BJES Basrah Journal for Engineering Sciences

Basrah Journal for Engineering Sciences, Vol. 23, No. 1, (2023), 43-49

Original Article

Journal homepage: www.bjes.edu.iq
ISSN (Online): 23118385, ISSN (Print): 18146120

OPEN ACCESS

Strength Characteristics of Clay Soil Reinforced with Natural Fibers

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Received: 29 November 2022; Revised: 15 January 2023; Accepted: 24 January 2023; Published: 2 July 2023

Abstract

The trend of using natural fibers in geotechnical engineering has become of great interest to improve weak soils due to some of its advantages such as local availability, environmental friendliness, and lower cost. In this study, a set of unconfined compression strength and direct shear tests were conducted to evaluate the performance of Al-Nasiriya clayey soil reinforced with natural fibers. Three different types of natural fibers were investigated as sustainable ones, including wheat straw fiber and palm frond fiber, as well as imperata cylindrica fiber. The effects of various fiber contents (0.25 %, 0.5 %, 0.75 %, and 1 %) and lengths (20 mm, 30 mm, and 40 mm) were experimentally evaluated. The results indicated that the compressive strength increased significantly with the increase of fiber content and length up to an optimum value and then decreased. The optimum fiber content and length were 0.5 % and 30 mm, respectively. Compared to the unreinforced soil, the compressive strength values at the optimum content and length increased by 102 %, 126 %, and 66 % for samples reinforced with wheat straw, palm fronds, and imperata cylindrica fibers, respectively. The shear properties improved due to soil reinforcement with natural fibers. Compared to the unreinforced soil, the internal friction angle of the samples reinforced with wheat straw, palm fronds, and imperata cylindrica fibers increased by 17.7 %, 42 %, and 9 %, respectively. Forever, the cohesion and shear strength are also improved due to inclusion of natural fibers.

Keywords: Fiber, Reinforcement, Randomly, Environmental.

https://doi.org/10.33971/bjes.23.1.6

1. Introduction

Soil reinforcement using randomly distributed discrete fibers is an effective technique that can be used to improve the mechanical properties of soil [1]. Compared with traditional materials used for soil reinforcement (strips, geotextile, geogrid, etc.), soil reinforced with randomly distributed discrete fibers has some advantages. The preparation of randomly distributed fiber-reinforced soil simulates soil stabilization by admixture. The discrete fibers are simply added and mixed with the soil as chemical binders (cement, lime, and fly ash). One of the main advantages of using randomly distributed fibers is the maintenance of strength isotropy and the absence of the potential planes of weakness that can develop in soils with oriented reinforcement [2]. Many investigations have used different types of synthetic fibers to improve the mechanical behavior of soils. Pradhan et al. (2012) [3] reported that the addition of randomly distributed polypropylene fibers improves peak and residual shear strength of soil. Estabragh et al. (2011) [4] observed that increasing the content of nylon fibers increases the coefficient of swelling and compression. Moreover, the addition of fiber significantly improved the shear strength and internal friction angle. Several experimental studies have been prepared using synthetic fibers to improve the engineering properties of Iraq's soft soil. Salim et al. (2018) [5] used recycled plastic fibers to improve the geotechnical properties of the soil. The results indicated that adding 4 % of recycled plastic fibers increased the compressive strength and Bearing California Ratio (CBR) values by 180 % and 210 %, respectively. Al-Neami et al. (2020) [6] prepared an experimental study of soil reinforced with polypropylene fibers. The results showed that soil cohesion improved with the increase of fiber content up to 0.5% then decreased. Synthetic fibers are used in soil reinforcement applications because of their good mechanical properties, but their manufacture is environmentally polluting [7, 8].

In recent years, many researchers have been interested in the utilization of alternative natural resources in soil reinforcement applications for environmental and economic considerations [9]. A wide range of experimental studies has been conducted around the world using different types of natural fibers as reinforcing materials for weak soils. Ghavami et al. (1999) [10] demonstrated that reinforcing the soil with natural fibers such as coconut, bamboo and sisal significantly improves ductility and strength. Additionally, the inclusion of natural fibers in the soil mass dramatically reduces the probability of drying-related fracture formation. Prabakar and Sridhar (2002) [11] reported that the shear strength parameters (c and ϕ) and failure deviator stress were clearly enhanced as a result of the inclusion of the soil with various percentages of sisal fibers. Qu and Sun (2016) [12] studied the effect of adding straw fibers on the strength of clay soils. The findings demonstrate that as fiber content is increased to an optimal level, the preconsolidation pressure lowers and the coefficients of swelling and compression generally increase. Sharma et al. (2017) [13] conducted a number of unconfined compression tests on natural fiber-reinforced soil. Kaushik and Singh (2021) [14] demonstrated that the reinforcement of the subgrade soil with coir fiber significantly improves the California Bearing Ratio (CBR). Studies that investigated the effect of fiber reinforcement on clay soils were limited compared to sandy soils. Further studies are needed to investigate the behavior of cohesive soils reinforced with local natural fibers. Moreover, few investigations have examined the shear behavior of clay soils reinforced with local natural fibers. Tan et al. (2019) [15] examined the shear strength of clay soils reinforced with root and geomat. Praveen and Kuree (2020) [16] investigated the effect of adding coir fibers on the shear strength parameter of clayey sand soils. Xue et al. (2021) [17] enhanced the performance of loess shearing behavior reinforced with straw fibers. In general, very limited studies used randomly distributed natural fibers to improve soil strength properties in Iraq and Al-Nasiriya city. There is a need to utilize natural fibers as sustainable materials in soil reinforcement applications because they are locally available, low cost, and environmentally friendly.

In this study, three different types of local natural fibers such as straw fibers and palm fibers were used to improve the strength properties of the cohesive Al-Nasiriya soil. A series of unconfined compression strength (UCS) and direct shear tests were prepared to evaluate the performance of Al-Nasiriya clay soils randomly reinforced with local natural fibers. The fundamental purpose of this study is to discover how local natural fibers influence the UCS values and shear strength characteristics of Al-Nasiriya clay soil. The findings from this work can be applied to field applications involving soils with properties similar to the fiber-clay mixture, to formulate an acceptable mixture for reinforced soil, and to carry out short and long sustainability evaluations of such soils.

2. Materials

2.1. Soil sample

The soil used in this research was clay taken from one of the quarries of Nasiriya in Iraq as shown in Fig. 1. The latitude and longitude coordinates of the quarry are 31° 03′ 41″ N and 46° 09′ 55″ E, respectively. Laboratory tests were performed on the clay sample in accordance with ASTM standards to determine its geotechnical characteristics, such as specific gravity (Gs), maximum dry density (MDD), liquid limit (LL), plastic limit (PL), and optimum moisture content (OMC). According to the unified classification system (USCS), the clay soil utilized was categorized as low plasticity (CL). Table 1 lists the geotechnical properties of the soil.

Table 1. Geotechnical properties of clayey soil.

Property	Values
Specific gravity (Gs)	2.63
Liquid limit (LL)	41
Plastic limit (PL)	19
Plastic index (PI)	22
Maximum dry density (g/cm^3)	1.6
Optimum water content %	15
USCS classification	CL

Fig. 1 Area of study, Al-Nasiriya city [18].

2.2. Fibers

The short natural fibers used in this research are wheat straw (SF), palm frond (PF), and imperata cylindrica (IF) as reinforcing materials for clay soil as shown in Fig. 2. The outer surface of wheat straw and imperata cylindrica fibers is smooth, while that of palm frond fibers is rough. Natural fibers' water absorption capacity factor (WAC) is calculated using a procedure [19]. The WAC was calculated by submerging 10 gm of each type of dried natural fibers (at 60 C° for 2 days) in water at various times immersion times ranging from (1 to 120 min). The natural fibers were superficially dried after soaking to eliminate the water accumulated on their surface. The following equation was used to calculate the WAC coefficient:

$$WAC = \frac{W_1 - W_2}{W_2} \tag{1}$$

Where W_1 = weight of wet natural fibers and W_2 = weight of dry natural fibers. The physical properties of the natural fibers are listed in Table 3.

Table 2. The physical properties of the natural fibers.

Property	SF	PF	IF
Average diameter (mm)	3	-	2.5
Fiber length (mm)	20,30,40	20,30,40	20,30,40
Average fiber width (mm)	-	3.5	-
Thickness (mm)	-	1.25	-
WAC %	230	150	270

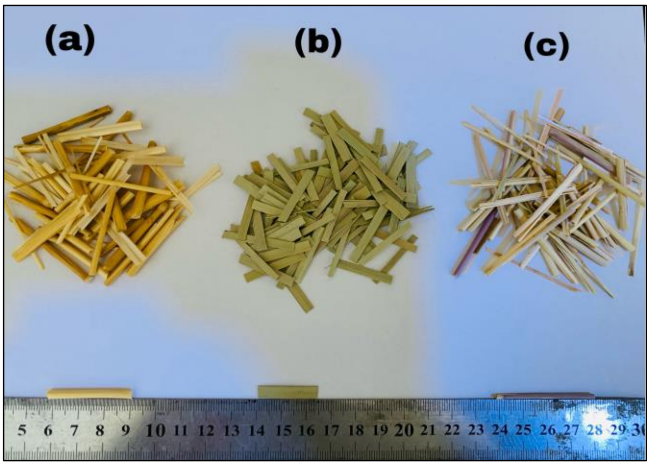


Fig. 2 Natural fibers, **(a)** SF, **(b)** PF and **(c)** IF.

3. Methodology

In this study, a series of UCS and direct shear tests were performed on unreinforced and fiber reinforced samples. Soil reinforced with fiber content (ρ_f = 0.25 %, 0.5 %, 0.75 %, and 1 % of soil mass weight ratio), and lengths (l_f = 20 mm, 30 mm, and 40 mm). The fiber content added to the soil was chosen based on previous studies that used the same percentages [20-22]. The effect of reinforcing local natural fibers with different content and lengths on the strength characteristics of the cohesive soil of Al-Nasiriya was studied.

3.1. Unconfined compressive strength test

The unconfined compression strength (UCS) test was used to evaluate the performance of reinforced and non-reinforced soil strength according to ASTM D2166. This test is commonly used in geotechnical engineering to find the approximate strength of cohesive soil because it is quick and economical. The mixture of moist soil with fibers was compacted into three layers in a cylindrical mould with a diameter of 35 mm and a height of 70 mm. For each layer, the number of blows required was 25 to achieve the target density in a standard Procter test. The variation of UCS values with fiber content and length is plotted. The unconfined compression test apparatus is shown in Fig. 4.

3.2. Direct shear test

The experimental investigation performed a series of direct shear tests in unconsolidated undrained conditions in accordance with ASTM D 6528. To achieve the standard Proctor maximum dry density, the moist soil and fiber mixture was compacted in a steel mould with dimensions of 60 mm × 60 mm in plan and 25 mm in depth. A wooden tamper extracts the sample from the steel mould and pushes it into the shear box. Direct shear samples with the optimal fiber content and length were prepared (0.5 percent, 30 mm). For each test, however, three samples were prepared. The specimens were subjected to normal stresses (σ_n) of 100, 200, and 300 kPa. The tests were performed at a rate of 1 mm/min. The effect of natural fiber-reinforced soil on peak shear stress (τ_f) and shear strength parameters (c and ϕ) were explored in comparison to unreinforced soil. Figure 5 shows the direct shear test equipment.

3.3. Sample preparation

The clayey soil samples were oven-dried at 105 °C (for 24 h), and then any clamps and soil aggregations were crushed using rubber steel and sieved with a diameter of 2 mm to form a pulverized dry powder. The samples were prepared with natural fibers of different content (ρ_f = 0.25 %, 0.5 %, 0.75 % and 1 % of soil mass weight ratio) and lengths (l_f = 20 mm, 30 mm and 40 mm).

$$\rho_f = \frac{W_f}{W_s} \tag{2}$$

Where, W_f = weight of fiber, W_s = weight of soil.

The dry soil powder was hand-mixed with the optimum moisture content (OMC =15 %) determined by the compaction test. Then, the natural fibers of the specified length and content were randomly mixed with the moist soil as shown in Fig. 3. All samples were prepared at MDD and OMC. The mixture of moist soil and fibers was placed in special molds for UCS and direct shear tests.

Fig. 3 Mixture of randomly distributed fibers and moist soil.

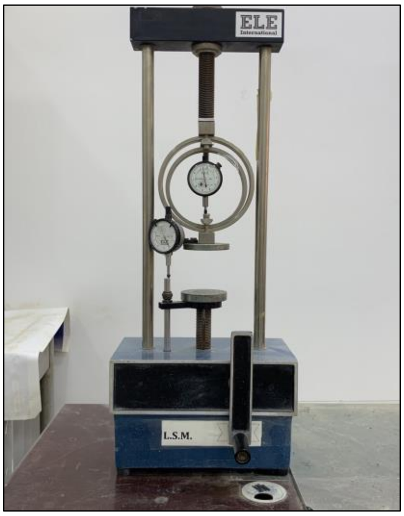


Fig. 4 The unconfined compression test apparatus.

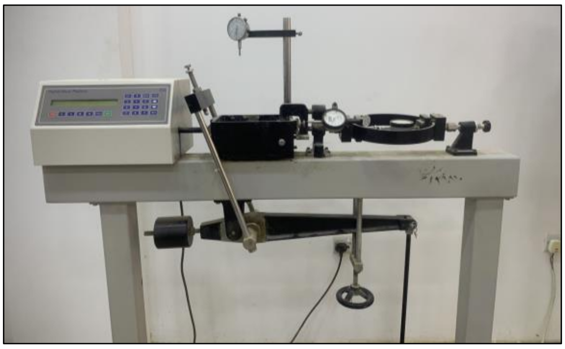


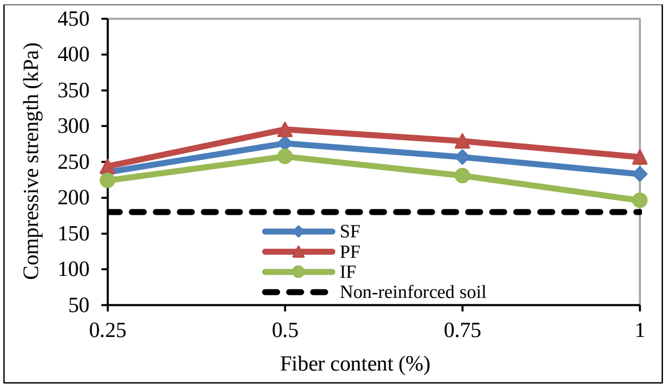
Fig. 5 The direct shear test equipment.

4. Results and discussion

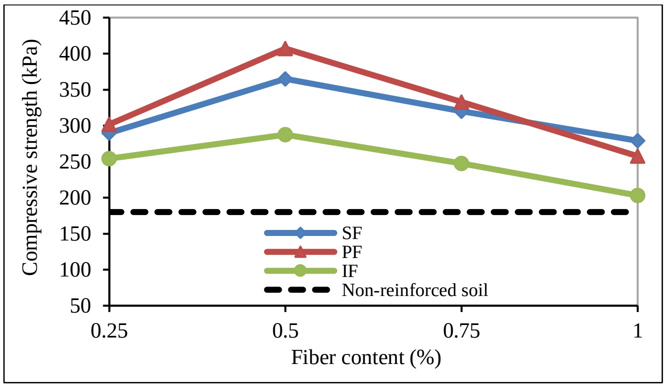
4.1. Unconfined compressive strength

The results of the compressive strength of soil reinforced with different content and lengths of natural fibers are shown in Fig. 6. The compressive strength of the non-fiber-reinforced soil sample was 180 kPa. The compressive strength of clay soil reinforced with natural fibers is effectively improved. The compressive strength of clay samples increases with increasing fiber content and then gradually decreases at a specified value. The optimum content of the clay samples reinforced with natural fibers was 0.5 %. The compressive strength values of clay samples reinforced with PF, SF, and IF at the optimum content were 407, 365, and 287.4 kPa, respectively. The values of the compressive strength of soil samples reinforced with PF were the highest due to the roughness of the surface of the fibers, which led to an increase in the interlocking between the soil particles and the surface of the fibers (increase interfacial shear resistance). This finding confirms the outcome reported by Tang et al. [23] that the surface roughness of the fibers is one of the important factors that increase the interfacial shear resistance of the fiber-soil compound.

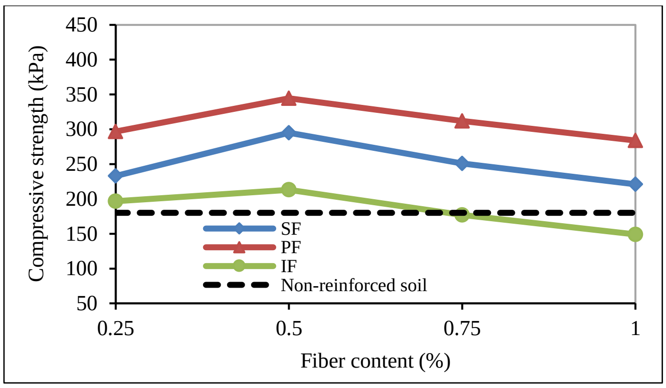
The difference in the length of the natural fibers used to reinforce the samples had a significant effect on the compressive strength. The maximum compressive strength values for all reinforced samples were at 30 mm fiber length. Several studies have demonstrated that the length of the fibers plays an important role in increasing the compressive strength of reinforced samples. The value of the compressive strength reaches a peak at a specific length and then gradually decreases with the increase in the length of the fibers. Li et al. reported that the compressive strength of the clay samples reinforced with fibers reaches the greatest value at a length of 5 cm for samples with a diameter of 15.2 cm [24]. Other studies indicated the same findings [1, 20].



(a) l_f = 20 mm.



(b) l_f = 30 mm.



(c) l_f = 40 mm.

Fig. 6 Compressive strength of samples.

4.2. Direct shear test

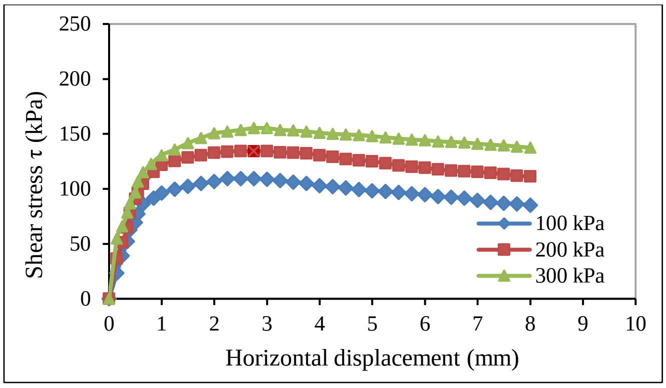
The shear stress-horizontal displacement relationship of unreinforced and fiber-reinforced samples is shown in Fig. 6. It can be seen from Fig. 7 that the reinforcement of clay soils with natural fibers changed the shear-displacement behavior from softening to hardening. The shear stress rises to a maximum value τ_f and then remains approximately constant as the horizontal displacement increases. The shear-horizontal displacement relationship shows that the shear stress τ increases with the increase in the normal stress (σ_n). The normal stress applied to the sample increase the contact area and interlocking between the soil particles and the fibers. compared to the unreinforced sample, Samples reinforced with local natural fibers reach peak shear stresses with large displacements before failure. The maximum horizontal displacement observed for fiber-reinforced samples before failure was 6 mm at normal stress of 300 kPa, while the maximum horizontal displacement for unreinforced samples was 2.75 mm at the same normal stress. Additionally, Fig. 7 shows that the addition of natural fibers raises peak shear strength and lowers the loss of residual shear strength. Samples reinforced with natural fibers (SF, PF, and IF) increase the peak shear stress values from 155 kPa to 177, 227, and 166 kPa at a normal stress of 300 kPa.

The failure envelope corresponding to peak shear stress and normal stress is shown in Fig. 8. Compared to the unreinforced sample, reinforcement of clay soils with 0.5 % of natural fibers (SF, PF, and IF) significantly improves the shear strength parameters (c and ϕ). The internal friction angle increases by 17.7 %, 42 %, and 9 %, respectively. Furthermore, the cohesion increases by 8 %, 43 %, and 3.5 %, respectively. The shear strength parameters for samples (c and ϕ) are listed in Table 3.

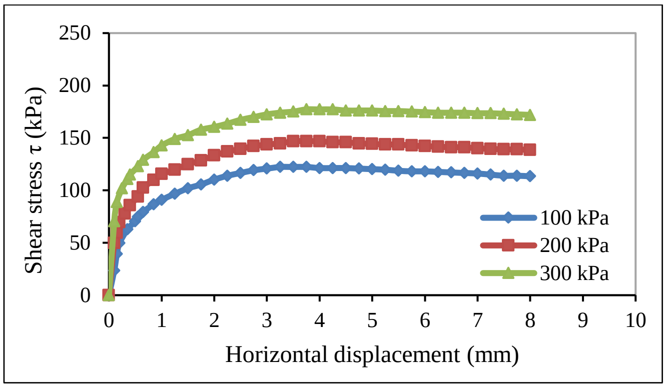
Table 3. The shear strength parameters of samples.

Samples	Cohesion (kPa)	Internal friction angel (Ø°)
Unreinforced Soil	86.9	13
Soil + SF	94	15.5
Soil + PF	124.2	18.3
Soil + IF	90	14.2

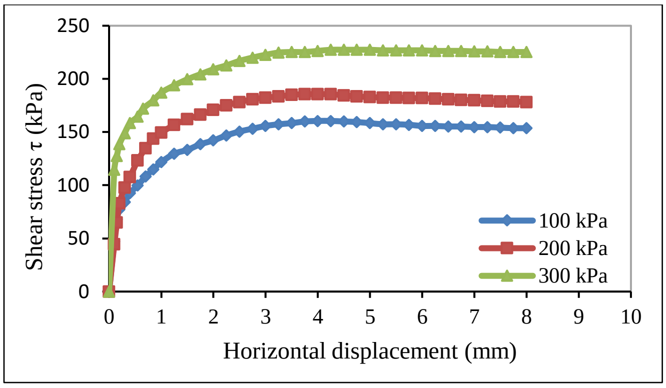
According to these indicators, natural fibers play an important role in improving the shear characteristics of clay soils. The embedded natural fibers increase tensile resistance by transferring shear stresses that arise in the sample to an interface friction force between the fibers and soil. The findings of this study were compared to previous studies that examined the effect of fibers on shear characteristics. The comparison between the previous studies and the current study is listed in Table 4. Xue et al. [17] investigated the shearing behavior reinforcement of loess by recycled straw fiber addition in an experimental investigation. The shear strength enhanced when large-scale stress-controlled direct shear procedures were used. Tan et al. [15] conducted a direct shear test to determine the shear strength of grass root-geomat reinforced soil. The results showed that adding geomat and grass roots to the soil improved its shear strength substantially. Praveen and Kurre [16] carried out a set of direct shear tests on soil reinforced with coir fibers. The results observed that the addition of (2 and 4 %) of coir fiber enhanced the internal friction angle from 21° to 32° and 29° respectively. Changizi and Haddad [25] observed that the inclusion 0.5 % of recycled polyester fibers improves shear strength by 80 % and increases failure strain. In addition, the shear strength parameter (ϕ and C) increases by 19 % and 8 % when the polyester fiber varies from 0.3 % to 0.5 %, respectively.



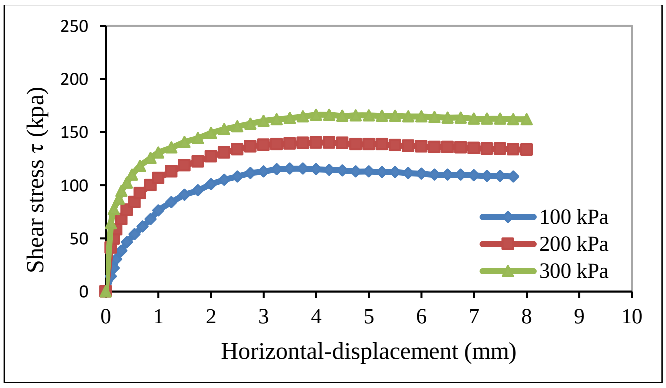
(a) Unreinforced soil.



(b) Soil reinforced with SF.



(c) Soil reinforced with PF.



(d) Soil reinforced with IF.

Fig. 7 Shear stress-horizontal displacement curve.

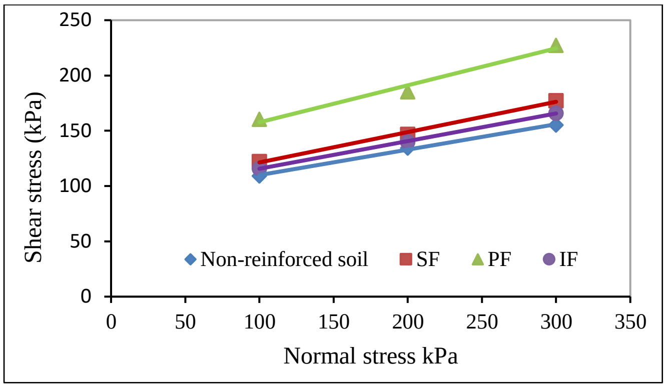


Fig. 8 The failure envelope of samples.

Table 4. Comparison between previous studies and current study.

	Type of Soil				
	Lantian loess	**Silty clay**	**Clayey sand**	**Clay**	**Clay**
Ref	[17]	[15]	[16]	[25]	Current study
USCS	CL	CL	SC	CL	CL
Test method	Direct shear	Direct shear	Direct shear	Direct shear	Direct shear
Type of reinforcer	Straw fiber	Root, geomat	Coir fiber	Polyester fiber	SF, PF, and IF
Normal stress (kPa)	100, 200, 300	25, 50, 100	50, 100, 150	100, 200, 300	100, 200, 300
% Increase in (c) (kPa)	47.5	86	-	8	SF = 8 PF = 43 IF = 3.5
% Increase in ϕ (deg)	14.5	5	34	19	SF = 17.7 PF = 42 IF = 9

5. Conclusions

To investigate the effect of natural fiber reinforcement on the strength of AL-Nasiriya clayey soil, a series of unconfined compressive and direct shear tests were performed. This study's findings can be summarized as follows:

1. The inclusion of wheat straw, palm fronds, and imperata cylindrica fibers significantly improves the strength characteristics due to the interlocking between the soil particles and the surface of the fibers.
2. The compressive strength of the fiber-reinforced samples improved significantly with the increase of fiber content and length to the optimum value and then decreased. The optimum fiber content and length were 0.5 % and 30 mm, respectively.
3. Compared to the unreinforced soil, the compressive strength values at the optimum content and length increased by 102 %, 126 %, and 66 % for samples reinforced with wheat straw, palm fronds, and imperata cylindrica fibers, respectively.
4. The cohesion of samples reinforced with wheat straw, palm fronds and jute increased by 8 %, 43 %, and 3.5 %, respectively.
5. The internal friction angle of the samples reinforced with wheat straw, palm fronds, and imperata cylindrica fibers increased by 17.7 %, 42 %, and 9 %, respectively.

6. Recommendation

Based on the unconfined compression tests data, the optimum fiber content to be added to the soil to give the highest UCS value was 0.5 %.

References

[1] A. Aldaood, A. Khalil, M. Bouasker, and M. AL-Mukhtar, "Experimental Study on the Mechanical Behavior of Cemented Soil Reinforced with Straw Fiber", Geotechnical and Geological Engineering, Vol. 39, pp. 2985-3001, 2021. https://doi.org/10.1007/s10706-020-01673-z

[2] T. Yetimoglu, and O. Salbas, "A study on shear strength of sands reinforced with randomly distributed discrete fibers", Geotext. Geomembranes, Vol. 21, Issue 2, pp. 103-110, 2003. https://doi.org/10.1016/S0266-1144(03)00003-7

[3] P. K. Pradhan, R. K. Kar, and A. Naik, "Effect of Random Inclusion of Polypropylene Fibers on Strength Characteristics of Cohesive Soil", Geotechnical and Geological Engineering, Vol. 30, pp. 15-25, 2012. https://doi.org/10.1007/s10706-011-9445-6

[4] A. R. Estabragh, A. T. Bordbar, and A. A. Javadi, "Mechanical Behavior of a Clay Soil Reinforced with Nylon Fibers", Geotechnical and Geological Engineering, Vol. 29, pp. 899-908, 2011. https://doi.org/10.1007/s10706-011-9427-8

[5] N. M. Salim, K. Y. H. Al-Soudany, and A. A. Ahmed, "The Impact of Using Recycled Plastic Fibres on the Geotechnical Properties of Soft Iraqi Soils", IOP Conference Series: Materials Science and Engineering, Vol. 433, 2018. https://doi.org/10.1088/1757-899X/433/1/012017

[6] M. Al-Neami, F. Raheel, and Y. Al-Ani, "Behavior of Cohesive Soil Reinforced by Polypropylene Fiber", Engineering and Technology Journal, Vol. 38, Issue 6, pp. 801-812, 2020. https://doi.org/10.30684/etj.v38i6a.109

[7] A. Sagheb, E. Vafaeihosseini, and R. P. Kumar, "The Role of Building Construction Materials on Global Warming Lessons for Architects", National Conference on Recent Trends in Civil Mechanical Engineering, pp. 175-178, 2011. https://www.researchgate.net/publication/269031946

[8] R. Dris, J. Gasperi, M. Saad, C. Mirande, and B. Tassin, "Synthetic fibers in atmospheric fallout: A source of microplastics in the environment", Marine Pollution Bulletin, Vol. 104, Issue 1-2, pp. 290-293, 2016. https://doi.org/10.1016/j.marpolbul.2016.01.006

[9] H. Danso, D. B. Martinson, M. Ali, and J. B. Williams, "Physical, mechanical and durability properties of soil building blocks reinforced with natural fibres", Construction and Building Materials, Vol. 101, pp. 797-809, 2015. https://doi.org/10.1016/j.conbuildmat.2015.10.069

[10] K. Ghavami, R. D. Toledo Filho, and N. P. Barbosa, "Behaviour of composite soil reinforced with natural fibres", Cem. Concr. Compos, Vol. 21, pp. 39-48, 1999. https://doi.org/10.1016/S0958-9465(98)00033-X

[11] J. Prabakar, and R. S. Sridhar, "Effect of random inclusion of sisal fibre on strength behaviour of soil", Construction and Building Materials, Vol. 16, pp. 123-131, 2002. https://doi.org/10.1016/S0950-0618(02)00008-9

[12] J. Qu, and Z. Sun, "Strength Behavior of Shanghai Clayey Soil Reinforced with Wheat Straw Fibers", Geotechnical and Geological Engineering, Vol. 34, pp. 515-527, 2016. https://doi.org/10.1007/s10706-015-9963-8

[13] V. Sharma, and A. Kumar, "Influence of relative density of soil on performance of fiber-reinforced soil foundations", Geotextiles and Geomembranes, Vol. 45, pp. 499-507, 2017. https://doi.org/10.1016/j.geotexmem.2017.06.004

[14] D. Kaushik, and S. K. Singh, "Use of coir fiber and analysis of geotechnical properties of soil", Materials Today:Proceedings, Vol. 47, Part 14, pp. 4418-4422, 2021. https://doi.org/10.1016/j.matpr.2021.05.255

[15] H. Tan, F. Chen, J. Chen, and Y. Gao, "Direct shear tests of shear strength of soils reinforced by geomats and plant roots", Geotextiles and Geomembranes, Vol. 47, pp. 780-791, 2019. https://doi.org/10.1016/j.geotexmem.2019.103491

[16] G. V. Praveen, and P. Kurre, "Influence of coir fiber reinforcement on shear strength parameters of cement modified marginal soil mixed with fly ash", Materials Today: Proceedings, Vol. 39, pp. 504-507, 2020. https://doi.org/10.1016/j.matpr.2020.08.238

[17] Z. F. Xue, W. C. Cheng, L. Wang, and G. Song, "Improvement of the Shearing Behaviour of Loess Using Recycled Straw Fiber Reinforcement", KSCE Journal of Civil Engineering, Vol. 25, pp. 3319-3335, 2021. https://doi.org/10.1007/s12205-021-2263-3

[18] N. J. F. Al-Khafaji, M. A. K. Alshaher, M. A. A. Asmail, and S. H. Glood, "Development and application of a health record system in main office and branches of Dhi-Qar health directorate", The Third International Conference on e-Technologies and Networks for Development (ICeND2014), pp. 98-103, 2014. https://doi.org/10.1109/ICeND.2014.6991361

[19] M. Bouasker, N. Belayachi, D. Hoxha, and M. Al-Mukhtar, "Physical characterization of natural straw fibers as aggregates for construction materials applications", Materials, Vol. 7, Issue 4, pp. 3034-3048, 2014. https://doi.org/10.3390/ma7043034

[20] M. Li, S. X. Chai, H. Y. Zhang, H. P. Du, and L. Wei, "Feasibility of saline soil reinforced with treated wheat straw and lime", Soils and Foundations, Vol. 52, Issue 2, pp. 228-238, 2012. https://doi.org/10.1016/j.sandf.2012.02.003

[21] S. Rabab'ah, O. Al Hattamleh, H. Aldeeky, and B. Abu Alfoul, "Effect of glass fiber on the properties of expansive soil and its utilization as subgrade reinforcement in pavement applications", Case Studies in Construction Materials, Vol. 14, pp. 1-12, 2021. https://doi.org/10.1016/j.cscm.2020.e00485

[22] A. S. Zaimoglu, and T. Yetimoglu, "Strength Behavior of Fine Grained Soil Reinforced with Randomly Distributed Polypropylene Fibers", Geotechnical and Geological Engineering, Vol. 30, pp. 197-203, 2012. https://doi.org/10.1007/s10706-011-9462-5

[23] C. S. Tang, B. Shi, and L. Z. Zhao, "Interfacial shear strength of fiber reinforced soil", Geotextiles and Geomembranes, Vol. 28, pp. 54-62, 2010. https://doi.org/10.1016/j.geotexmem.2009.10.001

[24] L. Wei, S. X. Chai, H. Y. Zhang, and Q. Shi, "Mechanical properties of soil reinforced with both lime and four kinds of fiber", Construction and Building Materials, Vol. 172, pp. 300-308, 2018. https://doi.org/10.1016/j.conbuildmat.2018.03.248

[25] F. Changizi, and A. Haddad, "Strength properties of soft clay treated with mixture of nano-SiO2 and recycled polyester fiber", Journal of Rock Mechanics and Geotechnical Engineering, Vol. 7, Issue 4, pp. 367-378, 2015. https://doi.org/10.1016/j.jrmge.2015.03.013