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Research Article

Study on Mechanical Properties of Cement–Jute Fiber Modified Weak Expansive Soil

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Sixteen groups of comprehensive tests were undertaken to examine the modifications in the mechanical characteristics of weak expansive soil resulting from the inclusion of a composite material comprising cement and jute fibers. The aim of the tests was to analyze the unconfined compressive strength and shear strength. The results reveal that (1) as the modified material content increased, the stress–strain curve of the modified soil progressively became steeper, with a more pronounced peak value. Under the same strain condition, the stress variation increased accordingly. After the stress reached its maximum, a sudden phenomenon of brittle axial compression failure occurred. (2) With the increase in cement content, the unconfined compressive strength and shear strength of the modified expansive soil gradually increased, reaching the highest shear strength when the cement content was 8%. With the increase in jute fiber content, the unconfined compressive strength and shear strength of modified expansive soil increased first and then decreased, reaching the highest value when the content was 0.5%. (3) The cohesion of modified expansive soil increased with the increase in cement content. When the cement content was 8%, the cohesion of the soil sample was as high as 298.29 kPa. The cohesion of modified expansive soil increased first and then decreased with the increase in fiber content. When the jute fiber content was 0.5%, the cohesion reached the maximum value. (4) The internal friction angle of the modified expansive soil increased with the increase in cement content. When the cement content was 8%, the internal friction angle of the soil sample increased by 2.64°. The cohesion of modified expansive soil increased first and then decreased with the increase in fiber content. When the jute fiber content was 0.5%, the internal friction angle reached the maximum value.

1. Introduction

Expansive soil is a kind of clay soil with water expansion and water loss shrinkage. Expansive soil contains hydrophilic minerals, such as illite, kaolinite, and montmorillonite or montmorillonite–illite mixture, so it is hydrophilic, the liquid limit is often greater than 40%, and has a unique expansive structure system [1, 2]. China has a vast territory, and the expansive soil area occupies half of the country in China. It is one of the countries with the most extensive distribution of expansive soil. When the water content of expansive soil changes, it will cause soil expansion or shrinkage deformation, causing engineering problems. For example, the roadbed filled with expansive soil will have expansion and shrinkage deformation, resulting in uneven settlement, shallow surface landslide, collapse, slip, and other problems [3], as shown in Figure 1.

The commonly used modified material for modified expansive soil is cement. With the incorporation of cement, the internal structure and chemical composition of expansive soil change, which leads to the change of mechanical properties such as strength of expansive soil [4]. Wang et al. [5] systematically investigated cement-modified expansive soil from three perspectives: phase composition, macroscopic mechanical properties, and microscopic structure. Huang et al. [6] determined that the optimal content of cement-modified expansive soil ranged between 6% and 10%. Wang et al. [7] analyzed the microscopic mechanism and road performance of cement-modified expansive soil under the action of dry–wet cycles. Phanikumar and Ramanjaneya

Figure 1: Cutting slope slip and subgrade cracks.

Table 1: Fundamental physical and mechanical properties of expansive soil.

Dry density (g·cm^{-3})	Natural moisture content (%)	Liquid limit (%)	Plastic limit (%)	Proportion	Maximum dry density (g·cm^{-3})	Free expansion rate (%)
1.38	23.21	50.4	25.7	2.68	1.67	52

Raju [8] concluded that cement-modified expansive soil can significantly improve the bearing capacity and compressive strength of pavement. Lu et al. [9] observed that the inclusion of cement enhanced the resilient modulus and compressive strength of expansive soil subjected to freeze–thaw cycle conditions. Cai et al. [10] obtained the dynamic load distribution and attenuation law of subgrade after adding cement in a field test of railway construction in an expansive soil area. Comparable to reinforced soil, the fiber modification mechanism of expansive soil entails additional confinement of soil deformation through the redistribution of stress between soil particles and fibers. This results in the enhancement of the physical and mechanical attributes of the modified expansive soil. Since most materials used for reinforced soil are bars placed horizontally, only lateral deformation can be controlled [11]. In contrast, the fiber is randomly and uniformly distributed in the expansive soil [12]. As such, fiber-modified soil can effectively limit not only lateral deformation but also vertical deformation [13, 14]. Fan et al. [15] utilized lignin fibers to improve expansive soil in seasonal freezing areas, examining the feasibility and effectiveness of enhancing the shear capacity of the modified expansive soil. Mohamed et al. [16] discussed the improvement of sawdust ash on the properties of expansive soil. Zhu et al. [17] explored the impact of incorporating polypropylene fiber on the expansion and shrinkage properties of expansive soil. Using numerical simulation for cross-verification, Tiwari and Satyam [18] investigated the influence of polypropylene fiber on the strength and durability of expansive soil subgrade. Yuan et al. [19] examined the mechanical properties and microstructural changes of glass fiber-modified expansive soil. Mohamed et al. [20] studied the soil stability of some tropical soils. Jamsawang et al. [21] used dredged sediments treated with cement and fly ash as road materials to study the mechanical and microstructural characteristics of road materials.

In summary, research on the modification of expansive soil using cement has reached a relatively mature stage, yielding significant results. Nevertheless, relying solely on cement for the modification of expansive soil can potentially result in the formation of cracks in the cementitious material, leading to a decrease in the strength of the modified soil [22]. Further, environmental factors like rainfall can induce erosion, causing the dissolution and washout of cement hydration products. This significantly diminishes the effectiveness of soil modification and substantially reduces the durability, as well as the physical and mechanical properties, of the expansive soil. At present, basalt and glass fibers are more commonly used in fiber-modified expansive soil; however, their high ductility may not effectively improve the ductility of expansive soil, as fibers can be easily pulled out when the soil cracks [23].

Jute fiber shows promise as a modifier for expansive soil due to its high hygroabsorbency [24, 25]. Through the uniform incorporation of an adequate quantity of jute fiber into expansive soil, it can absorb infiltrating water, mitigate the formation of water molecular films around soil particles, and enhance the soil's characteristics related to expansion and shrinkage [26]. Moreover, jute fiber biodegrades slowly without polluting the soil, which aligns with the concept of sustainable development. Therefore, investigating the modification of expansive soil using a cement–jute fiber composite holds significant engineering value.

In the present study, the influence of cement–jute fiber composite modified material on the mechanical parameters such as unconfined compressive strength and shear strength of expansive soil was explored by means of comprehensive testing of different cements and jute fiber contents. The aim of the study was to explore the mechanical property changes in cement–jute fiber-modified expansive soil, analyze the modification effect of cement–jute fiber on expansive soil, and provide foundational research for the engineering application of cement–jute fiber composite-modified expansive soil.

2. Materials and Methods

2.1. Materials. The basic physical and mechanical properties of the test soil sample are presented in Table 1, demonstrating the typical characteristics of weak expansive soil.

Table 2: Basic physical and mechanical properties of ordinary Portland cement.

Setting time (s)		Compressive strength (MPa)		Flexural strength (MPa)	
Initial condensation	Final condensation	3 days	28 days	3 days	28 days
172	220	34.6	54.2	6.7	9.2

Table 3: Basic physical and mechanical properties of jute fiber.

Diameter (μm)	Length (mm)	Density (g·cm^{-3})	Elongation (%)	Young's modulus (GPa)	Tensile strength (MPa)	Specific tensile strength (MPa·g^{-1}·cm^{-3})
50–60	5–7	1.3–1.48	1.5–1.8	10–30	390–800	302–548

Figure 2: Jute fiber with scale.

Ordinary Portland cement was used in the test, with a density of 3.08 g·cm^{-3}, a 0.08 mm sieve residue of 1.6%, a specific surface area of 375 m^2·kg^{-1}, a mortar fluidity of 187 mm, and a water consumption of 27.30% for standard consistency. The various physical and mechanical properties of the cement are listed in Table 2.

The experimental chopped jute fiber exhibited fast water dispersion, low ductility, good hygroscopicity, and biodegradability. The main physical and mechanical properties are shown in Table 3. The length of jute fiber is shown in Figure 2.

2.2. Methods. To examine alterations in the physical and mechanical attributes of cement–jute fiber composite-modified expansive soil across various levels of modified material content, a total of 16 comprehensive tests were performed, employing unconfined compressive strength tests [27] and direct shear tests [28]. During the test process, soil samples were dried for 24 hr and then artificially crushed. The samples were prepared uniformly according to the mass ratio standard (the mass ratio of dry soil to other modified materials). Cement contents of 2%, 4%, 6%, and 8% and jute fiber contents of 0.1%, 0.3%, 0.5%, and 0.7% were mixed uniformly into the expansive soil. The specific test scheme is as follows:

(1) The expansive soil and cement–jute fiber-modified expansive soil samples were designed, respectively. The sample preparation was carried out in accordance with the standard of mass ratio. The cement content was 2%, 4%, 6%, and 8%, and the jute fiber content was 0.1%, 0.3%, 0.5%, and 0.7%. The expansive soil was uniformly mixed, and the cement–jute fibers with different contents were divided into grades for the processing of test data. Among them, grade 1 was 2% + 0.1% of cement–jute fiber, grade 2 was 2% + 0.3%, and the remaining grades were analogized in turn, a total of 16 groups, a comprehensive test.

(2) The contrast test of graded particles was carried out. The soil was sampled by quartering method, and the soil samples after adding modified materials were sealed for 24 hr. The soil samples of each group were subjected to particle analysis test by screening method and laser particle size analyzer, respectively. The percentage of each particle group in the total mass of the soil sample was measured, and the distribution of soil particle size was explored and the particle gradation curve was drawn.

(3) Microscopic analysis: Scanning electron microscopy was used to observe and analyze the microstructure of two kinds of soil samples: plain expansive soil and modified expansive soil with optimal dosage of cement–jute fiber, and their macroscopic mechanical properties were expounded through microscopic mechanism.

(4) Compaction experiment: The modified soil samples were placed in a plastic bag and sealed for 24 hr. The soil samples were compacted according to the test steps, and the dry density and water content of each soil sample were determined. The relationship between dry density and water content was plotted, and the relationship between optimal water content and maximum dry density was explored.

(5) The determination of the liquid and plastic limits of the soil is particularly important for understanding and mastering the characteristics of the soil. The liquid and plastic limits of the soil in each group are determined by the liquid and plastic limit measurement method, and the liquid and plastic limits of the samples in each group are compared and analyzed.

(6) In order to improve the accuracy of the test, before the free expansion rate test, the sample was placed in

Figure 3: Modified expansive soil failure sample.

Figure 4: Plain expansive soil failure sample.

the darkness of the room and stood for 12 hr. The free expansion rate test was carried out according to the test steps and the test data of each group of expansive soil were compared. The inhibition effect of different dosages of admixture on the expansion characteristics of expansive soil samples was studied and analyzed.

(7) According to the setting, cement–jute fiber-modified expansive soil was prepared and sealed for 24 hr. According to the measured maximum dry density, soil samples with different contents of modified materials were made, and the unconfined compressive strength indexes of each soil sample were tested in turn.

(8) According to the geotechnical test method standard GB/T50123-2019 [29], the remolded soil samples cured for 28 days were treated, and the direct shear test was carried out under the condition of controlling the matrix suction and different net vertical stress.

3. Results and Discussion

3.1. Unconfined Compressive Strength Test. The unconfined compressive strength test involved applying other stresses aside from the axial stress to the test soil sample, before other forces were applied. The ultimate bearing strength of the soil to resist damage was measured. Through such tests, a more intuitive representation of the enhancement in compressive strength resulting from expansive soil modification can be provided. They hold significant value in guiding practical engineering applications. The soil samples damaged by modified expansive soil and plain expansive soil during the testing process are shown in Figures 3 and 4, respectively. The size of the expansive soil sample used is a cylindrical soil sample with a diameter of 50 mm and a height of 50 mm.

(1) Stress–strain relationship curves at 7 days of curing.

The stress–strain curves of cement–jute fiber composite modified expansive soil at different curing ages exhibited similar trends. For the purpose of simplicity, only the stress–strain curves of modified expansive soil at a 7-day curing age are presented herein, as shown in Figure 5. When the modified material content remained constant, the stress on the soil sample gradually increased as the strain increased. The curve velocity slowed before reaching the maximum stress, and after reaching the maximum stress, the stress gradually decreased as the strain increased.

As the content of the modified material constantly increased, the curve trend became progressively steeper, with a more pronounced peak value. Under the same strain conditions, the change in stress correspondingly increased. When the stress reached its maximum, a sudden brittle axial compression failure phenomenon was observed.

(2) The influence of modified material content on unconfined compressive strength.

The influence curves of cement–jute fiber composite modified material on the unconfined compressive strength of expansive soil are shown in Figure 6. At a curing age of 7 days, the cement with contents of 2%, 4%, 6%, and 8% reached their highest values when the jute fiber content was 0.5%, being 1.76, 2.67, 3.67, and 4.41 times that of plain expansive soil, respectively. At a curing age of 14 days, such values were 2.12, 3.12, 4.34, and 5.40 times the plain expansive soil, respectively. At a curing age of 28 days, such values were 2.61, 3.85, 5.31, and 6.32 times that of plain expansive soil, respectively.

An observation can be made that the addition of cement significantly improved the unconfined compressive strength of expansive soil. The unconfined compressive strength of modified expansive soil gradually increased with the increase in cement content when the curing age was fixed and the jute fiber content remained unchanged. Such findings could be attributed to the fact that, after mixing cement with expansive soil, oxides such as CaO, Fe_2O_3, and Al_2O_3 would

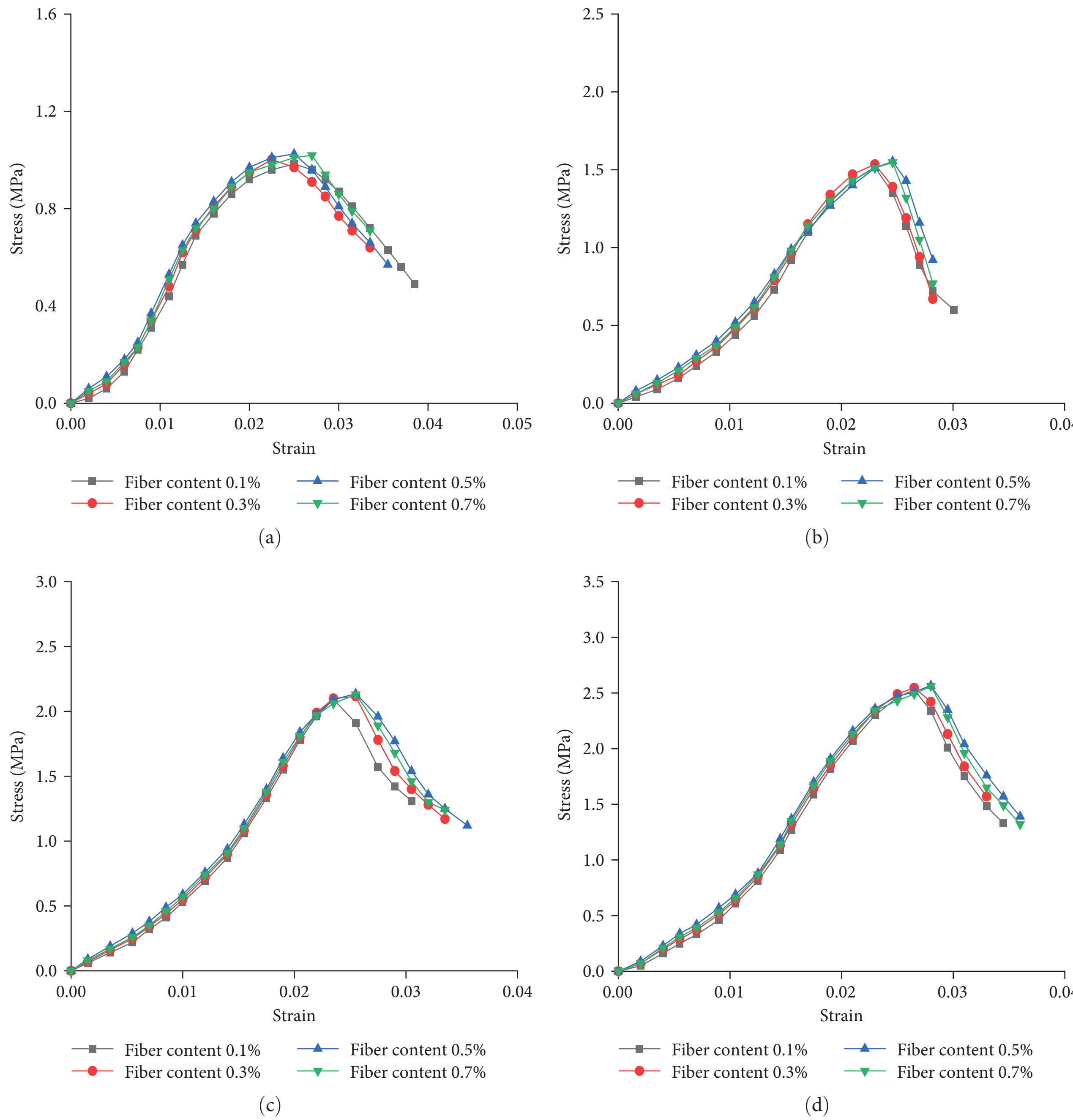

FIGURE 5: Stress–strain relationship curves at 7 days of curing. (a) Cement content of 2%; (b) cement content of 4%; (c) cement content of 6%; and (d) cement content of 8%.

hydrate upon contact with water and produce hard substances like calcium silicate hydrate gel. The cementing substance wrapped the soil particles and formed a dense 3D skeleton, sharing the stress produced by axial compression with the soil particles. As the cement content further increased, the hydration reaction in the soil became more adequate, generating more cementitious substances. The cement particles that did not participate in the reaction filled the soil's pores, further enhancing the soil's compressive capacity.

After 7 days of curing, the unconfined compressive strength levels of expansive soil modified with 0.1%, 0.3%, 0.5%, and 0.7% jute fiber and 8% cement content were 4.34, 4.38, 4.41, and 4.40 times higher than that of plain expansive soil, respectively. At 14 days of curing, such values were 5.33, 5.37, 5.40, and 5.39 times higher, respectively. After 28 days of curing, such values were 6.25, 6.29, 6.32, and 6.29 times higher, respectively. The described results indicate that the addition of jute fiber improved the unconfined compressive strength of modified expansive soil to various extents

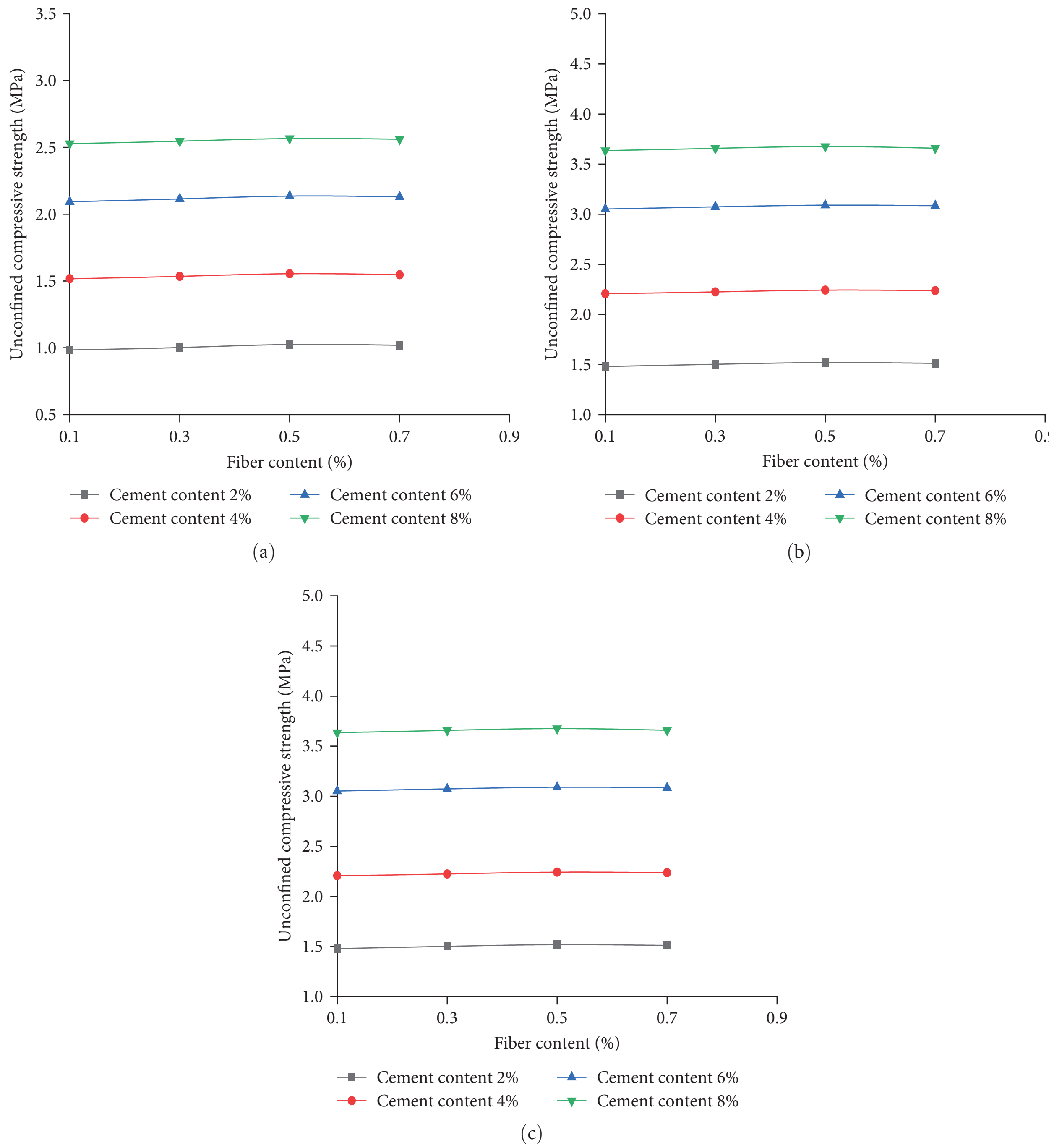

Figure 6: The relationship curves between unconfined compressive strength and modified material content: (a) 7 days, (b) 14 days, and (c) 28 days.

compared to plain expansive soil. Further, at a specific curing age and constant cement content, the unconfined compressive strength of modified expansive soil first increased and then decreased with increasing jute fiber content, reaching its maximum value at 0.5% fiber content.

The modification effect of jute fiber on expansive soil was constrained and less potent compared to cement. The inclusion of jute fiber led to a more comprehensive 3D spatial arrangement within the expansive soil because of its irregular and uniform dispersion. Some of the jute fiber volume became embedded in soil particles coated with cement or cementitious material. This, in turn, reinforced the cohesion among soil particles, facilitated more efficient stress sharing and transfer within the soil, and ultimately enhanced its unconfined compressive strength.

The improvement method of composite material-modified expansive soil can significantly improve the performance of expansive soil, thereby increasing its utility and achieving a substantial modification effect that cannot be attained through the use of a single modifying material.

FIGURE 7: Modified expansive soil shear failure specimen.

FIGURE 8: Shear failure sample of plain expansive soil.

Under the same conditions, the performance of the composite modification method is generally much better than that of the single modification method, and the modification effect is better. Thus, the composite modification method is significantly better than its single modification method.

3.2. Direct Shear Test. Soil shear strength is the primary indicator for assessing soil stability. The ultimate strength of soil during the process of shear failure serves as a representation of the soil's ability to withstand shear stress. The characteristics of shear failure in soil are also a crucial research focus within the field of soil mechanics. Figures 7 and 8 show the shear failure specimens of modified expansive soil and plain expansive soil, respectively. The size of the expansive soil sample used is a cylindrical soil sample with a diameter of 61.8 mm and a height of 20 mm.

(1) Shear strength fitting.

The trends of cement–jute fiber composite-modified expansive soil under different curing ages were similar. For the purposes of simplicity, only the scatter diagrams of the relationship between vertical pressure and shear strength of the modified expansive soil under the curing age of 28 days and the relevant fitting curves are listed, as shown in Figure 9.

As demonstrated in Figure 9, under the same vertical pressure, with the gradual increase in cement content, the shear strength of cement–jute fiber composite-modified expansive soil exhibited a rising trend. The highest value of 451.58 kPa was reached when the cement content was 8% and the curing age was 28 days, which is 337.69 kPa higher than that of plain expansive soil. The effect on the shear strength of modified expansive soil was found to be significant.

As cement was continuously incorporated, the cementitious materials generated by the hydration reaction connected the expansive soil particles into considerably solid and dense skeleton particles. Some soil particles were completely wrapped in cement, which greatly improved the overall stiffness of the modified expansive soil. Moreover, as the curing time extended, cement hydration progressed further, resulting in the formation of additional cementitious materials that filled the pores within the soil. This led to a denser and more solid composition of the modified expansive soil. Consequently, its shear strength steadily increases throughout the curing process.

The shear strength of cement–jute fiber composite-modified expansive soil initially increased and then decreased with the continuous addition of jute fiber, reaching its highest value when the fiber content was 0.5%. This phenomenon occurred because an appropriate amount of jute fiber was added to the cement-mixed expansive soil, in which the cement–expansive soil particles bonded with each other. Because of its low ductility and high toughness, soil particles were resistant to breaking or being pulled out as a whole when subjected to stress. This resulted in the formation of a stable 3D spatial structure. Additionally, as the fiber content increased, the density of fibers on the soil shear plane also rose, further enhancing their ability to share and withstand shear stress. When the content of jute was excessive, clumping was likely to occur in the soil, and the voids in the fiber would change significantly, leading to the destruction of the stable 3D space system in the soil. As such, the overall stiffness of the modified expansive soil would decrease relatively.

With the gradual increase in vertical pressure, the contact between soil particles became denser, and shear failure was less likely to occur. Therefore, if the same shear displacement was generated, greater shear stress was required. The main factors of resistance to shear failure of plain expansive soil are its skeleton, friction force, and cohesion. Thus, the change in shear strength of the soil was limited under the condition of vertical pressure change.

In Figure 10, an observation can be made that the shear strength of modified expansive soil exhibited a linear increasing trend with the increase in vertical pressure when the content of the modified material remained unchanged. Linear fitting of the scatter plots was performed, and the results are displayed in Table 4. The correlation coefficients (R^2) were all greater than 0.98, indicating a high degree of linear correlation. Such results illustrate that a more accurate determination of the internal friction angle (ϕ) and cohesion (c) for modified expansive soil can be achieved by utilizing the fitting curve derived from the scatter diagram depicting the correlation between shear strength and vertical pressure in the direct shear test.

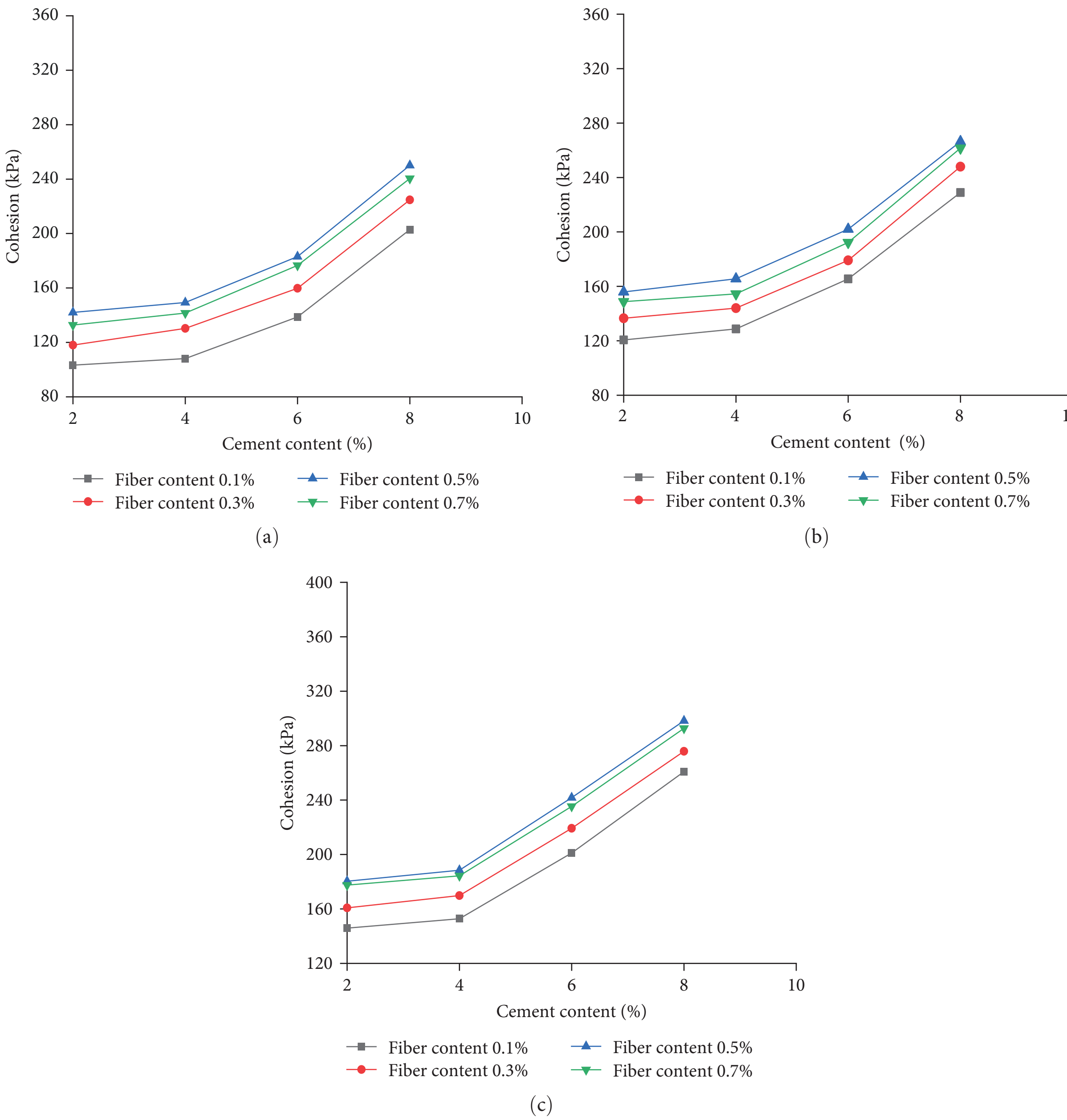

FIGURE 9: The relationship curves between the cohesive force and the content of modified materials: (a) 7 days, (b) 14 days, and (c) 28 days.

(2) Influence of modified material content on cohesion and internal friction angle of expansive soil.

The impact of cement–jute fiber composite-modified materials on the cohesion of expansive soil is depicted in Figure 9. An observation can be made that at a consistent curing age, the cohesion of modified expansive soil exhibited a continuous increase as the cement content increased. However, the cohesion displayed an initial increase followed by a subsequent decrease with the increasing fiber content. With a cement content of 2%, the soil sample's cohesion, containing 0.5% fiber content, reached the highest value of 142.05 kPa, an increase of 103.47 kPa compared to the unmodified expansive soil. When the cement content was 4%, the highest cohesion achieved for the soil sample with 0.5% fiber content was 149.34 kPa, marking an increase of 110.76 kPa compared to the unmodified expansive soil. With a cement content of 6%, the peak cohesion value for the soil sample with 0.5% fiber content reached 183.11 kPa, which represented a difference of 144.53 kPa compared to the unmodified expansive soil. At an 8% cement content, the cohesion of the soil sample with 0.5% fiber content reached 250.08 kPa, demonstrating a substantial increase of 211.50 kPa in comparison to the unmodified expansive soil. This cohesion value was also 6.48 times higher than that of the unmodified expansive soil.

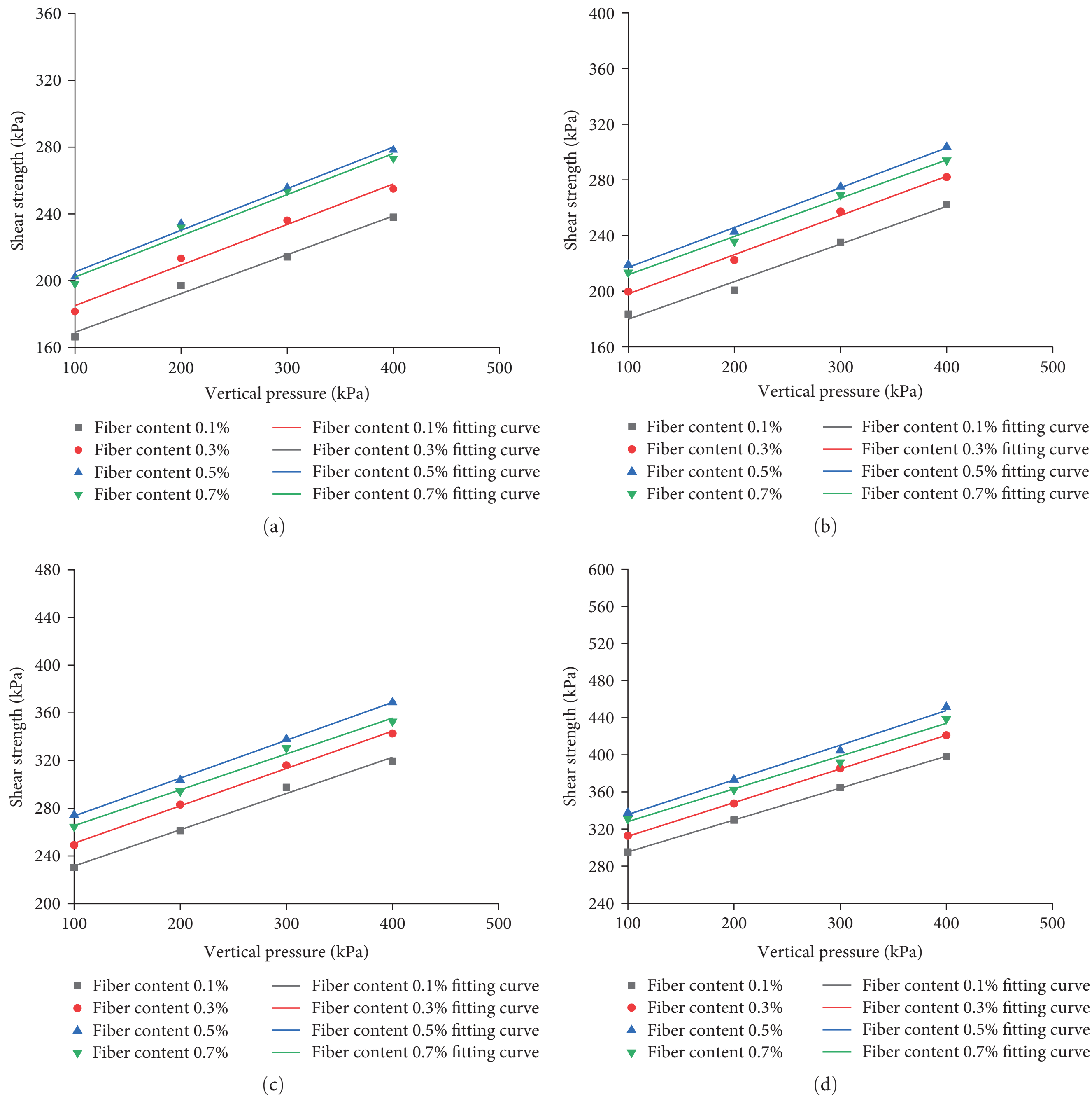

Figure 10: Shear strength and vertical pressure fitting curves at 14 days. (a) Cement content of 2%; (b) cement content of 4%; (c) cement content of 6%; and (d) cement content of 8%.

At a cement content of 2%, the maximum cohesion recorded for the soil sample with 0.5% fiber content was 155.87 kPa, which represented an increase of 117.29 kPa compared to the unmodified expansive soil. When the cement content was 4%, the cohesion of the soil sample with 0.5% fiber content reached 165.56 kPa, marking a rise of 126.98 kPa compared to the unmodified expansive soil. With a cement content of 6%, the highest cohesion value for the soil sample with 0.5% fiber content was 201.98 kPa, indicating an increase of 163.40 kPa in comparison to the unmodified expansive soil. At an 8% cement content, the cohesion of the soil sample with 0.5% fiber content reached 266.42 kPa, showing a substantial increase of 227.84 kPa compared to the unmodified expansive soil. This cohesion value was also 6.91 times higher than that of the unmodified expansive soil.

At a cement content of 2%, the cohesion of the soil sample with 0.5% fiber content measured 180.35 kPa, indicating an increase of 141.77 kPa compared to the unmodified expansive soil. When the cement content was 4%, the highest cohesion value for the soil sample with 0.5% fiber content reached 188.46 kPa, marking a rise of 149.88 kPa compared

Table 4: Shear strength fitting equation at 28 days.

Dosage	7 days		14 days		28 days	
	Fitting formula	R^2	Fitting formula	R^2	Fitting formula	R^2
0	$y = 0.191x + 38.58$	0.994	$y = 0.191x + 38.58$	0.994	$y = 0.191x + 38.58$	0.994
2% + 0.1%	$y = 0.223x + 103.28$	0.996	$y = 0.229x + 120.64$	0.996	$y = 0.232x + 145.87$	0.988
2% + 0.3%	$y = 0.237x + 118.01$	0.998	$y = 0.242x + 136.61$	0.982	$y = 0.243x + 160.77$	0.986
2% + 0.5%	$y = 0.238x + 142.05$	0.998	$y = 0.247x + 155.87$	0.989	$y = 0.249x + 180.35$	0.991
2% + 0.7%	$y = 0.236x + 132.75$	0.996	$y = 0.246x + 148.78$	0.995	$y = 0.247x + 177.51$	0.982
4% + 0.1%	$y = 0.245x + 108.12$	0.995	$y = 0.252x + 128.76$	0.983	$y = 0.270x + 152.84$	0.985
4% + 0.3%	$y = 0.250x + 130.35$	0.999	$y = 0.260x + 144.05$	0.988	$y = 0.282x + 169.85$	0.993
4% + 0.5%	$y = 0.258x + 149.34$	0.996	$y = 0.269x + 165.56$	0.983	$y = 0.286x + 188.46$	0.997
4% + 0.7%	$y = 0.254x + 141.54$	0.994	$y = 0.274x + 154.45$	0.989	$y = 0.275x + 184.32$	0.995
6% + 0.1%	$y = 0.280x + 138.71$	0.991	$y = 0.281x + 165.51$	0.997	$y = 0.304x + 201.13$	0.992
6% + 0.3%	$y = 0.286x + 159.80$	0.991	$y = 0.304x + 179.12$	0.993	$y = 0.314x + 219.28$	0.997
6% + 0.5%	$y = 0.290x + 183.11$	0.994	$y = 0.309x + 201.98$	0.991	$y = 0.318x + 241.74$	0.999
6% + 0.7%	$y = 0.279x + 176.62$	0.992	$y = 0.307x + 192.30$	0.994	$y = 0.301x + 235.34$	0.992
8% + 0.1%	$y = 0.306x + 202.88$	0.989	$y = 0.310x + 228.92$	0.987	$y = 0.344x + 260.88$	0.999
8% + 0.3%	$y = 0.308x + 224.78$	0.999	$y = 0.311x + 247.98$	0.993	$y = 0.363x + 275.84$	0.999
8% + 0.5%	$y = 0.310x + 250.08$	0.999	$y = 0.325x + 266.42$	0.986	$y = 0.374x + 298.29$	0.990
8% + 0.7%	$y = 0.308x + 240.41$	0.996	$y = 0.302x + 261.60$	0.986	$y = 0.353x + 292.73$	0.990

to the unmodified expansive soil. With a cement content of 6%, the peak cohesion value for the soil sample with 0.5% fiber content was 241.74 kPa, demonstrating an increase of 203.16 kPa in comparison to the unmodified expansive soil. At an 8% cement content, the cohesion of the soil sample with 0.5% fiber content reached 298.29 kPa, showing a substantial increase of 259.71 kPa compared to the unmodified expansive soil. This cohesion value was also 7.73 times higher than that of the unmodified expansive soil. Clearly, the use of the cement–jute fiber composite-modified material significantly enhances the cohesion of expansive soil.

The influence curves for cement–jute fiber composite-modified materials on the internal friction angle of expansive soil are depicted in Figure 11. As illustrated, when the curing age and cement content remained constant, the internal friction angle of the modified expansive soil initially increased and then decreased as the fiber content increased. This occurred because an excessive amount of jute fibers disrupts the 3D spatial structure within the soil matrix, resulting in an increase in soil voids and a decrease in the internal friction angle. Under conditions where the curing period and jute fiber content remained constant, the internal friction angle of modified expansive soil gradually increased with the increase in cement content, with its effect being more pronounced than that of jute fiber. This phenomenon arose from the fact that cement enhanced the overall stiffness of expansive soil, rendering the soil less prone to shear displacement deformation. As a result, the internal friction angle of the soil exhibited a more pronounced increase.

In the 7-day cured soil samples, with cement contents of 2%, 4%, 6%, and 8%, the soil samples containing 0.5% jute fiber reached maximum internal friction angles of 13.39°, 14.47°, 16.17°, and 17.22°, respectively. These values represented increases of 2.58°, 3.66°, 5.36°, and 6.41°, respectively, compared to the unmodified expansive soil. Similarly, in the 28-day cured soil samples, with cement contents of 2%, 4%, 6%, and 8%, the soil samples with 0.5% jute fiber content achieved maximum internal friction angles of 13.98°, 15.96°, 17.64°, and 20.51°, respectively. These values marked increases of 3.17°, 5.15°, 6.83°, and 9.70°, respectively, compared to the unmodified expansive soil. Clearly, the use of the cement–jute fiber composite-modified material significantly enhanced the internal friction angle of expansive soil.

In the present study, findings were made that when the cement content was 8% and the jute fiber content was 0.5%, the unconfined compressive strength of expansive soil reached the highest. Further findings were made that adding jute fiber to lime stabilized expansive soil could reduce the expansion characteristics of expansive soil and improve the unconfined compressive strength of expansive soil. When the jute fiber content was 0.75%, the unconfined compressive strength increased the most [20]. In addition, the unconfined compressive strength of lime sludge clay mixed with cement increased with the increase in lime sludge content and reached the highest when the lime sludge content was 12% [8]. Further, related literature has investigated the properties of mica soil reinforced with jute fiber, slaked lime, or slag lime. Test results indicate that when the fiber content reaches 1%, both the unconfined compressive strength and material stiffness reach their peak values [25]. The effect of sawdust ash and high calcium fly ash on the mechanical properties of expansive soil has also been explored. It was observed that the addition of 1% cement to a mixture containing 10% high calcium fly ash and sawdust ash can optimize the strength of expansive soil. Through the described comparative analysis, it was evident that the approach of employing composite materials for expansive soil improvement can substantially enhance its performance [16]. In the present study, the effect of improving the unconfined compressive strength of expansive soil was also achieved when the content of cement and jute fiber was relatively small. The test analysis is shown in Table 5.

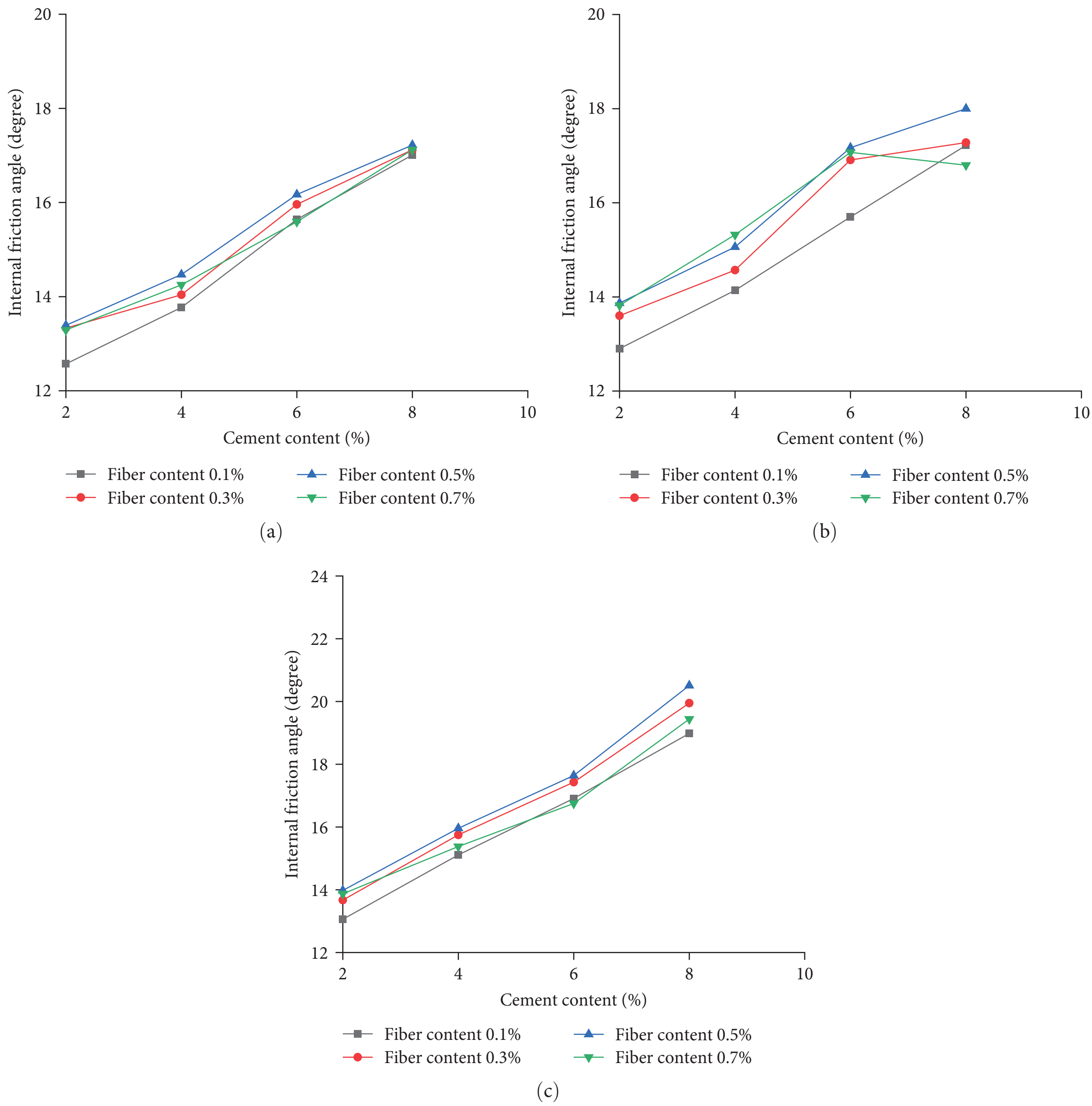

FIGURE 11: The relationship curves between the internal friction angle and the content of modified materials: (a) 7 days, (b) 14 days, and (c) 28 days.

TABLE 5: Comparative table of experimental study.

Reference	Research object	Optimal jute fiber content (%)	Optimal cement content (%)	Lime sludge (%)
The present study	Cement–jute fiber	0.5	8	–
Mohamed et al. [20]	Lime–jute fiber	0.75	25.7	–
Phanikumar and Ramanjaneya Raju [8]	Lime-sludge clay	–	–	12
Zhang et al. [25]	Lime–slag lime	1	–	–
Mohamed et al. [16]	Sawdust ash–high calcium fly ash–cement	–	1	–

4. Conclusion

In the present study, the influence of varying cement and jute fiber contents on the mechanical properties of expansive soil was investigated. The change rules and modification effects were analyzed mechanically, leading to the following conclusions:

(1) As the content of the modified material increased, the stress–strain curve of the modified soil became progressively steeper, and the peak value was more pronounced. Under identical strain conditions, the stress change increased accordingly. After the stress reached its maximum, the modified soil exhibited a sudden, brittle axial compression failure.

(2) With the increase in cement content, the unconfined compressive strength and shear strength of the modified expansive soil gradually increased and reached the highest shear strength when the cement content was 8%. With the increase in jute fiber content, the unconfined compressive strength and shear strength of modified expansive soil increased first and then decreased and reached the highest value when the content was 0.5%.

(3) The cohesion of modified expansive soil increased with the increase in cement content. When the cement content was 8%, the cohesion of the soil sample was as high as 298.29 kPa. The cohesion of modified expansive soil increased first and then decreased with the increase in fiber content. When the jute fiber content was 0.5%, the cohesion reached the maximum value.

(4) The internal friction angle of the modified expansive soil increased with the increase in cement content. When the cement content was 8%, the internal friction angle of the soil sample increased by 2.64°. The cohesion of modified expansive soil increased first and then decreased with the increase in fiber content. When the jute fiber content was 0.5%, the internal friction angle reached the maximum value. The present findings provide valuable insights into the modification of expansive soils using cement–jute fiber composite materials. These findings hold the potential for improving the mechanical properties of such soils, making them suitable for a range of engineering applications.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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