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Strength and Bearing Capacity of Rectangular Footing Rested on a Soil Layer Reinforced with Waste Materials

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Abstract

A series of unconfined compression and direct shear tests were carried out to investigate the compressive strength and shear strength parameters of clay soil reinforced with different contents and lengths of wheat straw and palm frond fibers and by adding different percentages of furnace slag. The bearing capacity and settlement characteristics of the rectangular footing based on a clay soil layer reinforced with wheat straw fibers, palm fronds and furnace slag at different thicknesses were also studied by conducting model footing tests. The results indicated that the compressive strength and shear strength parameters improved significantly when adding 0.5% of natural fibers and 20% of furnace slag. The maximum compressive strength of soil samples reinforced with wheat straw fiber MT1 and palm frond fiber MT2 was 365 and 407 kPa, respectively. Compared to the unreinforced sample, samples reinforced with natural fibers and furnace slag significantly improve the shear strength parameters c and ϕ. The cohesion of soil sample reinforced with wheat straw and palm frond fibers increased by 8% and 43% respectively, while the internal friction angles improved by 19% and 40% respectively. The sample treated with furnace slag MT3 showed improved significantly in cohesion by 76% and less effect in internal friction angle. Compared to unreinforced soil samples, the cohesion of soil samples reinforced with wheat straw and palm fibers and treated with furnace slag MT4 and MT5 increased by 77% and 92% respectively, and less effect in internal friction angle. Moreover, the bearing capacity and settlement characteristics of the rectangular footing improved significantly with the increase in the thickness of the top layer reinforced with natural fibers and treated with furnace slag. The ultimate bearing capacity of layer reinforced with wheat straw fibers MT1 increases to 193.2, 220.15 and 247.5 kPa at thicknesses of 0.5 B, 1.0 B, and 1.5 B respectively, while the settlement decreased by 10.4%, 15% and 20.48% respectively at same thicknesses.

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]. Soil reinforced by random fiber distribution has various advantages over oriented or aligned soils [2]. 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 [3]. Although synthetic fibers have good mechanical properties as soil reinforcement elements, they are the cause of the depletion of natural resources and environmental pollution [4]. In response to these economic and environmental considerations, a new trend emerged to utilize natural fibers in soil reinforcement applications [5, 6].

Many studies prepared tests such as unconfined compression and direct shear using different types of natural fibers to improve the mechanical properties of the soil [7-12]. These investigations reported that the inclusion of fibers in the soil increases the compressive strength and shear strength parameters [13]. Model footing tests resting on fiber reinforced soil were prepared in many investigations to examine the bearing capacity and settlement properties. Wasti and Bütün [14] observed an increase in the bearing capacity of the strip footing rested on sandy soils reinforced with discrete randomly distributed polypropylene fibers. Kumar et al. [15] used 1% of randomly distributed synthetic fibers to reinforce the sandy soil supporting the strip footing. The results indicated that the addition of 1% of synthetic fibers to the top soil layer supporting the strip footing up to depths of 0.5 B, 1.0 B, 1.5 B, and 2 B improves the bearing capacity. In general, previous studies that examined the effect of fiber embedding on the behavior of cohesive soils were few compared to granular soils. Most of the investigations that studied the behavior of the foundation based on fiber-reinforced soils were prepared using synthetic fibers and sandy soils. Limited studies investigated the characteristics of bearing capacity and settlement of a footing rested on clay soil reinforced with local natural fibers and furnace slag.

In this study, wheat straw and palm fronds fibers were used, in addition to furnace slag as reinforcement materials for the strength characteristics of Nasiriyah clay soil. A series of unconfined compressive strength (UCS), direct shear, and model footing tests were prepared to evaluate the performance of clay soil reinforced with local natural fibers and furnace slag. The main purpose of this study is to discover how natural fibers and furnace slag affect the mechanical properties of the cohesive Nasiriyah soil. The results obtained from this work can be applied in the field to soils with similar properties.

2. Materials

2.1. Soil sample

The soil sample used in this work was taken from one of the quarries of Nasiriyah in Iraq. The latitude and longitude coordinates of the quarry are 31° 03′ 41″ N and 46° 09′ 55″ E, respectively. According to ASTM specification, a set of laboratory tests of the soil sample was conducted to determine the geotechnical properties listed in Table 1.

Table 1. Geotechnical properties of soil.

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

2.2. Fibers

The local natural fibers used in this Work are Wheat Straw (WSF) and Palm Fronds (PPF) as soil sample reinforcement materials as shown in Fig. 1. The selection of wheat straw fibers and palm frond fibers was based on their unique mechanical properties, including high surface roughness that enhances interlocking with soil particles, flexibility that improves stress resistance, and durability that contributes to the stability of the reinforced soil. The outer surface of wheat straw fibers is fine and rough to palm frond fibers. Natural fibers' Water Absorption Capacity factor (WAC) is calculated using a procedure of Bouasqer [16]. 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:

$$WAC = \frac{W_1 - W_2}{W_2} \times 100 \quad (1)$$

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 2.

Fig. 1 Samples of natural fibers.

Table 2. The physical properties of the natural fibers.

Property	WSF	PPF	Unit
Average diameter	3	-	mm
Fiber length (l_f)	20, 30, 40	20, 30, 40	mm
Average Fiber width	-	3.5	mm
Thickness	1	1.25	mm
WAC	250	150	%

2.3. Furnace slag

Furnace slag is a pozzolanic and mildly cementitious substance that is non-crystalline in structure [17]. Several studies have utilized different types of furnace slag from iron and steel manufacturing processes as reinforcement materials for weak soils [18, 19]. In this study, the furnace slag resulting from the combustion of fuel in the thermal power plant was used as a soil reinforcement material as shown in Fig. 2. Approximately 1 ton per year is the amount of furnace slag produced from the thermal power plant located in Nasiriyah, Iraq. The furnace slag was crushed and sieved 2 mm. The properties of furnace slag are shown in Table 3.

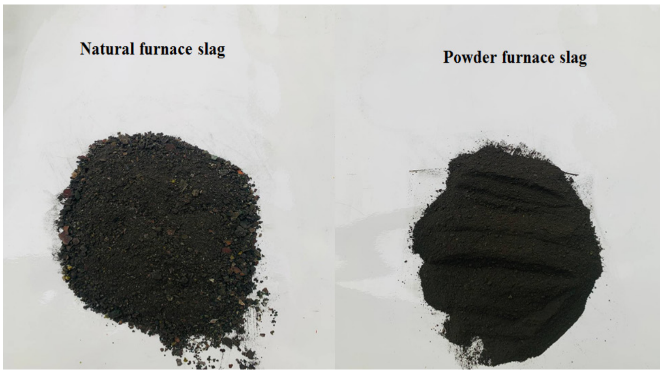


Fig. 2 Samples of furnace slag.

Table 3. Physical properties of furnace slag.

Property	Values
Silica content (%)	32.24
Alumina content (%)	12.17
Calcium Oxide (%)	38.5
Specific gravity (Gs)	2.3
Liquid limit (LL)	49

3. Methodology

The experimental work consists of two parts. The first part includes a series of unconfined compression and direct shear tests. Details of the reinforcement materials for the first part samples are listed in Table 4. The second part includes a series of model footing tests of a rectangular foundation based on a reinforced clay soil layer. Details of the reinforcement materials for the second part samples are listed in Table 5. According to previous studies, the rate of adding fiber to pure soil and soil treated with chemical bonds ranged between 0.2% and 4% by weight of soil mass. In this study, the soil was reinforced with natural fibers at the content ρ_f = 0.25%, 0.5%, 0.75, and 1% of soil mass weight ratio, and lengths l_f = 20, 30, and 40 mm. In addition, the soil was reinforced with furnace slag using three different percentages 15%, 20%, and 25%.

Table 4. Details of sample preparation for the first part of the tests.

Type of tests	Composite	l_f (mm)	ρ_f (%)	Furnace slag (%)	Samples ID
Unconfined Compressive Strength	Unreinforced soil	-		-	Un
	Soil + WSF	20, 30, 40	0.25, 0.5, 0.75, 1	-	MT1
	Soil + PPF	20, 30, 40	0.25, 0.5, 0.75, 1	-	MT2
	Soil + FRS	-	-	15, 20, 25	MT3
Direct shear	Unreinforced soil	-	-	-	Un
	Soil + WSF	30	0.5	-	MT1
	Soil + PPF	30	0.5	-	MT2
	Soil + FRS	-	-	20	MT3
	Soil + WSF + FRS	30	0.5	20	MT4
	Soil + PPF + FRS	30	0.5	20	MT5

Table 5. Details of sample preparation for the second part of the tests.

Type of tests	Composite	l_f (mm)	ρ_f (%)	Furnace slag (%)	Type of footing	Thickness of top layer h_1	Samples ID
Model Footing	Unreinforced soil	-	-	-	Rectangular	0.0B	Un
	Soil + WSF	30	0.5	-		0.5B, 1.0B, 1.5B	MT1
	Soil + PPF	30	0.5	-		0.5B, 1.0B, 1.5B	MT2
	Soil + FRS	-	-	20		0.5B, 1.0B, 1.5B	MT3
	Soil + WSF + FRS	30	0.5	20		0.5B, 1.0B, 1.5B	MT4
	Soil + PPF + FRS	30	0.5	20		0.5B, 1.0B, 1.5B	MT5

3.1. Unconfined compressive strength test

Unconfined compressive tests were carried out in two stages. The first stage includes preparing a group of samples reinforced with natural fibers to determine the optimal content and length. The second stage includes preparing a set of samples reinforced with furnace slag to determine the optimal ratio. Test samples were prepared according to ASTM D2166. The mixture of moist soil and reinforcement material was compacted into three layers in a cylindrical mold 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. All samples were prepared at MDD and OMC.

3.2. Direct shear test

A series of direct shear tests were carried out under unconsolidated undrained conditions in accordance with ASTM D 6528. Test samples were prepared using optimum values of reinforcement materials. To achieve the standard Proctor maximum dry density, the samples were compacted in a steel mold with dimensions of 60 mm × 60 mm in plan and 25 mm in depth. A wooden tamper extracts the sample from the steel mold and pushes it into the shear box. 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 soil reinforcement with natural fibers and furnace slag on peak shear stress τ_f and shear strength parameters c and ϕ were studied.

3.3. Model footing test

In this study, the tests were carried out using apparatus designed by Altaweal [20] as shown in Fig. 3. A set of model footing tests were performed on a steel rectangular plate with dimensions of 0.1 m × 0.2 m × 25 mm in a steel test tank of 0.6 m × 0.6 m in plan and 0.5 m in depth. The size of the test tank is designed to match the size of the model footing following the requirements of the Bossineq's approach. The test tank was filled with soil in three layers, the thickness of each layer was 15 cm. The layers were prepared at MDD and OMC. The top layer was reinforced with natural fibers and furnace slag in three thicknesses: h_1 = 0.5 B, 1.0 B, 1.5 B, where B is the width of the model footing.

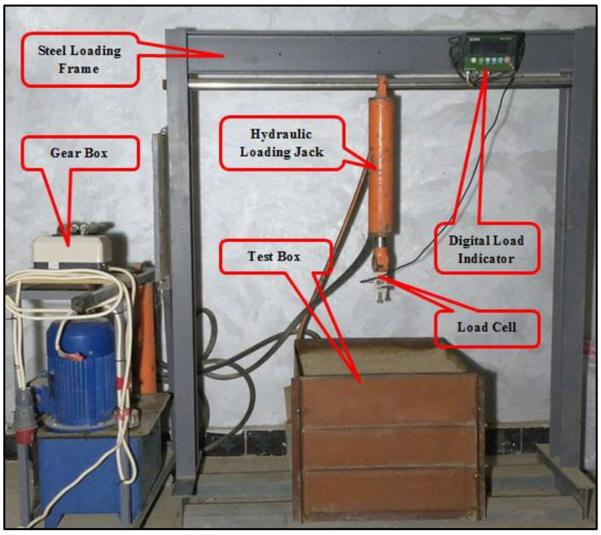


Fig. 3 Laboratory test machine [20].

The tests were carried out from two layers of the soil system: the reinforced top layer is underlain by the unreinforced lower layer as shown in Fig. 4. The top layer with reinforcement material is prepared according to Table 5.

The surface of the reinforced top layer is leveled and the model footing is laid in the center of the test tank. The model footing was statically loaded by a manually operated hydraulic jack and the applied load was measured using a load cell of the approximate capacity of 10 kN. The load was applied in eleven intervals and the corresponding settlement of model footing was observed by two sensitive dial gauges for every 50 kg load increment. The ultimate bearing capacity was obtained using 0.1 B Method. In this method, the ultimate point is taken at a value settlement corresponding to 10 % of the foundation.

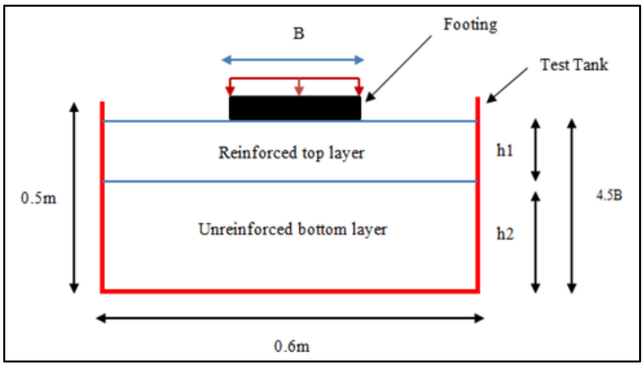


Fig. 4 Schematic of layer system in the model footing tests.

4. Results and discussion

4.1. Unconfined compressive strength test

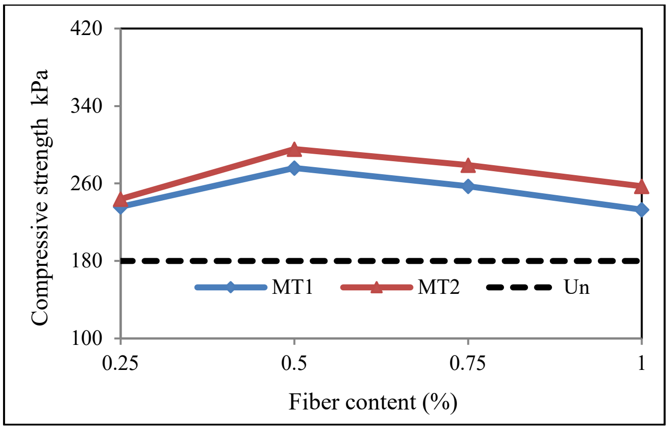
4.1.1. Optimal fiber content and length

The results of the compressive strength of soil reinforced with different content and lengths of natural fibers MT1 and MT2 are shown in Fig. 5. 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 MT1 and MT2 increases with increasing fiber content and then gradually decreases at a specified value. Figure 5 shows the maximum compressive strength of the reinforced samples MT1 and MT2 when the fiber content is 0.5%. The maximum compressive strength of samples M1 and M2 was 365 and 407 kPa, respectively. The values of the compressive strength of soil samples reinforced with PPF 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. [21] that the surface roughness of the fibers is one of the important factors that increase the interfacial shear resistance of the fiber-soil compound.

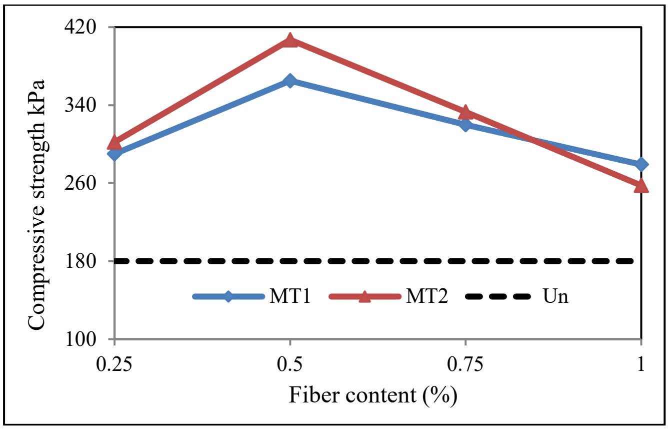
The difference in the length of the natural fibers used to reinforce the samples had a significant effect on the compressive strength. The maximum compressive strength values for samples M1 and M2 at the length of the fibers were 30 mm. Several studies have demonstrated that the length of the fibers 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. Wei et al. [22] 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. Based on the results of this study, the optimal values for length and fiber content were 0.5% and 30 mm.

4.1.2. Optimum percentage of furnace slag

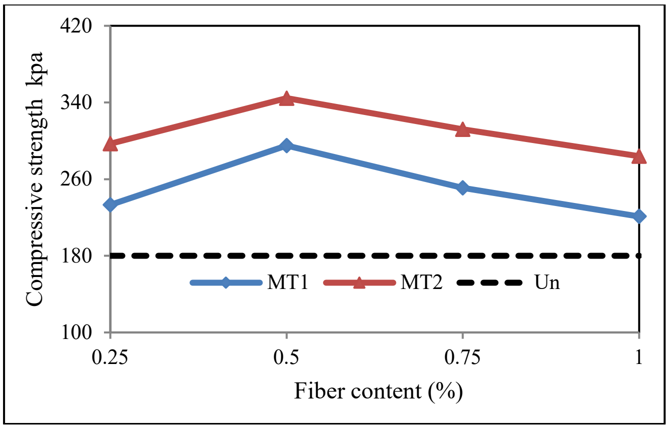
The relationship between compressive strength and the percentage is shown in Fig. 5. It can be seen from the figure that the compressive strength of sample MT3 is effectively improved compared to the unreinforced sample. The compressive strength of sample MT3 increases with an increasing percentage of furnace slag and then decreases. The sample reinforced with 20% of furnace slag gave the highest compressive strength of 474 kPa. The optimum percentage of furnace slag was 20%.



(a) l_f = 20 mm.



(b) l_f = 30 mm.



(c) l_f = 40 mm.

Fig. 5 Compressive strength of samples.

4.2. Shear strength characteristics

The shear stress-horizontal displacement relationship of unreinforced and reinforced samples is shown in Fig. 6. It can be seen from the figure that the reinforcement of soil with natural fibers and furnace slag 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. It can be seen from the figure that the addition of natural fibers and furnace slag raises peak shear strength and lowers the loss of residual shear strength.

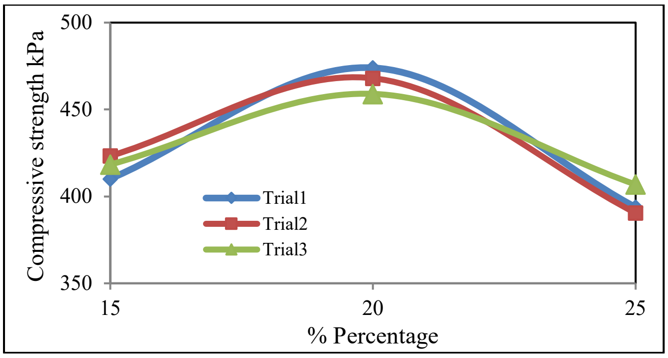
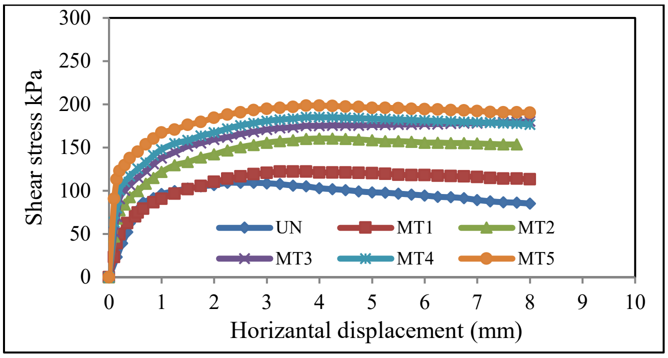
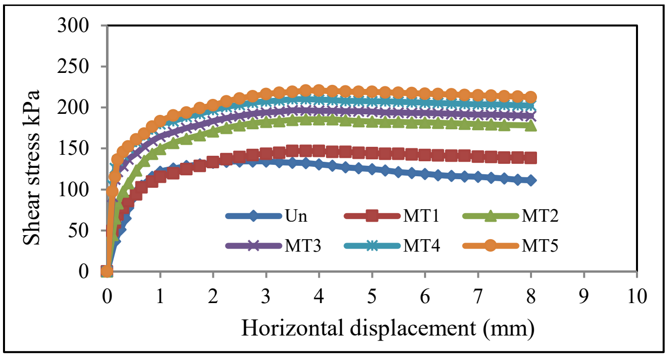


Fig. 6 Compressive strength of sample MT3.

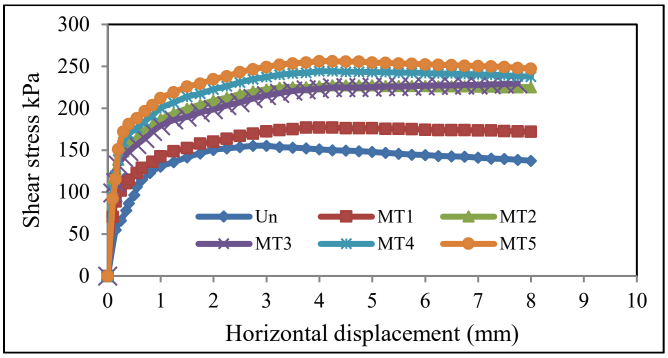
Compared to the unreinforced soil, samples reinforced with natural fibers MT1 and MT2 increase the peak shear stress values from 155 kPa to 177 and 227 kPa at a normal stress of 300 kPa. Compared to the unreinforced soil, the peak shear stress of sample MT3 increased by 48% at the same normal stress. In addition, the shear strength of samples MT4 and MT5 increased by 57% and 65%, respectively. The failure envelope corresponding to peak shear stress and normal stress is shown in Fig. 7 and 8 respectively.



(a) σ_n = 100 kPa



(b) σ_n = 200 kPa



(c) σ_n = 300 kPa

Fig. 7 shear stress-displacement curve.

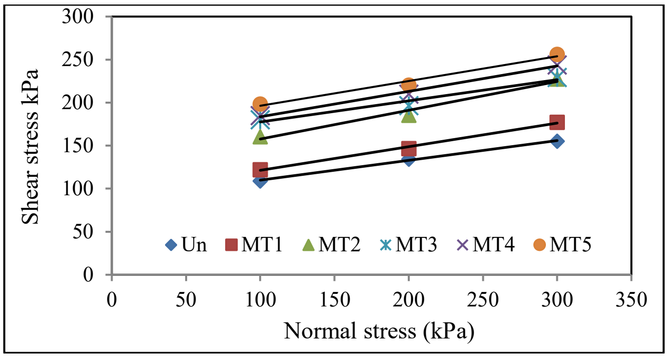


Fig. 8 the failure envelope of samples.

Compared to the unreinforced sample, samples reinforced with natural fibers and furnace slag significantly improve the shear strength parameters c and ϕ. The shear strength parameters of the reinforced samples are listed in Table 6. The internal friction angle of samples MT1 and MT2 increased by 17.7% and 42%, respectively. Furthermore, the cohesion increases by 8% and 43%, respectively. The cohesion of the sample reinforced with furnace slag MT3 improved by 76%, while the internal friction angle was not clearly affected. The cohesion of the samples reinforced with natural fiber and furnace slag MT4 and MT5 improved by 77% and 92%, while the internal friction angle improved by 26% and 23%, respectively. Based on these indicators, the reinforcement of clay soils with natural fibers and kiln slag significantly improves the shear characteristics.

Table 6. Geotechnical properties of soil.

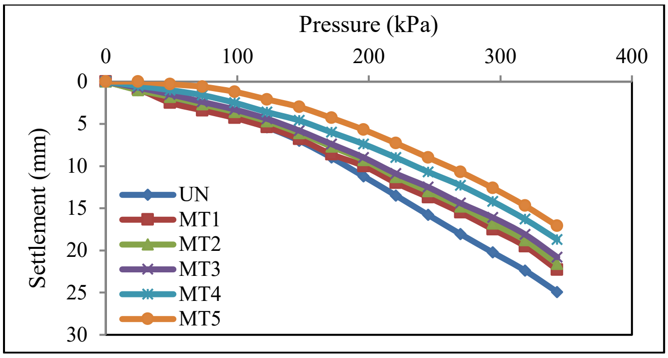
Samples	τ_f (kPa)			Shear Strength Parameters	
	σ_n = 100 kPa	σ_n = 200 kPa	σ_n = 300 kPa	C (kPa)	ϕ°
Un	109.2	134.3	155	86.9	13
MT1	122	147	177	94	15.5
MT2	160	186	277	124.2	18.3
MT3	180.3	196.5	229.5	152.97	13.8
MT4	185.0	196.5	244.1	154	16.45
MT5	198.6	220.6	256.1	167.6	16

4.3. Model footing test

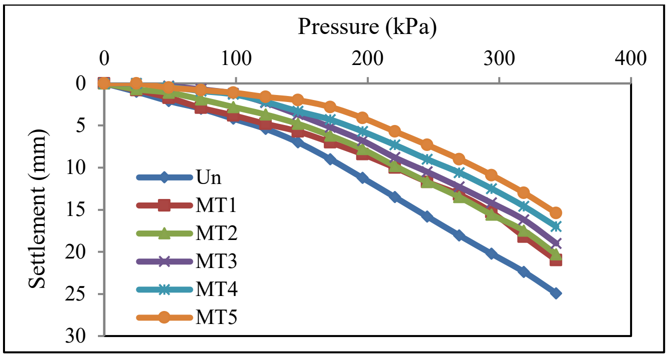
4.3.1 Effect of reinforced layer thickness on bearing capacity

The pressure settlement relationship obtained from the rectangular model footing test is shown in Fig. 9. It can be seen from that figure that the ultimate bearing capacity increases with the increase in the thickness of the reinforced top layer. The ultimate bearing capacity of unreinforced soil was 182.6 kPa. Compared to the unreinforced soil, the ultimate bearing capacity value of the soil reinforced with wheat straw fiber MT1 increases to 193.2, 220.15 and 247.5 kPa at thicknesses of 0.5B, 1.0B, and 1.5B, respectively. The increase in the ultimate bearing capacity of the soil reinforced with palm fronds fibers MT2 is 1.29 times that of the unreinforced soil when the thickness of the top layer reinforced is 1.5B.

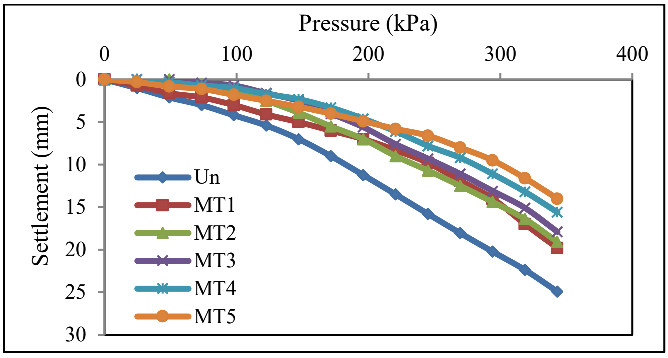
Compared to the unreinforced soil, the ultimate bearing capacity value of the soil reinforced with furnace slag MT3 increases by 12%, 21.2%, and 28.3% at thicknesses of 0.5B, 1.0B, and 1.5B, respectively. When the thickness of the top layer reinforced with wheat straw fibers and furnace slag MT4 increases from 0.5B to 1.0B and 1.5B, the ultimate bearing capacity increases from 235 kPa to 260.4 and 280 kPa, respectively. Compared to the unreinforced soil, the ultimate bearing capacity value of the soil reinforced with palm fronds fiber and furnace slag MT5 increases to 259.5, 282.5 and 300 kPa at thicknesses of 0.5B, 1.0B, and 1.5B, respectively.



(a) h1 = 0.5B



(b) h1 = 1.0B



(c) h1 = 1.5B

Fig. 9 The pressure-settlement curve.

4.3.2. Effect of reinforced layer thickness on settlement

The relationship between the thickness of the reinforced top layer and the settlement of the rectangular model footing is shown in Fig. 10. To clarify the effect of the thickness of the reinforced top layer on the settlement, the values of the settlement were taken at a pressure level of 343.2 kPa. It can be seen from that figure that the settlement decreases with the increase in the thickness of the reinforced top layer. At a pressure level of 343.2 kPa, the settlement of the unreinforced soil was 24.9 mm. Compared to the unreinforced soil, the settlement of soil reinforced with wheat straw fiber MT1 decreased to 22.3, 21, and 19.8 mm at thicknesses of 0.5B, 1.0B, and 1.5B, respectively. The decrease in settlement of the soil reinforced with palm frond fibers MT2 is 1.3 times that of the unreinforced soil when the thickness of the top layer reinforced is 1.5B. Compared to the unreinforced soil, the settlement of soil reinforced with furnace slag was reduced by 16%, 23%, and 28% at thicknesses of 0.5B, 1.0B, and 1.5B, respectively. When the thickness of the top layer reinforced with wheat straw fibers and furnace slag (MT4) increases from 0.5B to 1.0B and 1.5B, the settlement decreases from 18.7 mm to 17 mm and 15.6 mm, respectively. Compared to the unreinforced soil, the settlement value of the soil reinforced with palm fronds fiber and furnace slag MT5 slag was reduced by 31%, 38%, and 43% at thicknesses of 0.5B, 1.0B, and 1.5B, respectively.

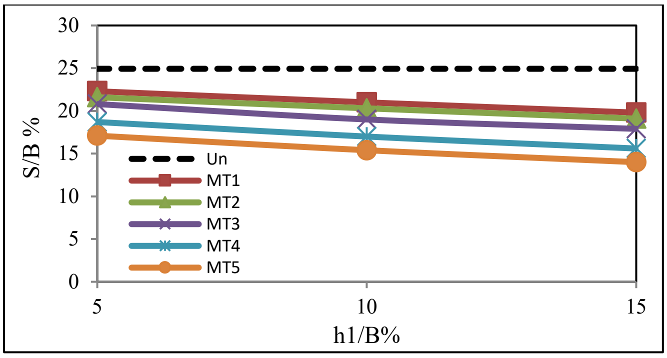


Fig. 9 Settlement reduction of samples.

5. Conclusions

To investigate the effect of reinforcing clay soils with local natural fibers and furnace slag on the strength properties, a series of unconfined compressive, direct shear, and model footing tests were performed. This study's findings can be summarized as follows:

1. Compared with the unreinforced soil, the compressive strength of samples randomly distributed reinforced with wheat straw fiber and palm frond fibers MT1 and MT2 improved by 55.7% and 50.6%, respectively. In addition, the UCS values increases by 62% when 20% of furnace slag is added to the soil.
2. The shear strength increases by 12%, 31 and 48% for samples MT1, MT2, and MT3, respectively, while samples MT4 and MT5, the shear strength improves by 57% and 65%, respectively.
3. The internal friction angle of samples MT1 and MT2 increases by 17.7% and 42%, respectively. Furthermore, the cohesion increases by 8% and 43%, respectively. The cohesion of the sample MT3 improved by 76%, while the internal friction angle was not clearly affected. The cohesion of the samples MT4 and MT5 improved by 77% and 92%, while the internal friction angle improved by 26% and 23%, respectively.
4. Compared to the unreinforced soil, the increased thickness of the reinforced top layer increases the ultimate capacity of the rectangular footing and reduces settlement.

References

[1] J. Li, C. Tang, D. Wang, X. Pei, and B. Shi, “Effect of discrete fibre reinforcement on soil tensile strength,” Journal of Rock Mechanics and Geotechnical Engineering, Vol. 6, Issue 2, pp. 133-137, 2014. https://doi.org/10.1016/j.jrmge.2014.01.003

[2] 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
[3] F. Ahmad, F. Bateni, and M. Azmi, "Performance evaluation of silty sand reinforced with fibres," Geotextiles and Geomembranes, Vol. 28, Issue 1, pp. 93-99, 2010. https://doi.org/10.1016/j.geotexmem.2009.09.017
[4] T. Maliakal, and S. Thiyyakkandi, "Influence of Randomly Distributed Coir Fibers on Shear Strength of Clay," Geotechnical and Geological Engineering, Vol. 31, pp. 425-433, 2013.https://doi.org/10.1007/s10706-012-9595-1
[5] 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, part 1, pp. 797-809, 2015. https://doi.org/10.1016/j.conbuildmat.2015.10.069
[6] M. Milosevic, P. Valášek, and A. Ruggiero, "Tribology of natural fibers composite materials: An overview," Lubricants, Vol. 8, Issue 4, pp. 1-19, 2020. https://doi.org/10.3390/lubricants8040042
[7] 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, Issue 9, pp. 3319-3335, 2021. https://doi.org/10.1007/s12205-021-2263-3
[8] W. Yixian, G. Panpan, S. Shengbiao, Y. Haiping, and Y. Binxiang, "Study on Strength Influence Mechanism of Fiber-Reinforced Expansive Soil Using Jute," Geotechnical and Geological Engineering, Vol. 34, pp. 1079-1088, 2016. https://doi.org/10.1007/s10706-016-0028-4
[9] V. Sharma, H. K. Vinayak, and B. M. Marwaha, "Enhancing compressive strength of soil using natural fibers," Construction and Building Materials, Vol. 93, pp. 943-949, 2015. https://doi.org/10.1016/j.conbuildmat.2015.05.065
[10] 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
[11] Y.-X. Wang, P.-P. Guo, W.-X. Ren, B.-X. Yuan, H.-P. Yuan, Y.-L. Zhao, S.-B. Shan, and P. Cao, "Laboratory Investigation on Strength Characteristics of Expansive Soil Treated with Jute Fiber Reinforcement," International Journal of Geomechanics, Vol. 17, Issue 11, 2017. https://doi.org/10.1061/(asce)gm.1943-5622.0000998
[12] 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
[13] S. M. Hejazi, M. Sheikhzadeh, S. M. Abtahi, and A. Zadhoush, "A simple review of soil reinforcement by using natural and synthetic fibers," Construction and Building Materials, Vol. 30, pp. 100-116, 2012. https://doi.org/10.1016/j.conbuildmat.2011.11.045
[14] Y. Wasti, and M. D. Bütün, "Behaviour of Model Footings on Sand Reinforced with Discrete Inclusions," Geotextiles and Geomembranes, Vol. 14, Issue 10, pp. 575-584, 1996. https://doi.org/10.1016/S0266-1144(96)00044-1
[15] A. Kumar, R. Bhatia, and B. S. Walia, "An experimental study on the load settlement behavior of a fiber-reinforced sand bed," International Journal of Geotechnical Engineering, Vol. 5, Issue 3, pp. 343-350, 2011. https://doi.org/10.3328/IJGE.2011.05.03.343-350
[16] 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
[17] J. Setién, D. Hernández, and J. J. González, "Characterization of ladle furnace basic slag for use as a construction material," Construction and Building Materials, Vol. 23, Issue 5, pp. 1788-1794, 2009. https://doi.org/10.1016/j.conbuildmat.2008.10.003
[18] A. R. Goodarzi, and M. Salimi, "Stabilization treatment of a dispersive clayey soil using granulated blast furnace slag and basic oxygen furnace slag," Applied Clay Science, Vol. 108, pp. 61-69, 2015. https://doi.org/10.1016/j.clay.2015.02.024
[19] J. M. Manso, V. Ortega-López, J. A. Polanco, and J. Setién, "The use of ladle furnace slag in soil stabilization," Construction and Building Materials, Vol. 40, pp. 126-134, 2013. https://doi.org/10.1016/j.conbuildmat.2012.09.079
[20] A. A. Altaweel, and R. R. Shakir, "The Effect of Interference of Shallow Foundation on Settlement of Clay Soil," IOP Conference Series: Materials Science and Engineering, Vol. 1094, 2021. https://doi.org/10.1088/1757-899x/1094/1/012043
[21] C. S. Tang, B. Shi, and L. Z. Zhao, "Interfacial shear strength of fiber reinforced soil," Geotextiles and Geomembranes, Vol. 28, Issue 1, pp. 54-62, 2010. https://doi.org/10.1016/j.geotexmem.2009.10.001
[22] 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