in a dry environment. Despite the operating efficiency value at 28 days being inferior to that at 7 days, its efficacy is enhanced, suggesting that an extended maintenance time can further augment the interaction between the composite material and soil particles. The strength efficiency of samples, when mixing identical quantities of material over the same maintenance duration, varies. When (xg1%, f1%) is cured under dry conditions for 7 days, its compressive strength can attain 1795 kPa, whereas the compressive strengths of (xg1%, f0%) and (xg0%, f1%) are 1432 kPa and 1117 kPa, respectively. The efficiency improvement rates are 95.97% and 25.35%, respectively. The maximum compressive strength after 28 days of curing for (xg1%, f1%), (xg1%, f0%), and (xg0%, f1%) is 2002 kPa, 1699 kPa, and 1453 kPa, respectively. The efficiency improvement rates are 56.57% and 17.83%, respectively. It can be inferred that, under dry curing circumstances, xanthan gum exhibits superior efficacy in enhancing sample strength.

3.3. Failure Pattern

Figures 9–13 illustrate the failure modes of soil specimens subjected to conventional 28-day wet curing conditions. The untreated soil and the xanthan gum-treated soil display comparable damage patterns. Improved soil displays prominent fissures during uniaxial compression, creating a shear failure surface with an inclination angle ranging from 60° to 90°. No lateral bulging was observed in the sample, rather, axial damage was distinctly evident, marked by a significant and widespread primary crack, indicative of typical brittle failure. Upon examination, their stress–strain curves showed considerable resemblance, resulting in the conclusion that the incorporation of xanthan gum, in the absence of fiber blending, did not modify the soil's brittleness. Under wet curing conditions for 28 days (i.e., enclosed in sealed bags), a specific quantity of moisture was preserved in the samples, hence demonstrating the traits of plastic deformation.



(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 9. Uniaxial compressive test damage pattern under sealed preservation with 0% fiber content.



(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 10. Uniaxial compressive test damage pattern under sealed preservation with 0.1% fiber content.



(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 11. Uniaxial compressive test damage pattern under sealed preservation with 0.3% fiber content.



(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 12. Uniaxial compressive test damage pattern under sealed preservation with 0.5% fiber content.



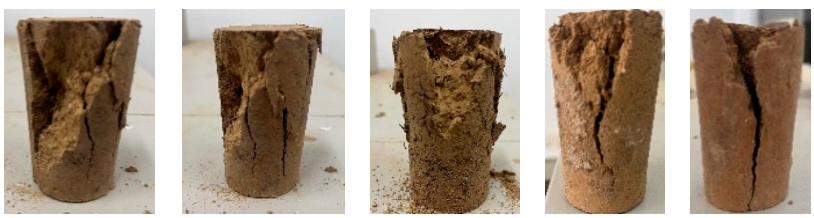
(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 13. Uniaxial compressive test damage pattern under sealed preservation with 1% fiber content.

With a longer curing time, the colloidal substance generated by xanthan gum progressively attaches to soil particles, creating an internal bonding solid that the diminishes crack size. As the fibers are incrementally introduced, they function as a binding agent inside the soil. At this point, damage to the samples is infrequently detected, and sporadic swelling occurs, when the volume at both ends surpasses that of the central region. As the fiber content rises, a gel-like substance develops among the fibers, xanthan gum, and soil, resulting in a robust network structure that fortifies the sample's strength. As the axial pressure escalates, no more cracks manifest in the sample. With the increase in axial pressure, no more cracks manifest in the sample, which subsequently begins to compress, demonstrating considerable plastic deformation at this juncture. This discovery aligns with the studies conducted by Liu et al. [20], resulting in the conversion of substantial fissures into smaller ones.

In humid regions, soil absorbs moisture and expands, resulting in increased particle separation and alterations in its structure and qualities. Clay swells upon water absorption and softening, resulting in less strength, whereas moist circumstances augment the soil's flexibility. During unconfined compression, the soil exhibits lateral expansion deformation under applied stress, rather than failing along a defined shear plane, demonstrating traits of plastic expansion damage. In wet protection, the force disseminates laterally, resulting in expansion-type damage marked by a substantial center and a diminutive end. Prolonging the curing duration will modify the internal composition of the soil. In soil mixed with a curing agent, the interaction between xanthan gum and coconut fiber during wet curing may alter the failure mode from brittle shear failure to multi-shear conical failure. The emergence of several fissures within the soil matrix results in increased anisotropy; these fissures are constrained by robust particle bonds during the expansion phase, leading to persistent directional alterations and finally creating a multi-crack conical damage surface.

Figures 14–18 illustrate the soil damage morphology during 28-day air-dry conservation settings, indicating that the samples exhibited increased brittleness throughout curing. The brittle behavior was more evident in samples with increased biopolymer concentration. The picture illustrates the transition from the brittle damage pattern of low xanthan gum–fiber soil mixtures to the ductile damage pattern of high xanthan gum–fiber soil mixtures in the samples. This indicates that the quantity of coir fibers is crucial for diminishing brittleness and enhancing ductility. In conclusion, the incorporation of xanthan gum altered the brittleness and strength of the soils, whereas the fibers enhanced their ductility.



(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 14. Uniaxial compressive test damage pattern under sealed preservation with 0% fiber content.



(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 15. Uniaxial compressive test damage pattern under sealed preservation with 0.1% fiber content.



(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 16. Uniaxial compressive test damage pattern under sealed preservation with 0.3% fiber content.



(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 17. Uniaxial compressive test damage pattern under sealed preservation with 0.5% fiber content.



(**a**) XG0% (**b**) XG1% (**c**) XG1.5% (**d**) XG2% (**e**) XG2.5%

Figure 18. Uniaxial compressive test damage pattern under sealed preservation with 1.0% fiber content.

Throughout the desiccation process, the soil mass expels moisture and contracts, resulting in a reduction in interparticle distance and the formation of microfractures therein. As drying progresses, these micro-cracks enlarge, stretch, and gradually develop into larger fissures. Drying maintenance will cause the soil structure to exhibit pronounced fissures, compromising its integrity and uniformity. Dry maintenance will diminish the flexibility of the soil and augment its brittleness. When exposed to external force, it is easier to develop a shear band in a specific direction, resulting in the specimen sustaining damage along the shear band, exhibiting distinct characteristics of brittle shear failure. The cementation among xanthan gum soil particles is augmented, resulting in increased soil strength and greater brittleness, with damage occurring along the shear surface at an inclination of approximately $(45^\circ + \varphi/2)$.

3.4. Stress–Strain Curves of Xanthan Gum and Coir Fiber Amended Soil

Figures 19 and 20 illustrate the stress–strain curves of samples subjected to two distinct curing conditions: dry and wet curing for a duration of 28 days. Figure 19 unequivocally demonstrates that samples with xanthan gum display elevated peak stress following 28 days of wet curing. This indicates that prolonging the curing duration may facilitate interactions between xanthan gum and soil particles, so strengthening their bond and improving compressive strength. Furthermore, an increase in xanthan gum concentration markedly improves the sample strength during the curing process. For example, the maximum stress of the sample combined at a ratio of XG 2.5% and F 0.1% rose by 232 kPa after 28 days of wet curing, but the maximum stress of the sample combined at XG 1.0% and F 0.1% grew by merely 111 kPa. This suggests that an extended curing duration facilitates the greater incorporation of xanthan gum into the soil.

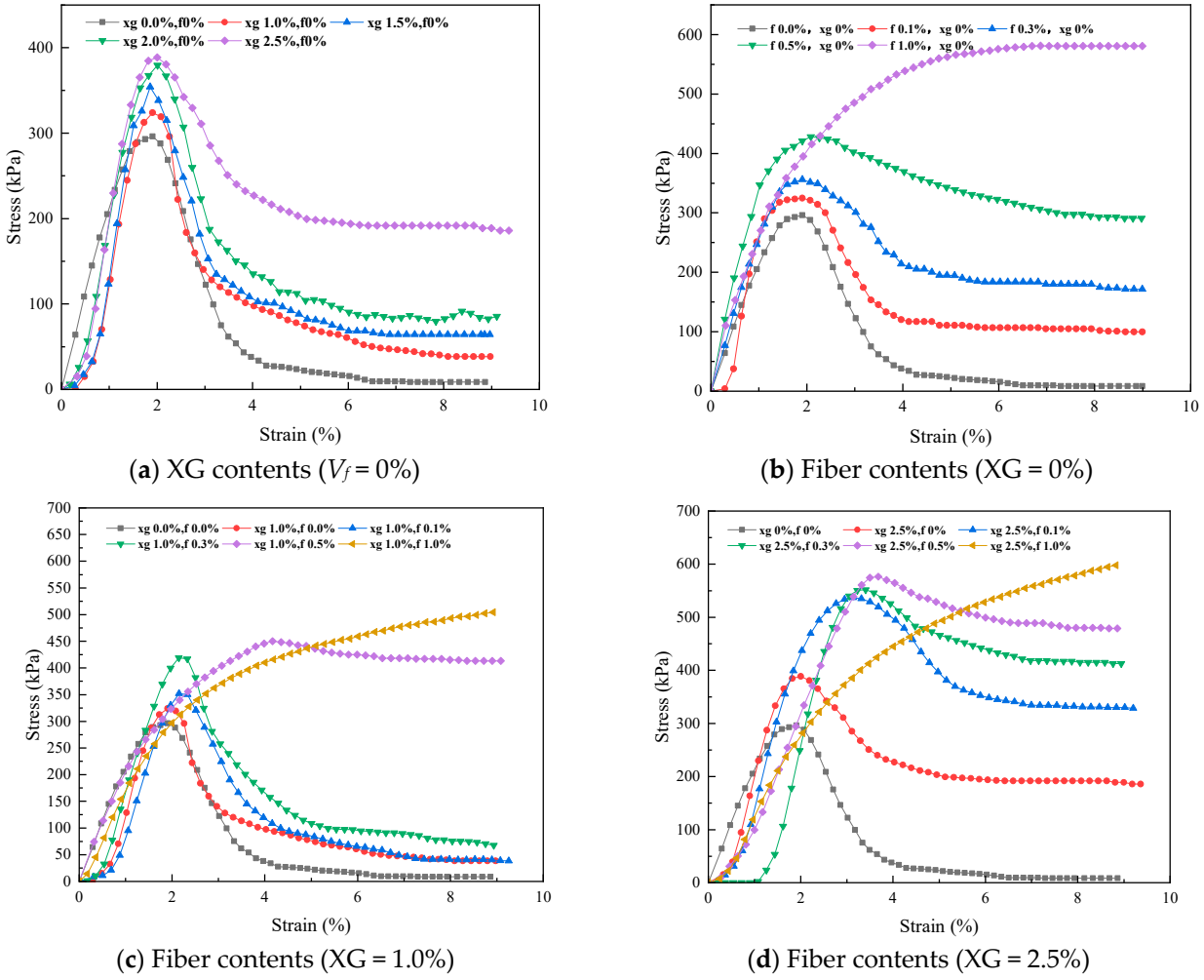
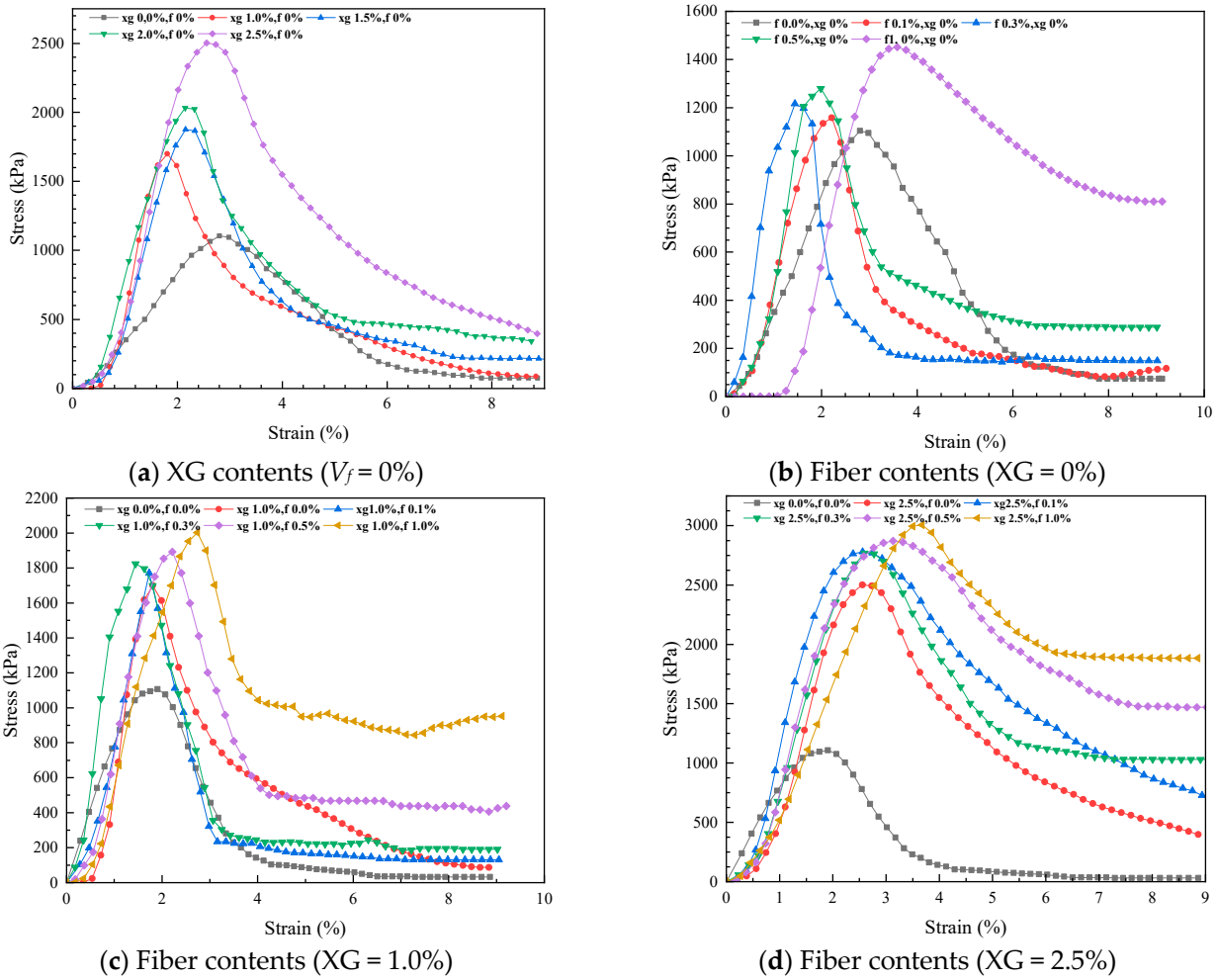


Figure 19. Stress–strain curve of the uniaxial compressive test under wet curing conditions.

The anionic carboxyl (-COOH) and hydroxyl (-OH) groups in xanthan gum's structure can interact with soil cations (e.g., Na^+, K^+, Ca^{2+}, etc.), resulting in the formation of ionic or hydrogen bonds. The deprotonated carboxyl groups of xanthan gum generate negative charges, which attract cations in the soil and facilitate their exchange with negatively charged clay minerals. This interaction can modify the surface charge characteristics of soil particles, facilitating particle aggregation. Furthermore, when xanthan gum dissolves in water, it produces a viscous hydrogel that occupies the voids between soil particles, establishing an interconnected network structure. This structure boosts the soil strength

and stiffness while simultaneously reducing hydraulic conductivity, hence raising peak stress [21,22].



(**a**) XG contents (V_f = 0%)

(**b**) Fiber contents (XG = 0%)

(**c**) Fiber contents (XG = 1.0%)

(**d**) Fiber contents (XG = 2.5%)

Figure 20. Stress–strain curve of the uniaxial compressive test under dry curing conditions.

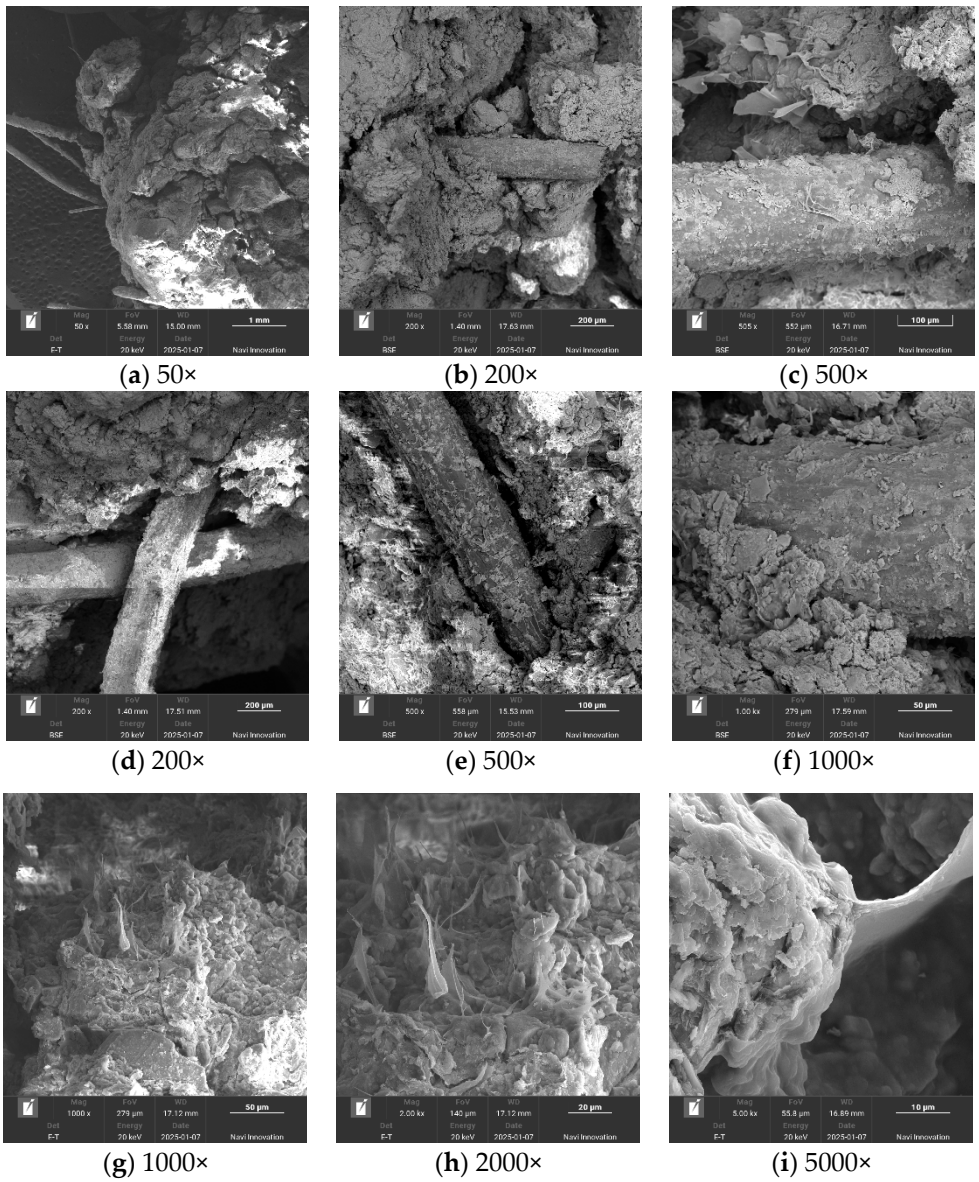
Figure 20 illustrates the stress–strain curves of the specimens cured in dry circumstances for 28 days. Figures 19a and 20a demonstrate that the incorporation of xanthan gum markedly increases the peak stress of the specimens. Figures 19b and 20b demonstrate that the fiber retain residual stress following the compression and destruction of the specimens. During a 28-day dry curing process, the moisture in the gum gel will progressively evaporate, concurrently resulting in the formation of a solid gum film. These solidified films can tightly adhere soil particles and fiber, so markedly improving the bonding strength between them, which contributes to an increase in the peak stress of the specimens [23].

Under dry curing circumstances, the gum film may experience shrinkage and become brittle, with this brittleness becoming more pronounced as the curing duration and gum quantity rise. Figure 4 illustrates that, irrespective of the gum quantity, the stress–strain curves exhibit a softening effect post-peak stress when fiber content escalates. After the specimen's stress attains its maximum value, an increased compressive strain can more efficiently leverage the tensile characteristics of the fiber, resulting in the improved ductility of the samples and subsequently augmenting the residual stress post-damage [24].

3.5. Microanalysis

Figure 21a–c illustrate the interior morphology of the soil samples at magnifications of 50×, 200×, and 500×, respectively. The bonding blocks formed between the xanthan

gum and the soil particles are relatively distributed, making it challenging to join the soil particles. The reduced concentration of xanthan gum results in an increased number of voids in the material. Scattered xanthan gum gels are affixed to the fiber.



(**a**) 50× (**b**) 200× (**c**) 500×

(**d**) 200× (**e**) 500× (**f**) 1000×

(**g**) 1000× (**h**) 2000× (**i**) 5000×

Figure 21. The picture of microscopic morphology at different magnifications.

Figure 21d–f illustrate the internal morphology of the soil examined at magnifications of 200×, 500×, and 1000×. As the xanthan gum level increases, it binds the soil particles to create gel agglomerates, filling the interstitial spaces and thereby improving the specimen's compressive strength. The fiber's surface is partially devoid of its cuticle covering, revealing a distinct and organized depression that facilitates interfacial interaction between the coconut fiber surface and the xanthan gum. The coarse texture of the coconut shell fiber is evident, together with the presence of gelatinous substances, suggesting that the incorporation of coconut shell fiber positively influences the adhesion among soil particles.

The fiber facilitates the distribution of xanthan gum and soil particle gels within the soil (illustrated in Figure 21g–i, where the hydrogel is magnified 5000 times to reveal internal details), providing a framework for the agglomerates formed by soil particles and xanthan gum, which adhere to the surface of the coconut shell fiber, creating a cohesive soil structure and coconut shell fiber that serves an adhesive function. Additionally, the rough surface of

the coconut shell fiber generates frictional force when the soil structure is subjected to stress, exerting a restraining influence on the soil body and resisting deformation. The fiber's binding action on soil particles improves the stability of the soil structure. Consequently, the fiber can influence the likelihood of the abrupt displacement of soil particles under axial load [25]. The xanthan gum in the specimen binds easily to smaller soil particles, while the woven network structure of the coconut shell fiber more effectively stabilizes bigger soil particles, hence enhancing the specimen's strength.

4. Conclusions

The research used a mixture of xanthan gum and coconut shell fiber to enhance the clay, examining the associated mechanical properties of the soil. The effects on the mechanical properties of the subgrade and slope soils in engineering were evaluated, offering a viable solution for subgrade deterioration and slope instability in various locations of the country. The primary conclusions are as follows:

(1) The unconfined linear compressive strength of xanthan gum alone or in coir fiber-treated soils increased with its concentration. Notably, the unconfined compressive strength of coir fiber-treated clays surpassed that of xanthan gum at a curing duration of 0 days, indicating that the unconfined compressive strength of the specimens was governed by the coir fibers in the untreated specimens.

(2) Xanthan gum can create a rigid film and enhance the compressive strength of the specimen within 7 days of conditioning in dry settings; however, 28 days of conditioning in wet conditions is necessary to optimize the gel's effect.

(3) Xanthan gum influences the compressive strength of the specimen and the extent of strength enhancement, whereas coir fibers augment the specimen's strength, transform its brittleness into ductility, and impart residual strength post-failure. The incorporation of xanthan gum altered the soil's strength and brittleness, while the inclusion of fibers modified its toughness.

(4) The xanthan gum or coconut fiber is utilized to enhance the specimen's strength through the incorporation of additional materials, and the strengthening efficacy after 28 days under dry conditions is inferior to that observed at 7 days. The xanthan gum's contribution to the specimen is predominantly realized within the first 7 days. During the subsequent 7 to 28 days, xanthan gum's influence diminishes, yet it continues to facilitate the incremental strength enhancement of the specimen.

(5) Xanthan gum incorporated into the soil will generate a gel-like layer, uniformly covering the surface and occluding the pores, thus stabilizing the soil structure. Fiber is incorporated into the soil to create a conducive environment for the gelling material, facilitating the adhesion of the product to the growth, and thereby resulting in a strong bond between the fibers and the soil. Additionally, the fiber establishes a spatial mesh structure within the soil, which mitigates cracking and enhances the soil's resistance to deformation. The coconut fiber primarily serves a reinforcing function, while xanthan gum acts as a curing agent, their combined action alters the intrinsic properties of the soil.

In this paper, the long-term durability of xanthan gum in saturated environments is not considered, and we discuss the mechanical properties of xanthan gum at an optimal water content. In subsequent studies we can consider the mechanical properties and durability of xanthan gum-amended soils when the water content is too high, and investigate whether xanthan gum is effective in improving soil properties at a high water content.

(1) The effect of xanthan gum on the strength of improved soil is most significant near the optimal water content. At this time, xanthan gum can give full play to its role in filling the pores and enhancing the inter-particle bonding, so that the strength of the soil body reaches a high level.

(2) The strength of xanthan gum-amended soils decreases dramatically when the water content is too high, especially near saturation. This is because excess moisture weakens the bond between the xanthan gum and the soil particles, and also causes the gel structure of the xanthan gum to become loose due to water absorption and expansion, thus reducing the overall strength of the soil.

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