

## Research Article

# Experimental Investigation of Mechanical Behaviors of Fiber-Reinforced Fly Ash-Soil Mixture

Lihua Li,<sup>1</sup> Jiang Zhang,<sup>1</sup> Henglin Xiao ,<sup>1</sup> Zhi Hu ,<sup>1</sup> and Zhijie Wang<sup>2</sup>

<sup>1</sup>School of Civil Engineering, Architecture and Environment, Hubei University of Technology, Wuhan 430068, China

<sup>2</sup>School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, China

Correspondence should be addressed to Henglin Xiao; xiao-henglin@163.com and Zhi Hu; huzhi@hbut.edu.cn

Received 27 September 2018; Revised 29 December 2018; Accepted 3 January 2019; Published 3 February 2019

Academic Editor: Md Mainul Islam

Copyright © 2019 Lihua Li et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In recent years, applications of different types of solid waste in fiber-reinforced soil are developed to improve the strength of soil. This study presents an experimental investigation of mechanical properties of polypropylene fiber-reinforced fly ash-soil mixtures. A series of direct shear tests and unconfined compression tests were carried out. The effects of fly ash content and fiber content on compaction characteristics, shear strength, strength parameters, and unconfined compressive strength of the reinforced soil are investigated and discussed. Results reveal that when the fly ash content of the specimen exceeds 20% and the curing period exceeds 14 days, specimens become more brittle in the unconfined compression tests. It can be deduced that 30% fly ash and 1% fiber provide the optimum content, and the inclusion of fiber reinforcement has positive benefits on the mechanical properties of the reinforced soil to a certain extent.

## 1. Introduction

Fly ash, a waste generated in the process of burning coal to produce energy in thermal power plants, has caused a lot of pollution to the environment. The large increase of fly ash production and its environmental protection treatment have become a global concern [1]. At present, many scholars are engaged in utilizing fly ash in various aspects of geotechnical applications [2]. Mixing fly ash and fine-grained soil to improve its engineering properties has been widely recognized and applied.

The application of the reinforced soil method in geotechnical engineering has a long history, including in construction, roadways, railways, dikes, stabilization of soil slope, and improvement of soft soil. Certain desired properties such as load bearing capacity, shear strength, and permeability of soil can be improved by various techniques. One of the most commonly used techniques is the use of geosynthetics to reinforce the soil. Latha and Varman [3] conducted large triaxial tests to investigate the effect of the quantity of geotextile on the static and cyclic load response of sand. It can be observed that the inclusion of geotextile layers improves the peak shear strength, axial strain at

failure, and stiffness under static conditions, and higher dynamic moduli can be exhibited in reinforced specimens compared to the unreinforced sand under cyclic conditions. Abdi and Arjomand [4] conducted pullout tests aiming at studying the interaction of clays reinforced with geogrids embedded in thin layers of sand. Results revealed that encapsulating geogrids in thin layers of sand under pullout conditions enhances pullout resistance of reinforced clay. For the clay-sand-geogrid samples, an optimum sand layer thickness of 10 mm was determined, resulting in maximum pullout resistance, which increased with increasing confining pressure. Chen et al. [5] investigated the shear behavior of this geogrid-reinforced fill through large-scale triaxial tests. The shear deformation tends toward strain-hardening behavior with an increase in the number of geogrid layers and the confining pressure. Geogrids significantly improve the apparent cohesive strength of coarse-grained soil. The number of geogrid layers influences the geogrid-soil interface's mobilization and the slip surface type. Rose et al. [6] and Park and Tan [7] individually incorporated the fiber into the retaining wall and subgrade filler, and the engineering properties of the mixed material were systematically studied. Lovisa et al. [8] studied the effect

of water content on the shear strength of fiber-reinforced sand. The tests showed that the fiber can significantly improve the cohesion of sand under dry conditions. Sadek et al. [9] have investigated soil reinforcement using discrete randomly distributed fibers, and several models were suggested to estimate the improvement brought by fibers to the shear strength of soils. Anggraini et al. [10] carried out the indirect tensile test and unconfined compressive test to investigate the tensile and compression strengths of natural and treated soft soil. The tensile strengths and compression strengths of compacted specimens of natural soil and lime and coir fiber treated soil were obtained. Results revealed that both tensile and compressive strengths increase with the addition of lime and coir fiber and by increasing of the curing time.

Wu et al. [11] investigated the mechanical properties of silty clay reinforced with discrete, randomly distributed sisal fibers using triaxial shear tests. The sisal fibers were cut to different lengths, randomly mixed with silty clay in various percentages, and compacted to the maximum dry density at the optimum water content. The results indicated that with a fiber length of 10 mm and content of 1.0%, sisal fiber-reinforced silty clay is 20% stronger than nonreinforced silty clay. Gao et al. [12] performed a series of unconfined compressive strength tests on clay soil reinforced with basalt fibers under the condition of optimum water content and maximum dry density. Experimental results showed that basalt fibers can effectively improve the unconfined compression strength of clay soil. And, the optimal content and length are 0.25% and 12 mm, respectively. The results also showed that the basalt fiber-reinforced clay soil has the “poststrong” characteristic.

Because of few available literatures on the shear properties of fiber-reinforced fly ash-soil mixtures, effects of fly ash and fiber on the strength characteristics of fine-grained soil are still not clear and further research is needed. Therefore, this paper focuses on the mechanical behavior of clay mixed with different contents of fly ash and fiber reinforcement. A series of direct shear tests and unconfined compression tests are carried out in this study. The influence of fly ash content and fiber content on the shear strength, strength parameters, and unconfined compressive strength of the fiber-reinforced fly ash-soil mixture is thoroughly investigated.

## 2. Materials, Methods, and Testing Equipment

**2.1. Testing Materials.** The clay was obtained from a road construction site in Hongshan District, Wuhan. The fly ash was collected from a power plant in the Wuhan City, and it belongs to Class C fly ash. The physical parameters of clay and fly ash were obtained by laboratory tests shown in Table 1. The polypropylene fibers were used in this study, and the average dimensions are length 12 mm and diameter 0.023 mm as shown in Figure 1(a). The behavior parameters are shown in Table 2.

### 2.2. Testing Methods

**2.2.1. Preparation of Specimens.** In the tests, the performance of a total of 20 stabilized soil mixes was investigated

by varying the percentage of fly ash and polypropylene fibers. For each mix, two specimens were prepared. The soil was replaced by fly ash contents of 10%, 20%, 30%, 40%, and 50%, respectively, on dry weight basis. Further, four values of fibers (0%, 0.5%, 1.0%, and 1.5%) were considered for each of these mixes. The prepared mixtures were then stored in plastic bags for future use. The desired quantities of water were added to the mixtures as per the optimum water content and further mixed thoroughly to form a homogeneous mixture. The composite was used to estimate the direct shear test and unconfined compression test.

### 2.2.2. Compaction Tests and Direct Shear Tests.

According to ASTM D698-12e2, the standard compaction test was carried out on fly ash-soil mixture to obtain the optimum water content and maximum dry density, and the content of fly ash varied from 0% to 50%. The direct shear test equipment is shown in Figure 1(b). The maximum vertical and horizontal loads of the equipment are both 700 kN, and the size of specimen is 504.6 mm in diameter and 400 mm in height. The direct shear test was performed under a strain-controlled condition, and the shear rate was maintained at 1 mm/min during the test. Through a series of tests, the optimum content of fly ash and the effect of fiber on the reinforcement effect of the fly ash-soil mixture were studied. The specimens were compacted in three layers. The shaving treatment was needed between each compacted layers. Fly ash-soil mixture was filled in the upper and lower shear boxes. The ribs are placed at the shear plane of the upper and lower shear boxes, and the ends are fixed to prevent slippage during the shearing process. And, the test was performed under vertical normal stresses of 100 kPa, 200 kPa, and 300 kPa. When the shear strain reached 15%, the test was terminated.

### 2.2.3. Unconfined Compression Tests.

The unconfined compression test equipment is shown in Figure 1(c). For the unconfined compressive strength test, a metal mold with an inner diameter of 39.1 mm and a height of 80 mm was used and a detachable collar was attached at both ends to prepare a cylindrical specimen. The clay was uniformly mixed with desired amount of fly ash and fibers, and the fiber content varied from 0.5% to 1.5% (the fiber content was a percentage of the dry weight of the fly ash-soil mixture). The mixture was placed in a mold and, in order to ensure uniform compaction, the specimen was statically compressed on both ends until the required size of the specimen reached. The specimens were then demoulded with a hydraulic jack, wrapped in a sealed polyethylene bag, and cured in a desiccator for 1 day, 7 days, 14 days, and 28 days. After the required curing periods, specimens were tested for unconfined compressive strength using a strain rate of 1.2 mm/min.

## 3. Results and Discussion

**3.1. Compaction Behavior.** Figure 2 depicts the standard compaction curves of six different fly ash-soil mixtures (the

TABLE 1: Physical parameters of clay and fly ash.

Characteristic	Specific gravity	Natural density (g/cm <sup>3</sup> )	Optimum water content (%)	Maximum dry density (g/cm <sup>3</sup> )	Liquid limit (%)	Plastic limit (%)
Clay	2.68	1.35	27.8	1.42	34	17.8
Fly ash	2.16	2.16	22	1.36	44	NP



FIGURE 1: Testing equipment and materials: (a) polypropylene fibers, (b) direct shear test apparatus, and (c) unconfined compression test apparatus.

TABLE 2: Behavior parameters of fiber.

Fiber type	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation at break (%)
Polypropylene fiber	512	5.2	25

fly ash content varies from 0% to 50%). Figure 3 shows a comparison of the optimum water content and maximum dry density of the fly ash-soil mixture with different fly ash contents. It can be clearly seen from Figure 3 that as the fly ash content gradually increases, the maximum dry density of the fly ash-soil mixture is reduced from 1.52 g/cm<sup>3</sup> to 1.42 g/cm<sup>3</sup>. On the other hand, Figure 3 also reveals that as the fly ash content increases, the optimum water content of fly ash-soil mixture increases from 22.7% to 25.9%. Notably, the optimum water content of fly ash-soil mixture with 30% fly ash content reaches the maximum value, and the maximum dry density reaches the minimum value.

### 3.2. Direct Shear Tests

3.2.1. Stress-Strain Curve. Figure 4 shows shear stress-strain curves for fly ash-soil mixture specimens with a fly ash content of 0% (pure soil), 10%, 20%, 30%, 40%, and 50%, respectively. It was found that the shear strength of the fly

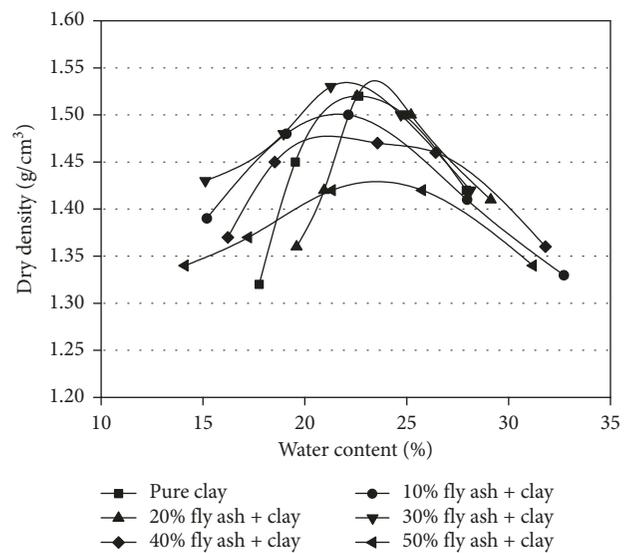


FIGURE 2: Standard compaction curves of fly ash-soil mixtures.

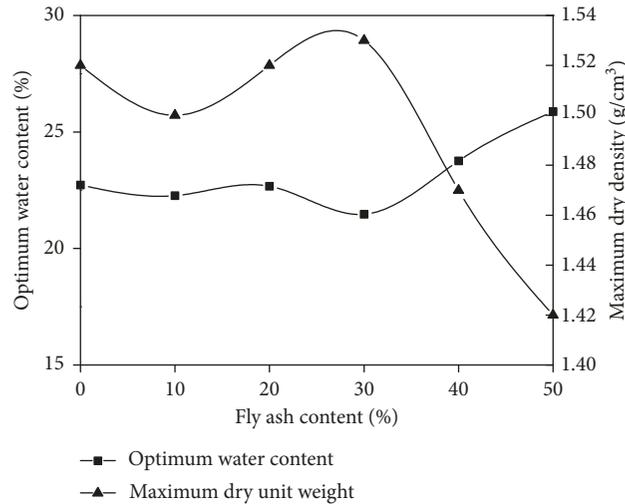


FIGURE 3: Variations of the optimum water content and maximum dry density of fly ash-soil mixtures.

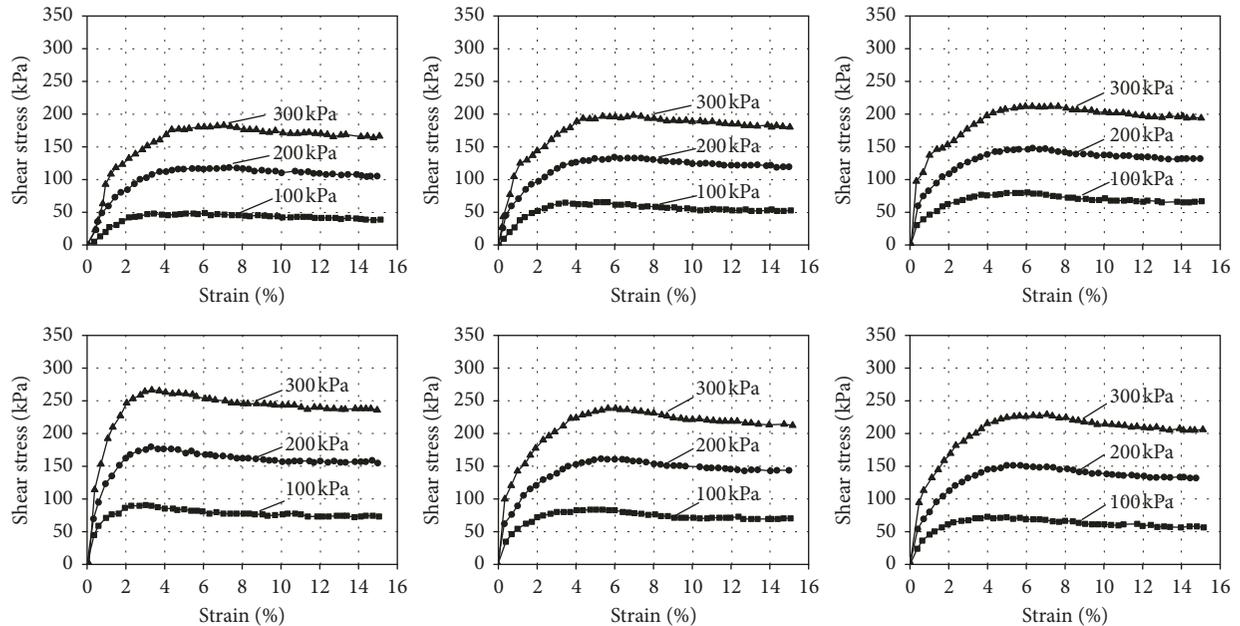


FIGURE 4: Shear stress-strain curves of fly ash-soil mixture specimens with different fly ash contents.

ash-soil mixture specimen reached the maximum when the fly ash content was 30%. For example, when the normal stress is 300 kPa, the shear strength of the fly ash content of 0%, 10%, 20%, 30%, 40%, and 50% of the fly ash-soil mixture is 183 kPa, 198 kPa, 212 kPa, 266 kPa, 238 kPa, and 229 kPa, respectively. It can be seen from the figure that the loss of residual shear strength of the fly ash-soil mixture decreases with increasing of the fly ash content under the same normal stress, which indicates that the increase of the fly ash content is beneficial to transform the shear properties of the fly ash-soil mixture specimen from brittle to ductile. The relationship between the shear stress peak value and fly ash content under different normal stresses is shown in Figure 5. The shear strength of the specimen with 30% fly ash content

reached the maximum value, which indicates that the optimum fly ash content is 30%, so this content is selected to further study the effect of fiber on the shear characteristics of the reinforced soil. The shear stress-strain curve is shown in Figure 6. It can be seen from the figure that the inclusion of more fiber contents significantly improved the shear characteristics of the specimens. When the shear strain reaches 15%, the shear stress of the specimen remains constant. In addition, there is no reduction of the shear stress, which indicates that the appearance of fibers in the soil can prevent the reduction in peak shear stress to some extent. It can be also seen from Figure 6 that, for any fiber-reinforced fly ash-soil mixture, before the strain reaches 2%, the shear stress value of the specimen does not reveal the superiority of the

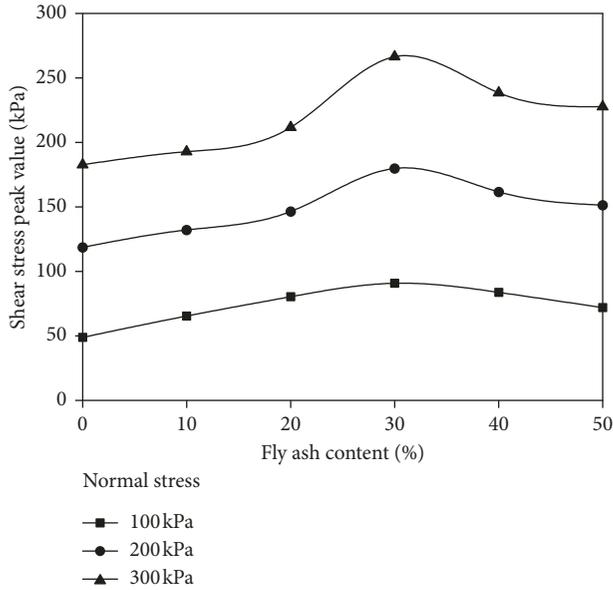


FIGURE 5: The relationship between shear stress peak value and fly ash content under different normal stresses.

fiber reinforcement. This can be due to the slippage of the fiber under low strain condition [13]. As shown in Figure 6, the fiber-reinforced fly ash-soil mixture has better ductility and less loss of residual shear strength than unreinforced fly ash-soil mixture. For large shear strains, fiber-reinforced specimens could maintain shear stress with increasing deformation, which indicates that these materials have superior ductility.

**3.2.2. Shear Strength and Strength Parameters.** The effect of fiber on the shear strength of fiber-reinforced fly ash-soil mixture can be evaluated by a strength ratio parameter  $R$ , and it can be defined as

$$R = \frac{\sigma_f^R}{\sigma_f}, \quad (1)$$

where  $\sigma_f^R$  is the shear stress of fiber-reinforced fly ash-soil mixture at failure and  $\sigma_f$  is the shear stress of fly ash-soil mixture at failure.

Table 3 and Figure 7 show the peak shear strength and strength ratios of the reinforced specimens with different fly ash contents. It can be seen that, for the same fiber content, the strength ratios of the fiber-reinforced fly ash-soil mixture specimens decrease with the normal stress varying from 100 kPa to 200 kPa, while increase slightly at 300 kPa. Moreover, it can be also seen that the shear strength of the reinforced specimens with different contents of fiber under the same normal stress varies greatly. For example, under the normal stress of 100 kPa, the shear strengths of fly ash-soil mixture reinforced with 0.5%, 1%, and 1.5% fiber content are 129.5 kPa, 187.5 kPa, and 156.5 kPa, respectively. This can be suggested that when the fiber content exceeds 1% in the fly ash-soil mixture, the increasing amplitude in shear strength may decrease.

The fiber content plays an important role in increasing the shear strength of the fiber-reinforced fly ash-soil mixture. It can be seen from Table 4 that the cohesion  $c$  of fly ash-soil specimen increases at first and then decreases with increasing fiber content. It is obvious that the contribution of fiber content to the  $c$  value is significantly different. When the fiber content increases from 0 to 0.5%, the  $c$  value increases by 29.37 kPa, and when fiber content increases from 0.5% to 1%, the  $c$  value increases by 50.1 kPa although the fiber increment is only 0.5%. It can be seen that the increase of  $c$  value is different with the same fiber content increment so that the contribution of fiber reinforcement is not linear with respect to  $c$  value, which is related to the reinforcement mechanism of fiber and soil.

The reinforcement mechanism of the fiber-reinforced fly ash-soil mixture in the direct shear test has two main aspects: the one-dimensional tensile action of a single fiber and the three-dimensional tensile action of the fiber web. Before the fiber is pulled out, the surface of fiber is surrounded by a large number of soil particles. Since the elastic modulus of fiber is much higher than that of the soil, once fibers are loaded at the same time, the inconsistency of the deformation will inevitably lead to a mutual displacement tendency between the fiber and soil. The fiber is in tension, and the interface force between the fiber and soil particle is generated. Here, the value of interface force mainly depends on the interface friction and adhesion [14]. This interface force inevitably restricts the relative sliding of the fiber so that the fiber in the soil can withstand a certain tensile stress, thereby sharing the external load. In addition, due to the fiber in tension, the bent portion of fiber can also restrain the deformation of soil particles and improve the mechanical properties of the soil. This reinforcement of fiber is mainly dominated by the one-dimensional tensile action of discrete fiber. In another case, a large number of fibers are randomly distributed in the soil and interwoven into a net. When one of the fibers is in tension, the other fibers must be forced together to form a three-dimensional forced net. Thus, the load is distributed to a wider area, which further improves the tensile effect of fiber. This reinforcement pattern of fiber is mainly based on the three-dimensional tensile action of the fiber web.

Different fiber inclusions may affect the main reinforcement pattern of fiber. For low fiber content, due to the large fiber spacing, an effective fiber web cannot be formed, so the contribution of the fiber to the  $c$  value mainly comes from the action of the discrete fiber. As the fiber content increases, more and more fibers begin to interweave into a net. At this time, the contribution of the fiber to the  $c$  value is superimposed on the three-dimensional tensile effect. Theoretically, more fiber content in the soil can cause greater fiber density on the shear plane and generate better performance of fiber to bear the shear stress. However, this is not the case. The test results have shown that the contribution of fiber reinforcement to the  $c$  value or other strength parameters has a critical amount. When exceeding the critical amount, the strength parameters may decrease with the increase in fiber content. For example, Prabakar and Sridhar [15] found when the fiber content exceeds 0.75%, the

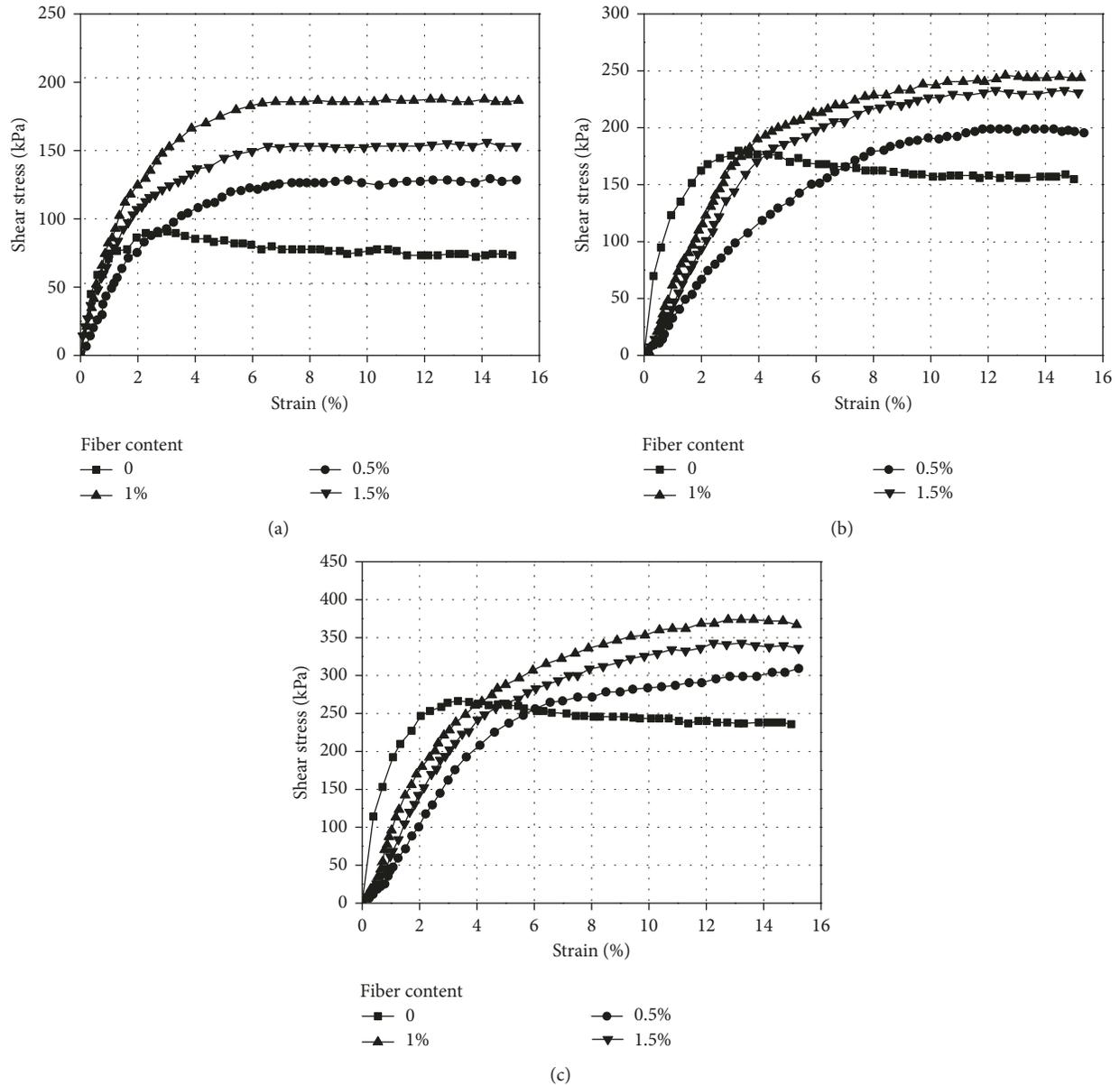


FIGURE 6: Shear stress-strain curves of reinforced fly ash-soil with different fiber contents and vertical normal stresses: (a)  $\sigma_n = 100$  kPa, (b)  $\sigma_n = 200$  kPa, and (c)  $\sigma_n = 300$  kPa.

TABLE 3: Peak shear strength of reinforced specimens.

Fiber content (%)	Normal stress: 100 kPa Peak stress (kPa)	Normal stress: 200 kPa Peak stress (kPa)	Normal stress: 300 kPa Peak stress (kPa)
0	90.8	179.9	266.4
0.5	129.5	198.8	309.2
1	187.5	246.1	373.7
1.5	156.2	232.9	342.8

$c$  value begins to decrease. Cai et al. [16] obtained the optimal fiber content of 0.3% of the dry soil weight by the direct shear test, and the optimum fiber length is 15 mm. The test results of Wu and Zhang [17] show that the shear strength of expansive soil increases with increasing fiber content at first,

then decreases, and the optimum fiber content is 0.3%. It can be seen that the general fiber content threshold is greater than 0.3% and the optimum fiber content in the direct shear tests of this study is 1%, which is consistent with the expected results.

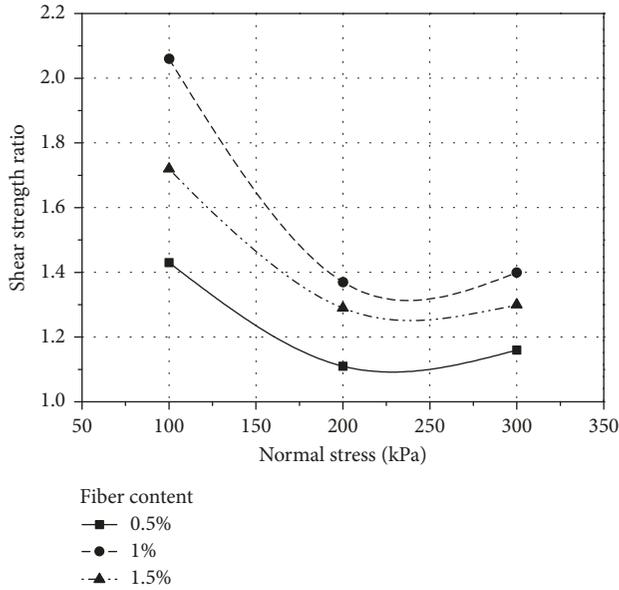


FIGURE 7: Peak shear strength ratios versus normal stress.

TABLE 4: Shear strength parameters of fiber-reinforced fly ash-soil mixture.

Fiber content (%)	Cohesion (kPa)	Internal friction angle (°)
0	3.43	41.28
0.5	32.8	41.94
1	82.9	42.95
1.5	57.37	43.01

It can also be seen from Table 4 that the increase in the internal friction angle of the fiber-reinforced fly ash-soil mixture specimens is not obvious and this phenomenon is almost consistent with the previous test results of Yang et al. [18]. However, in general, the internal friction angle of the fiber-reinforced fly ash-soil mixture is slightly higher than that of the plain soil, mainly because the majority of the fiber arrangement on the shear plane is not parallel to the shear direction, which is beneficial to increase the occlusal friction action between soil particles and fibers.

### 3.3. Unconfined Compression Properties

**3.3.1. Effect of Fly Ash Content and Curing Period.** Figure 8 shows the unconfined compressive strength of plain soil and fly ash-soil mixture with different fly ash contents. It can be seen from the figure that the unconfined compressive strength (UCS) of fly ash-soil mixture is higher than that of plain soil under the same curing period. The curve shows a tendency to increase at first and then decrease with increasing fly ash content. Furthermore, after the shear stress peak, the curve of the fly ash-soil is flatter than that of the plain soil, and the specimen with 30% fly ash content shows more ductility.

The relationship between the peak unconfined compressive strength of the fly ash-soil mixture specimen and

the curing period is shown in Figure 9. It can be clearly seen from the figure that the unconfined compressive strength values of the specimens with 0% and 10% fly ash contents are less affected by the fly ash content and the curing period. The unconfined compressive strength of the specimen with fly ash content exceeding 20% changes not significantly under the condition of curing from 7 days to 28 days. Among them, the unconfined compressive strength of the specimen with 30% fly ash content has greater improvement ratio with increasing curing period.

The changing amplitude of unconfined compressive strength (UCS\*) is defined as follows:

$$UCS^* = \frac{(UCS_{mix} - UCS_{clay})}{UCS_{clay}} \times 100 (\%), \quad (2)$$

where  $UCS_{clay}$  represents the average value of the unconfined compressive strength of the plain soil specimen, i.e., 223.47 kPa, and  $UCS_{mix}$  represents the unconfined compressive strength value of fly ash-soil mixture, kPa.

The magnitude of the increase in the unconfined compressive strength value of the specimen is investigated, and the values are shown in Table 5.

A common trend is observed that the unconfined compressive strength of fly ash-soil mixture specimen increases with the fly ash content and the curing period compared to pure soil, except for the 10% fly ash content, which may be caused by the uneven distribution of fly ash in the soil. For specimens with 30% fly ash content, the unconfined compressive strength values are greater than those of other fly ash contents at 7 days, 14 days, and 28 days, respectively, except for 1 day. Table 5 also shows that, for the specimen with 10% fly ash content, the increase of the unconfined compressive strength of the specimen slightly fluctuates with the increasing curing period. The occurrence of these fluctuations is likely due to the heterogeneous distribution of wet fly ash in the specimens.

In order to better evaluate the effect of the curing period and fly ash content on the ductility of specimen, the brittleness index  $I_b$  can be defined by

$$I_b = \varepsilon_{UCS} - \varepsilon_{UCS/2}, \quad (3)$$

where  $\varepsilon_{UCS}$  presents the axial strain at UCS and  $\varepsilon_{UCS/2}$  presents the axial strain at UCS/2.

The relationship between the brittleness index  $I_b$  value and curing period is plotted in Figure 10. It can be seen from Figure 10 that as the fly ash content and curing period increase, the brittleness index  $I_b$  gradually decrease. The lower the  $I_b$  value is, the greater the brittleness of the specimens is. It can be indicated from the decrease of  $I_b$  value that the failure mode of specimens changes from ductility to brittleness. When the fly ash content of the specimen exceeds 20% and the curing period exceeds 14 days, the  $I_b$  values become close to each other.

**3.3.2. Effect of Fiber Reinforcement.** The effect of fiber content (0.5%, 1%, and 1.5%) in fly ash-soil mixtures after 28 curing days on unconfined compressive strength is shown in

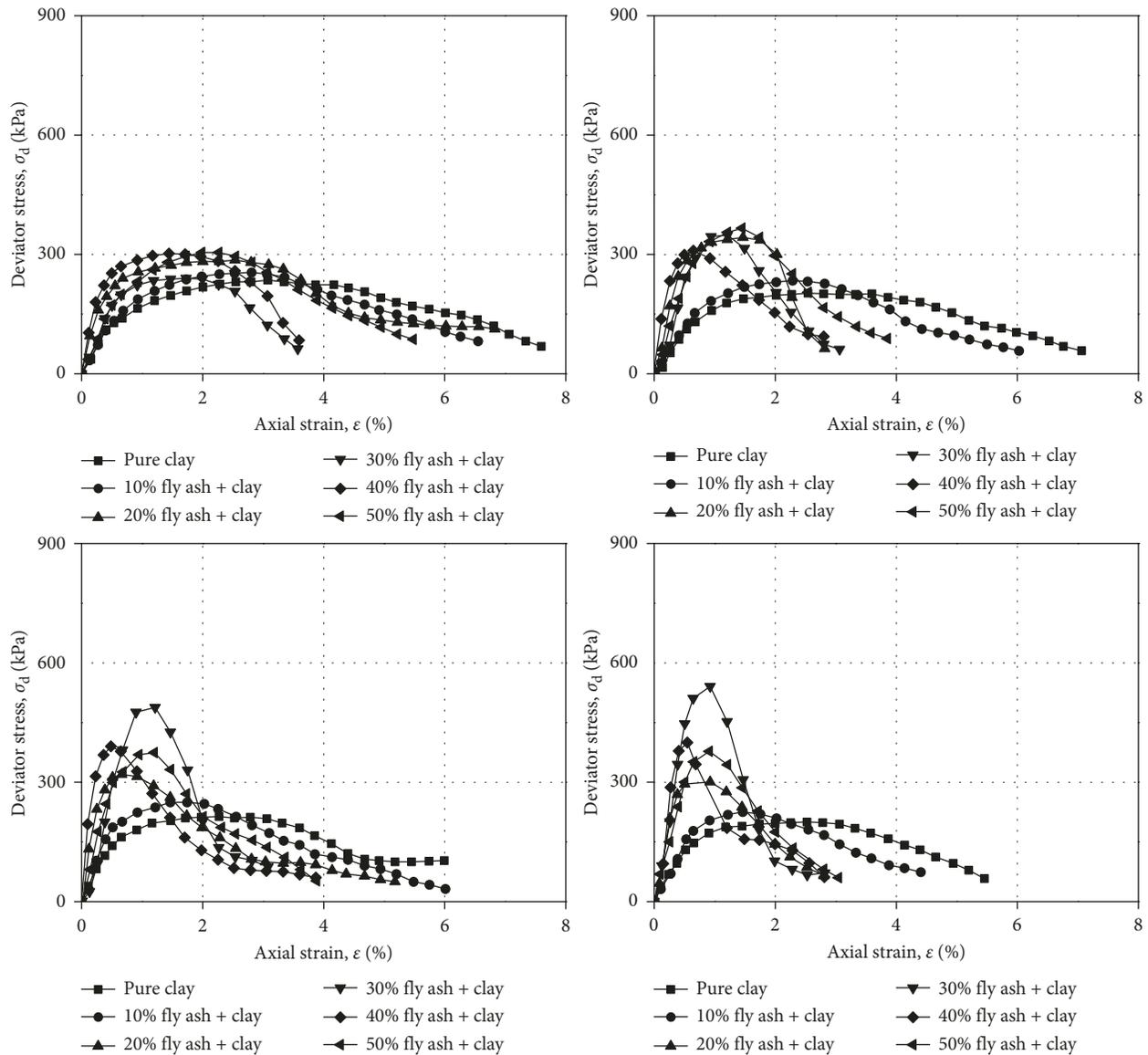


FIGURE 8: Relationship between deviator stress and axial strain with different fly ash contents under different curing periods.

Figure 11. From the above analysis, it can be obtained that the specimen with 30% fly ash content increases greatly in the unconfined compressive strength compared with other specimens at the curing period of 7 days, 14 days, and 28 days, respectively. Hence, in order to further study the effect of fiber content on the UCS of specimens, the fly ash content of the selected mixture was 30%. It can be seen from Figure 11 that the fly ash-soil mixture with 30% fly ash content exhibits brittle failure, and the specimen suddenly fails when the axial strain is less than 2%. However, the stress-strain curve of the fiber-reinforced specimen shows ductile failure when compared with the unreinforced fly ash-soil mixture. The axial strain of the specimen fail is between 3% and 4%, and the stress reduction of the fiber-reinforced specimen after peak is smaller than that of the unreinforced specimen. It is found that when the fiber content is 1%, the unconfined compressive strength of the specimen reaches

the maximum, but the residual strength after the peak is still lower than the specimen with the fiber content of 1.5%.

Adding fiber to the plain fly ash-soil can improve the unconfined compressive strength of fly ash-soil. This is mainly because the specimen can bear the partial tensile stress when shear deformation occurs under the action of the axial pressure, due to the presence of the fiber. This effect limits the deformation of the specimen, and the more the fiber content is, the greater the tensile stress that can be assumed, resulting that the unconfined compressive strength of fiber-reinforced fly ash-soil is higher than that of unreinforced fly ash-soil. With increasing the fiber content, the unconfined compressive strength of the specimen increases. After the initial cracks occur in the soil specimen, due to the existence of the fiber, the further development of the cracks can be delayed. Consequently, the axial pressure that the soil can withstand does not suddenly decrease, so the fiber-

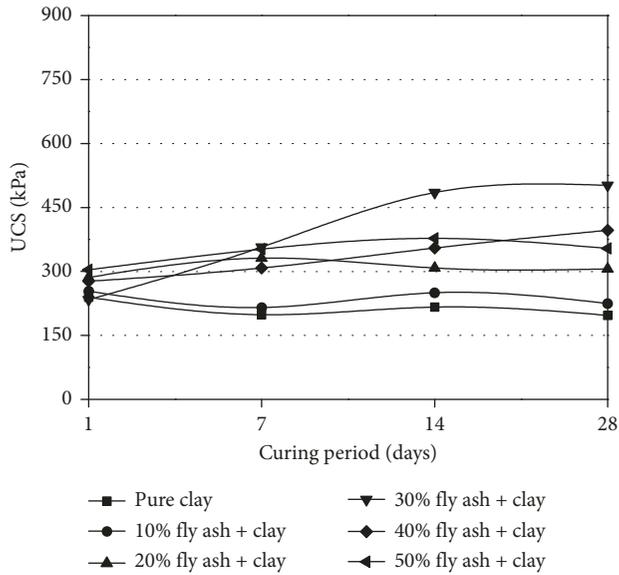


FIGURE 9: Relationship between UCS and curing period for different proportions of fly ash.

TABLE 5: Effect of fly ash inclusion and curing period on UCS\* of specimens.

Curing period (days)	Different fly ash ratios				
	10%	20%	30%	40%	50%
1	13.6	29.3	8.0	26.8	35.1
7	-2.2	52.0	59.4	39.0	57.4
14	13.5	39.6	119.7	61.4	69.8
28	-0.4	37.0	126.1	77.8	59.2

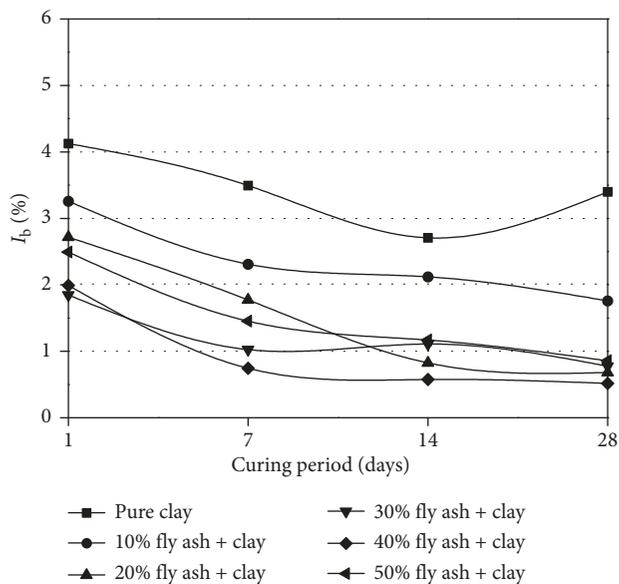


FIGURE 10: Relationship between  $I_b$  value and curing period.

reinforced fly ash-soil exhibits fracture toughness, as shown in Figure 10. And, the tensile stress assumed by the fiber mainly depends on the friction between the fibers and the

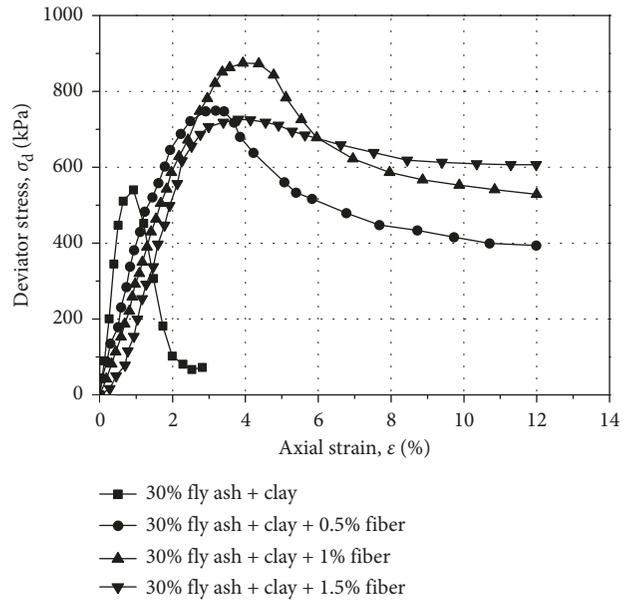


FIGURE 11: Effect of fiber content on stress-strain curve of specimen after 28 curing days.

soil particles as well as the cohesion of the soil. Since the fibers selected for the test are thinner and shorter and the surface of the fiber is smooth, the tensile stress assumed by the fiber mainly contributes to the improvement of soil cohesion.

### 4. Conclusions

In this paper, the mechanical characteristics of fiber-reinforced fly ash-soil mixtures were studied by standard compaction tests, direct shear tests, and unconfined compression tests. The fly ash contents were 10% to 50% by dry mass of the soil, and the fiber contents were 0.5% to 1.5% by dry mass of the 30% fly ash-soil mixtures. Based on the experimental results, the following conclusions can be drawn:

- (1) Compared to the unreinforced fly ash-soil mixture, the shear strength of fiber-reinforced fly ash-soil mixture increases significantly. However, the inclusion of fibers which is beyond 1% in the fly ash-soil mixture may result in a decrease in shear strength.
- (2) For the reinforced fly ash-soil mixture specimens with different fiber contents, the internal friction angle and cohesion increases with increasing fiber contents. Compared with the unreinforced fly ash-soil mixture, the cohesion and internal friction angle of the fiber-reinforced fly ash-soil mixture when fiber contents vary from 0.5% to 1% are increased by 29.37 kPa to 79.47 kPa and 0.66° to 1.67°, which indicates that the fiber content has more obvious effect on the cohesion of soil.
- (3) The unconfined compressive strength of fly ash-soil mixture is higher than that of plain soil under the

same curing period, and there is an obvious tendency to increase at first and then decrease when the fly ash content exceeds 10%. Moreover, after the shear stress reaches the maximum value, the curve of the fly ash-soil is flatter than that of the plain soil and the specimen with 30% fly ash content shows more ductility.

- (4) With increasing fly ash content and curing period, the brittleness index  $I_b$  value gradually decreases, which indicates the failure mode of specimen changes from ductility to brittleness. When the fly ash content of the specimen exceeded 20% and the curing period exceeded 14 days, the  $I_b$  values become very close.
- (5) When the fiber content is 1%, the unconfined compressive strength of the specimen reaches a peak. But, the residual strength is still lower than the specimen with the 1.5% fiber content.

### 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 they have no conflicts of interest.

### Acknowledgments

The authors are thankful for the financial support given by the Hubei Provincial Science Foundation for Distinguished Young Scholars (No. 2018CFA063), National Natural Science Foundation of China (Nos. 51678224, 51778217, and 51708190), Hubei Central Special Fund for Local Science and Technology Development (No. 2018ZYD005), and National Key R&D Program of China (No. 2016YFC0502208).

### References

- [1] Z. T. Yao, X. S. Ji, P. K. Sarker et al., "A comprehensive review on the applications of coal fly ash," *Earth-Science Reviews*, vol. 141, no. 4, pp. 105–121, 2015.
- [2] R. K. Goswami and C. Mahanta, "Leaching characteristics of residual lateritic soils stabilised with fly ash and lime for geotechnical applications," *Waste Management*, vol. 27, no. 4, pp. 466–481, 2007.
- [3] G. M. Latha and A. M. N. Varman, "Static and cyclic load response of reinforced sand through large triaxial tests," *Japanese Geotechnical Society Special Publication*, vol. 2, no. 68, pp. 2342–2346, 2016.
- [4] M. R. Abdi and M. A. Arjomand, "Pullout tests conducted on clay reinforced with geogrid encapsulated in thin layers of sand," *Geotextiles and Geomembranes*, vol. 29, no. 6, pp. 588–595, 2011.
- [5] X. Chen, J. Zhang, and Z. Li, "Shear behaviour of a geogrid-reinforced coarse-grained soil based on large-scale triaxial tests," *Geotextiles and Geomembranes*, vol. 42, no. 4, pp. 312–328, 2014.
- [6] L. S. Rose, S. T. Jeb, and L. W. Steve, "Engineering properties of sand-fiber mixtures for road Construction," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 127, no. 3, pp. 258–268, 2001.
- [7] T. Park and S. Tan, "Enhanced performance of reinforced soil walls by the inclusion of short fiber," *Geotextiles and Geomembranes*, vol. 23, no. 4, pp. 348–361, 2005.
- [8] J. Lovisa, S. K. Shukla, and N. Sivakugan, "Shear strength of randomly distributed moist fibre-reinforced sand," *Geosynthetics International*, vol. 17, no. 2, pp. 100–106, 2010.
- [9] S. Sadek, S. S. Najjar, and F. Freiha, "Shear strength of fiber-reinforced sands," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 136, no. 3, pp. 490–499, 2010.
- [10] V. Anggraini, A. Asadi, B. B. K. Huat, and H. Nahazanan, "Effects of coir fibers on tensile and compressive strength of lime treated soft soil," *Measurement*, vol. 59, pp. 372–381, 2015.
- [11] Y. Wu, Y. Li, and B. Niu, "Assessment of the mechanical properties of sisal fiber-reinforced silty clay using triaxial shear tests," *The Scientific World Journal*, vol. 2014, Article ID 436231, 9 pages, 2014.
- [12] L. Gao, G. Hu, N. Xu, J. Fu, C. Xiang, and C. Yang, "Experimental study on unconfined compressive strength of basalt fiber reinforced clay soil," *Advances in Materials Science and Engineering*, vol. 2015, Article ID 561293, 8 pages, 2015.
- [13] N. C. Consoli, F. Zorzea, M. D. Souza, and L. Festugato, "Studies on the dosage of fiber-reinforced cemented soils," *Journal of Materials in Civil Engineering*, vol. 23, no. 12, 2011.
- [14] C. Tang, B. Shi, W. Gao, F. Chen, and Y. Cai, "Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil," *Geotextiles and Geomembranes*, vol. 25, no. 3, pp. 194–202, 2007.
- [15] J. Prabakar and R. S. Sridhar, "Effect of random inclusion of sisal fibre on strength behaviour of soil," *Construction and Building Materials*, vol. 16, no. 2, pp. 123–131, 2002.
- [16] Y. Cai, B. Shi, W. Gao, F. Chen, and C. Tang, "Experimental study on engineering properties of fiber-lime treated soils," *Chinese Journal of Geotechnical Engineering*, vol. 28, no. 10, pp. 1283–1287, 2006.
- [17] J. Wu and X. Zhang, "Study on strength of polypropylene fiber reinforced expansive soil," *Soil Engineering and Foundation*, vol. 24, no. 6, pp. 71–73, 2011.
- [18] Y. Yang, S. Cheng, J. Gu, and X. Hu, "Triaxial tests research on strength properties of the polypropylene fiber reinforced soil," in *Proceedings of International Conference on Multimedia Technology IEEE*, pp. 1869–1872, Kyoto, Japan, 2011.



**Hindawi**  
Submit your manuscripts at  
[www.hindawi.com](http://www.hindawi.com)

