Research Article

Effects of the inclusion of industrial and agricultural wastes on the compaction and compression properties of untreated and lime-treated clayey sand

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Abstract
The reuse of industrial and agricultural wastes is an alternative method to provide low-cost building materials for the construction industry and reduce the environmental pollutions. This study evaluates the feasibility of using a couple of waste materials including palm fiber, palm fiber ash and fiber bundles both individually and in combination with lime to improve strength characteristics of clayey sand. A series of laboratory tests were performed on samples cured for 7, 14, 28 and 56 days to investigate the compaction properties, unconfined compressive strength (UCS) and failure characteristics of the untreated and lime-treated clayey sand. The results demonstrate that the application of all the additives resulted in a noticeable increase in strength, and both treated and untreated specimens exhibited more ductile behavior. It was also revealed that the mixture of lime and fiber performed more impressively compared to that of lime and fiber individually and the UCS of the improved specimens depends on fiber length and curing period. Inclusion of the various proportions of palm fiber, palm fiber ash and lime increased the optimum moisture content (OMC) and decreased the maximum dry density (MDD), while the addition of fiber bundles decreased the value of MDD and OMC. Palm fiber ash was more effective in increasing the UCS of specimens, and fiber bundles had the most significant impact on the variations of compaction properties.

Keywords Unconfined compressive strength · Palm fiber · Industrial wastes · Compaction properties · Lime

1 Introduction

In recent years, civil engineers have focused on soil improvement methods that are not only economical but also compatible with the environment in reducing the energy consumption for production of building materials [13, 20, 32, 60, 61]. Employing locally available materials such as industrial and agricultural wastes for the construction industry is an alternative to decrease the production costs of building materials and environmental contamination [24, 29, 33, 59]. Several studies have been conducted on the reinforcement of soils using natural and waste fibers to improve the strength properties of soils [3, 19, 25, 30, 38, 43, 45, 56, 68]. According to the previous investigations, strength properties of fiber-reinforced soils depend on fiber content, fiber length, friction between soil and fiber and fiber strength characteristics.

Palms are one of the most frequently found trees living in tropical and subtropical climates. Many studies have been carried out to study the behavior of reinforced soils using palm fiber, oil palm fiber, palm oil fuel ash and palm kernel shell [1, 47, 49, 53, 65]. Marandi et al. [44] studied the influence of date palm fiber on the strength and ductility behavior of silty sand. The results revealed that the addition of fiber has significant effects on maximum compressive strength, ductility and stiffness of the specimens.

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An increase in the palm fiber content and fiber length increased the ductility and decreased the stiffness of studied soil. Furthermore, an increase in the fiber increased the California bearing ratio (CBR). Azadegan et al. [9] demonstrated that by using more palm fibers as the reinforcing elements, the compressive strength, elasticity modulus and failure strain of clayey soil increased. Gungat et al. [27] investigated the utilization of palm oil shell for increasing the load-bearing capacity of road subgrade and reported that this additive can be used to improve the poor subgrade at the plantation area. Ikeagwuani et al. [31] studied the effects of lime and palm kernel shell ash on the compressibility characteristics of the black cotton soil. The results revealed that adding certain amount of fiber in combination with lime decreased the plasticity index and improved the compressibility characteristics of the black cotton soil. Otoko et al. [52] investigated the influence of palm oil fiber ash on soil stabilization and concluded that the CBR of studied soil increases by adding lime and palm oil fiber ash. Rajesh and Suresh [57] carried out a series of experimental tests on UCS of dispersive soil treated with lime and palm oil fuel ash. Adding lime and palm oil fuel ash increased the UCS of specimens. Moreover, the mixture of lime and palm oil fuel ash performed more efficiently in comparison with the additives individually.

Several studies have demonstrated the effectiveness of using polypropylene fibers as a reinforcing material in improving the strength properties of soils [21, 28, 39, 40, 50, 67, 69, 71]. Cai et al. [14] reported that an increase in polypropylene fiber content caused an increase in the strength and shrinkage potential of soil. Tang et al. [66] concluded that the inclusion of polypropylene fiber caused an increase in the unconfined compressive strength and shear strength. Moreover, an increase in the percentage of fiber caused the specimens to fail at higher axial strain levels. Polymer bags are used in the impaction of the industrial products which are woven from bundle polypropylene fibers. Chen et al. [15] recommended to use waste polymer textile bags in soil stabilization projects as a new method due to the availability of this waste material. (Almost 3 million tons of polymer bags are discarded every year in China.) They reported that fiber bundle, obtained by the fragmentation of polymer bags, is an industrial waste that can be used as reinforcing materials in soils to improve the strength and ductility of the treated clay.

Fibers can be used in combination with other admixtures such as lime, cement and fly ash to enhance the strength characteristics of soils [16, 18, 35, 38, 66]. Lime stabilization is a common chemical stabilization technique that can be used in combination with different additives to improve the engineering and mechanical properties of soils [5, 30, 34, 36, 42]. In this study, lime is used as a stabilizer beside the reinforcement additives.

A review of the above-mentioned studies demonstrates that there are very limited studies performed to investigate the influence of adding fiber bundles and palm fiber ash on the geotechnical properties of soils compared to the other waste materials. Accordingly, the objective of the current study is to investigate the influence of using fiber bundles and the wastes of palm skin as an alternative low-cost material (both individually and in combination with lime) on the compaction and strength properties of clayey sand. To achieve this aim, palm fiber, palm fiber ash and fiber bundles were used as reinforcement materials, and a series of laboratory experiments, including standard Proctor compaction and UCS tests, were conducted to evaluate the effects of additive content, fiber length and curing period on the compaction and compressive strength properties of untreated and lime-treated sandy clay. The feasibility of reducing lime content by replacing certain percentages of additives to achieve the desired UCS is also evaluated.

2 Materials used and experimental procedure

2.1 Soil and water

The studied soil has been classified as SM according to the Unified Soil Classification System (USCS) following ASTM D2487. The grain size distribution curve of the soil is illustrated in Fig. 1. Atterberg limits tests were performed in accordance with ASTM D4318. Based on the results, the liquid and plastic limits of the soil are equal to 35% and 20%, respectively. The compaction test was performed using the standard Proctor compaction test according to ASTM D698. The studied soil has a maximum dry density (MDD) of 18.30 kN/m^3 and optimum moisture content

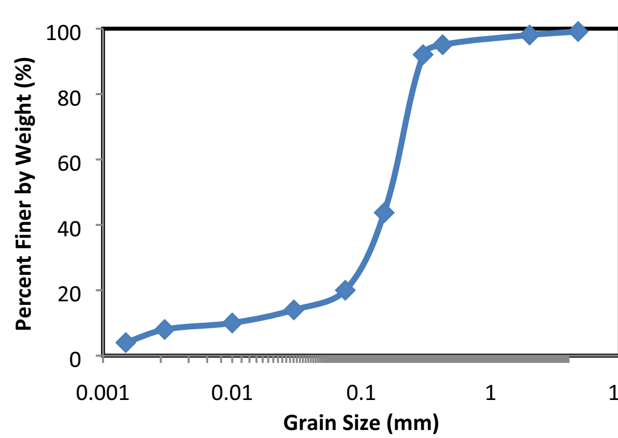


Fig. 1 Grain distribution size curve for the studied soil

Table 1 Chemical composition of studied lime

Chemical composition	% by total weight
CaO	85
CO_2	6
MgO	5
Insoluble materials	3
SiO_2	< 1

Table 2 Chemical composition of palm fiber ash

Chemical Composition	% by total weight
SiO_2	69.456
K_2O	9.03
Al_2O_3	5.51
CaO	5.46
Fe_2O_3	5.17
MgO	3.81
L.O.I.	1.12
Na_2O	0.29
Cl	0.154

(OMC) of 13%. Moreover, it has been frequently reported that the quality of water has a significant effect on the results of characterization tests as well as the mechanical properties of cementitious materials [2, 10, 26, 33, 41]. Therefore, in this study, distilled water was used for the characterization tests and tap water for molding the samples [22, 23, 58, 62].

2.2 Lime

In this research, hydrated lime is used as the stabilizer agent in clayey sand. The chemical composition of used lime is presented in Table 1.

2.3 Palm fiber and palm fiber ash

In the current study, agricultural wastes such as palm fiber and palm fiber ash were used as the reinforcement materials. Palm fibers were gained by cutting waste skin of palm tree obtained from Bam palm grove which is located in the south of Kerman, Iran. The fibers were cut into small pieces with the lengths varying between 20 and 40 mm. The specific gravity and the maximum tensile strength of palm fibers were 9 kN/m^3 and 67.46 MPa, respectively. Palm fiber ash that was produced from burning palm fibers had the specific gravity of 17.30 kN/m^3. Table 2 presents the chemical composition of used palm fiber ash. According to ASTM C 618, the pozzolanic material must incorporate at least 70% of the total quantity of the three principal oxides including Fe_2O_3, Al_2O_3 and SiO_2. According to Table 2, the summation of the three principle pozzolanic oxide components in the palm fiber ash composition is 76.05% of the total of oxide components so that it can be considered as a pozzolanic additive in stabilizing soil. Figure 2 shows a view of the used palm fiber and palm fiber ash in the laboratory samples.

2.4 Fiber bundles

Polymer bags, which are made of polypropylene, were used in the packaging applications. In the current research work, polymer bags were stringed and cut into pieces. Fiber bundles were split from polymer bags with the lengths of 10, 20, 30, 40 mm, thickness of 0.035 mm, specific gravity of 8.50 kN/m^3, maximum tensile strength of

Fig. 2 Applied **a** palm fiber, **b** palm fiber ash

92 MPa and water absorption of 0%. Figure 3 presents a view of the fiber bundles used in this study.

2.5 Standard proctor compaction and unconfined compression tests

Standard proctor compaction tests were carried out on the untreated soil, lime-stabilized specimens and the specimens with different percentages of palm fiber, palm fiber ash and fiber bundles. The unconfined compression tests were performed to evaluate the impact of different additives on the UCS of specimens. Specimens were prepared with various contents of lime (0%, 2%, 4% and 6% by weight of dry soil), palm fiber (0%, 0.5%, 1% and 1.5% by weight of dry soil), palm fiber ash (0%, 2%, 4% and 6% by weight of dry soil) and fiber bundles (0%, 0.5%, 1% and 1.5% by weight of dry soil). The tests were performed using four different fiber bundles lengths of 10 mm, 20 mm, 30 mm and 40 mm and two different palm fiber lengths of 20–40 mm. The specimens were initially prepared at their OMC and then compacted in three layers in a cylindrical mold with a diameter of 50 mm and height of 100 mm. The specimens were then stored and cured in plastic bags to avoid significant water content variations. The mixing procedure of the palm fibers with soil consisted of the following steps. At first, the palm fibers were manually separated from each other. They were then cut into different pieces with lengths of 20–40 mm. Then, all the dry materials (clayey sand and palm fiber) were mixed until a homogeneous mixture was achieved. The corresponding water quantity was then added to the dry mixture, and the mixing process was resumed for about 10 min. The mixing process of other additives (palm fiber ash, lime and fiber bundles) with clayey sand included the last two mentioned steps. In order to investigate the influence of curing time on the UCS development, all samples were tested after 7, 14, 28 and 56 days of curing. According to ASTM D4609, after 28 days of curing, the stabilized soil should gain a minimum enhancement of 345 kPa in the UCS in order to be considered beneficial [70]. Stabilizing soil with lime consists of pozzolanic and hydration reactions, and the time dependency of pozzolanic reactions is proved by many research studies. Moreover, it has been claimed that the best results from lime-stabilized soil are often obtained by the following long-term curing periods [11, 12, 35, 51]. Considering the aforementioned studies, the curing periods of up to 56 days were adopted in this study. However, the curing periods of 7, 14, 28 and 56 days were adopted in this study following the recent research studies conducted by the authors on lime-stabilized soil [35, 36]. Based on the recommendations of different researchers and standards, and in order to ensure the accuracy of the test results, three replicate specimens for each test were prepared and tested, and the average values were reported [37, 48, 64]. Further details regarding the compaction test, sample preparation and UCS test are provided in [33, 34]. Figure 4 illustrates the program of laboratory tests.

3 Results and discussion

Results from the laboratory work were analyzed and evaluated to investigate the effect of lime content, additives content, physical properties of additives and curing periods on the UCS variations, failure characteristics, OMC and MDD of the samples.

3.1 Standard proctor test results

According to the results of standard proctor compaction tests, inclusion of lime and palm fiber ash to the soil decreased the MDD and increased the OMC of the specimens. The decrease in the MDD of the samples is mainly due to the lower specific gravity of the additives than that

Fig. 3 Applied fiber bundles

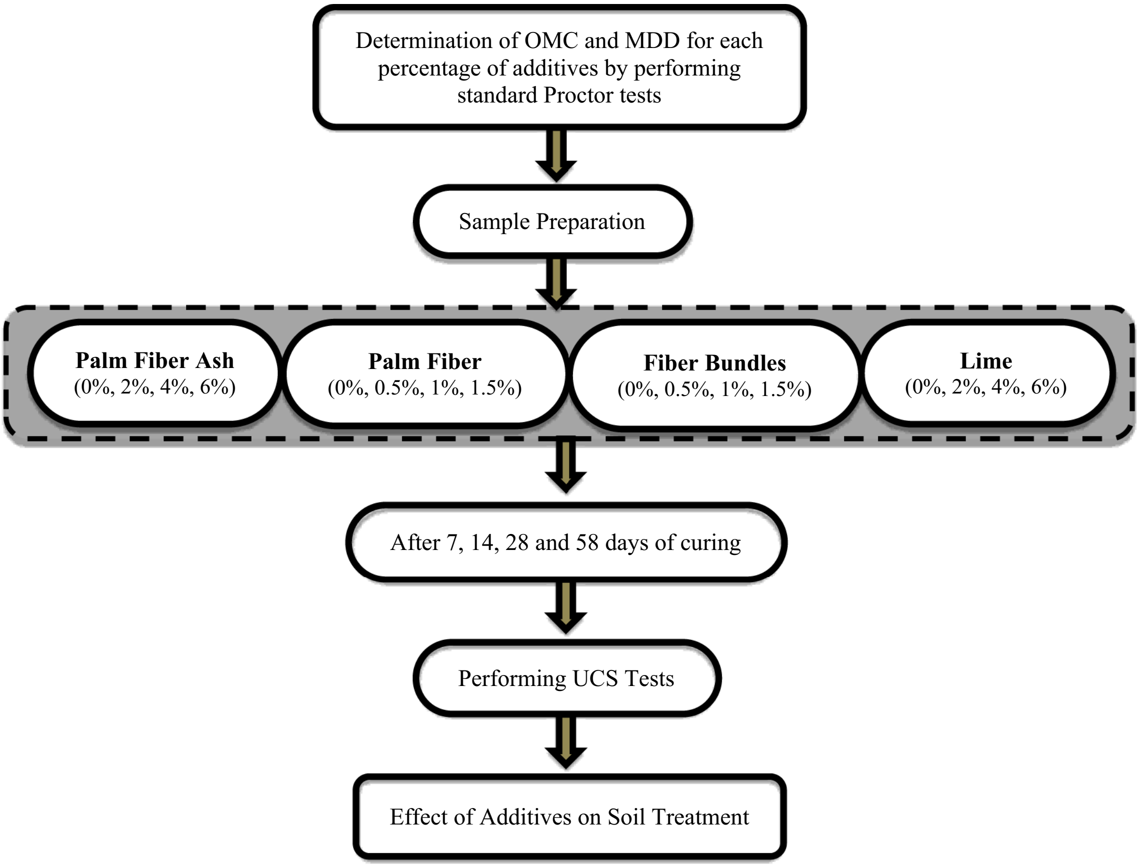


Fig. 4 Program of laboratory experiments

of the studied soil. Addition of palm fiber decreased MDD and increased OMC because of low specific gravity and higher water absorption of palm fiber compared to the studied soil. In contrast, inclusion of fiber bundles led to a reduction in both MDD and OMC of the specimens.

3.2 Unconfined compression test results

3.2.1 The effects of lime on UCS

Figure 5 shows the relationship between UCS of specimens versus lime contents at different curing periods. The strength of the specimens increased drastically with increasing the lime content. The addition of lime had a significant effect on the strength improvement in the specimens. The UCS of the stabilized soil increased with increasing the curing period. The maximum strength appeared in

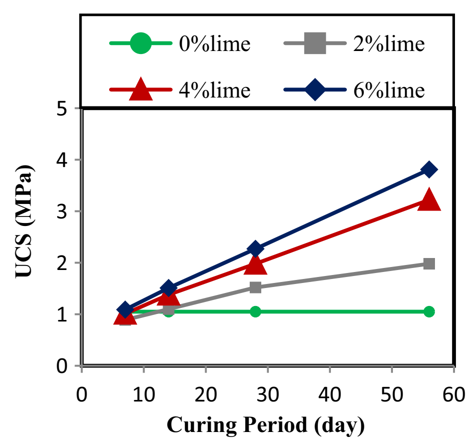


Fig. 5 The effects of the lime on the compressive strength at different curing times

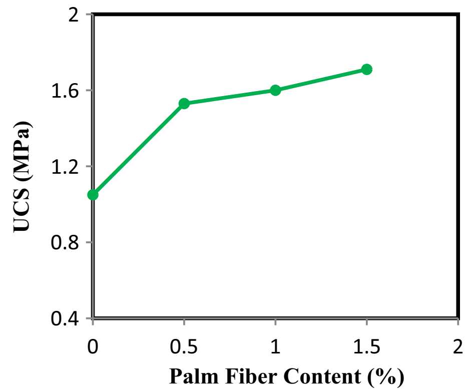


Fig. 6 The effect of the palm fiber on the compressive strength

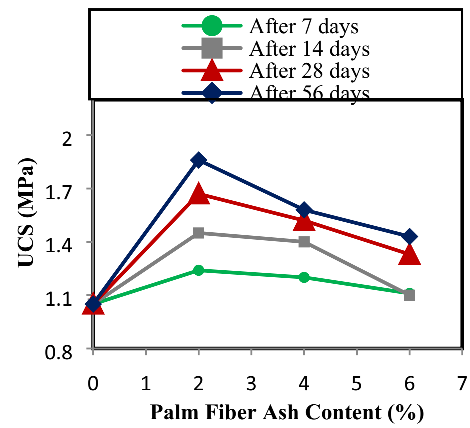


Fig. 8 The effects of palm fiber ash on the UCS at different curing times

the specimens containing 6% lime after 56 days of curing. The stabilization of soil with lime is a time-dependent process, and the main purpose of considering different curing periods was to allow the chemical reactions, including pozzolanic and hydration process between lime and soil, to develop over time [12, 17, 46].

3.2.2 The effect of palm fiber on UCS

The effect of adding palm fiber individually on the UCS of specimens is shown in Fig. 6. As can be seen in the figure, UCS values increased by increasing palm fiber content. Palm fiber has an appropriate tensile strength and a high water absorption property which resulted in a homogeneous and resistant mixture when applied to the soil. The results are consistent with the findings reported

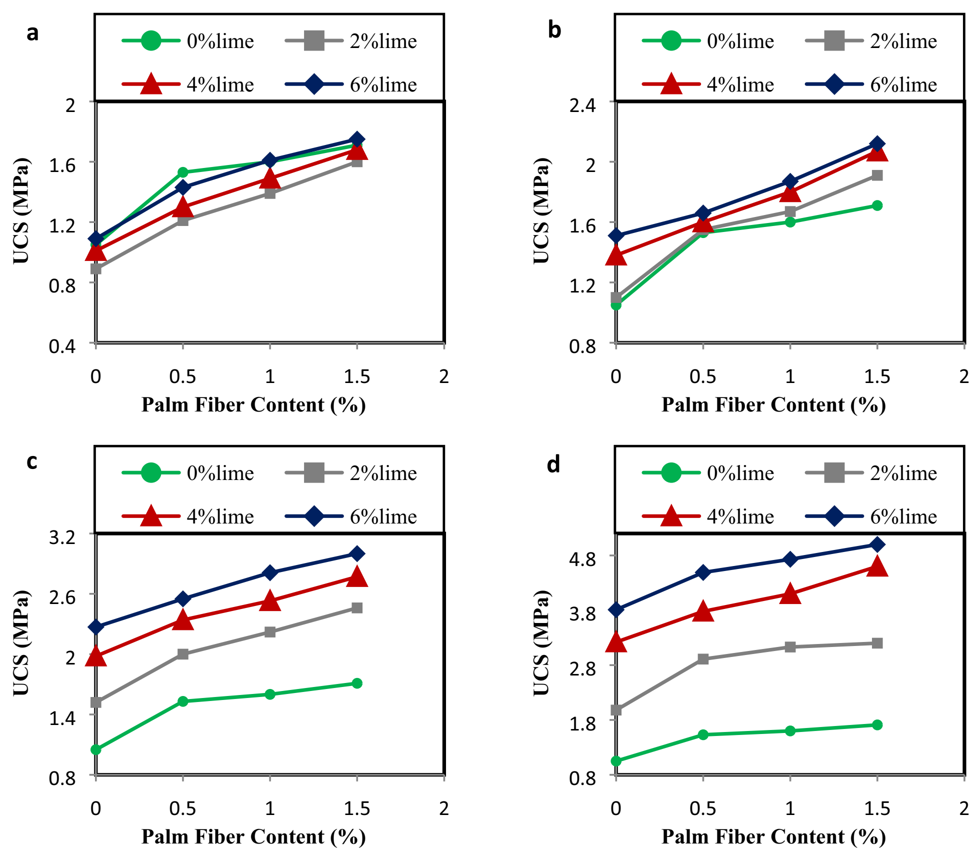
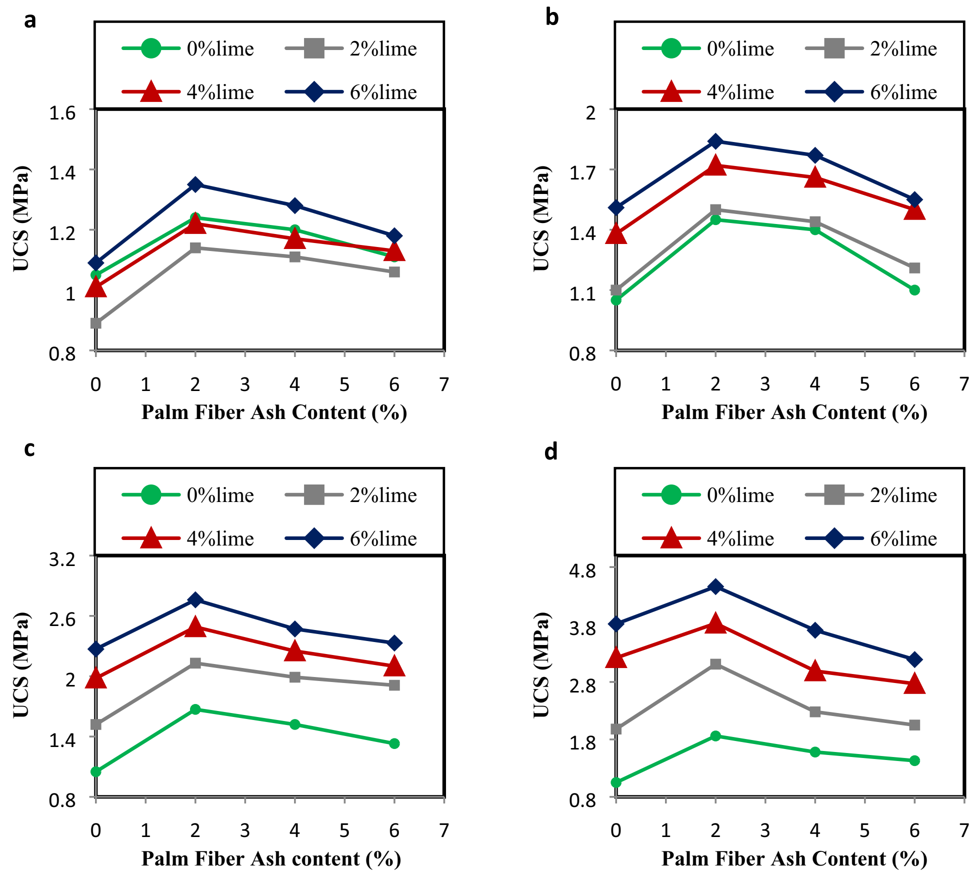


Fig. 7 The effects of the combination of lime and palm fiber on the compressive strength at different curing times. **a** After 7 days of curing, **b** after 14 days of curing, **c** after 28 days of curing, **d** after 56 days of curing

Fig. 9 The effects of the combination of lime and palm fiber ash on the compressive strength at different curing times. **a** After 7 days of curing, **b** after 14 days of curing, **c** after 28 days of curing, **d** after 56 days of curing



by Marandi et al. [44] on palm fiber-reinforced silty sand and Azadegan et al. [9] on palm fiber-reinforced clay. The variations of the UCS of lime-treated specimens with palm fiber content are presented in Fig. 7a–d after 7, 14, 28 and 56 days of curing. These figures reveal that an increase in the percentage of palm fiber is followed by an increase in the UCS of specimens. The results of the combination of lime and palm fiber are the same as those of each one individually. It can be seen that the changes in the UCS are significant at higher percentages of palm fiber and lime. It is evident that the remarkable growth of the UCS (up to 3.95 MPa) is related to the specimen with the lime content of 6%, palm fiber content of 1.5% and curing time of 56 days in comparison with the unmodified soil.

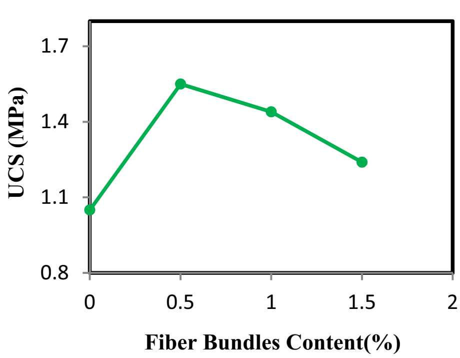


Fig. 10 The effects of the fiber bundle on the compressive strength

3.2.3 The effect of palm fiber ash on UCS

Figure 8 demonstrates the UCS of samples treated with various percentages of palm fiber ash after different curing periods. The UCS of the specimens increased with increasing the percentage of palm fiber ash up to 2% and decreased with further addition. As explained in Sect. 2.3, according to ASTM C 618, the palm fiber ash is a siliceous material which possesses pozzolanic properties due to its high quantities of silicon, aluminum and iron oxide (more than 70%). The UCS improvement achieved by the specimens incorporating palm fiber ash is motivated by the formation of calcium aluminate hydrate (CAH) and calcium silicate hydrate (CSH) as a result of developing pozzolanic reactions [4, 55, 63]. Improved soil with palm fiber ash takes a long time to reach its ultimate strength and is a time-dependent process. The results showed that with an increase in the curing period the UCS increased irrespective to palm fiber ash content. By adding 2% palm fiber ash, the UCS value increased from 1.05 to 1.86 MPa after 56 days of curing. Figure 9a–d illustrates the effects of adding palm fiber ash to the lime-stabilized specimens with different percentages of lime at different curing periods.

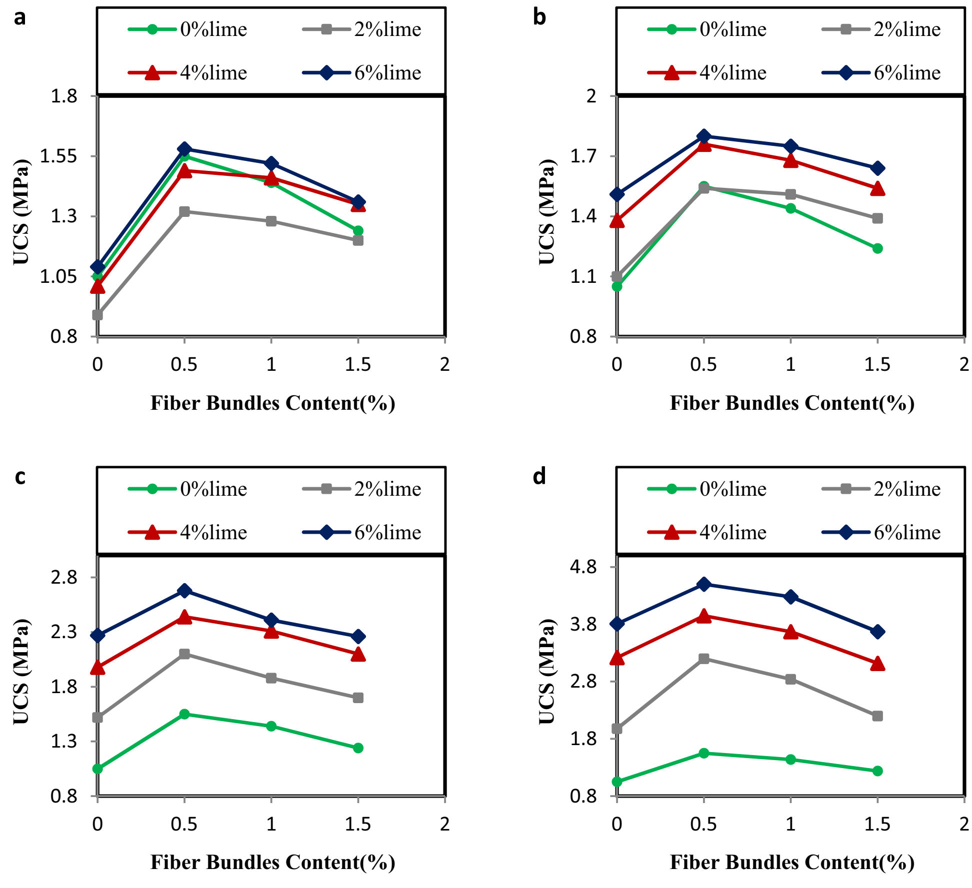


Fig. 11 The effects of the combination of lime and palm fiber ash on the compressive strength at different curing times. **a** After 7 days of curing, **b** after 14 days of curing, **c** after 28 days of curing, **d** after 56 days of curing

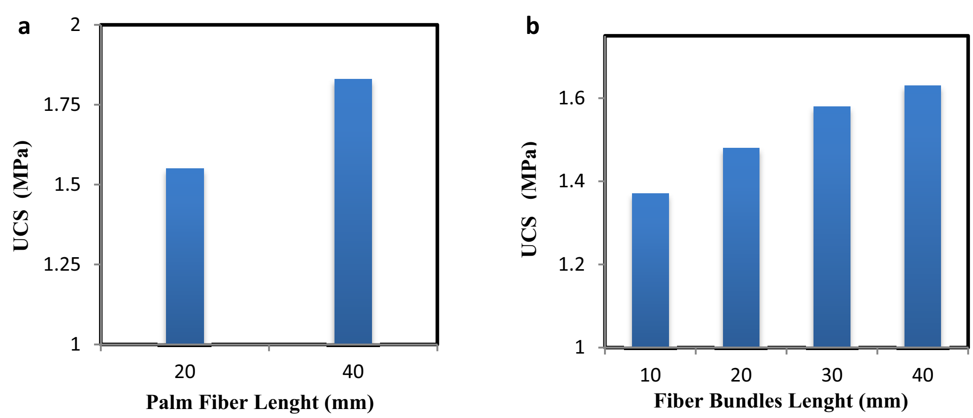


Fig. 12 The effect of **a** palm fiber length, **b** fiber bundles length on UCS

Figure 9a–d indicates that the combined use of lime and palm fiber ash generally leads to higher UCS values than the stabilized specimens with lime or palm ash. It is clear that the optimum amounts of palm fiber and lime are 2% and 6%, respectively, after 56 days of curing when the increase in the UCS is 3.41 MPa (from 1.05 to 4.46 MPa) compared to unmodified soil. Pourakbar et al. [54] performed a series of laboratory tests on stabilized clay with the mixture of palm oil fuel ash and cement. They proved the occurrence of pozzolanic reactions between palm oil fuel ash and hydrolysis of the cement.

3.2.4 The effect of fiber bundles on UCS

Figure 10 presents the variation in the UCS of samples treated with fiber bundles. As indicated in Fig. 10, an increase in fiber bundle content led to an initial increase followed by a slight decrease in UCS. The effect of changes in the fiber bundles content on the UCS of

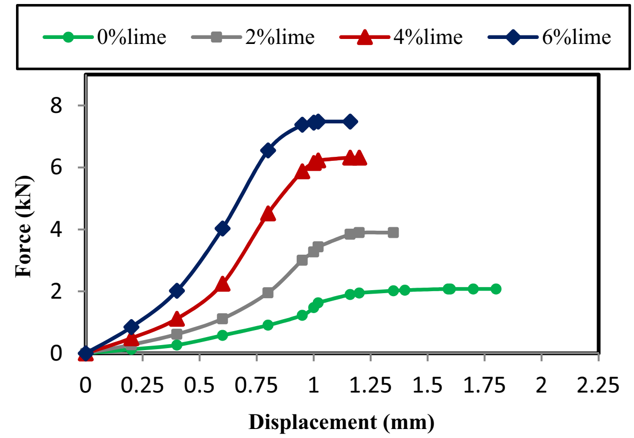


Fig. 13 Force–displacement curves for specimens with different lime contents obtained from UCS test after 56 days

lime-stabilized specimens is illustrated in Fig. 11a–d. The strength of the specimens increased when the fiber content increased from 0 to 0.5%. However, further addition of fiber bundles resulted in a decrease in the strength values. The addition of a small amount of fiber bundles (0.5%) increased the UCS of lime-stabilized specimen including 6% lime after 56 days of curing from 3.81 to 4.50 MPa. Although the additive could be easily distributed in the specimens when the fiber content was relatively low, too many fiber bundles inclusion could reduce their effectiveness on the strength development. Because the fiber bundles stick to each other and cannot make a strong binding with the soil particles, the contact area between additive and soil particles decreases so that the strength of soil decreases. Chen et al. [15] reported similar results by performing unconfined compression tests on fiber-reinforced silty clay.

3.2.5 The effect of fiber length on UCS

Figure 12a, b depicts the variations of UCS versus different lengths of additives with the optimum contents of palm fiber and fiber bundles, respectively. From Figs. 7 and 11, it can be concluded that two types of improved soil with palm fiber and fiber bundles reach their maximum strength with the palm fiber content of 1.5% and fiber bundles content of 0.5%. Both the length and percentage of fiber content play an important role in the strength of fiber-reinforced soil. The increase in the length of fiber increased the UCS of specimens. This finding is in agreement with the results of Marandi et al. [44] and Chen et al. [15]. They have also reported that the long fibers are more effective than the short fibers in the length ranges studied.

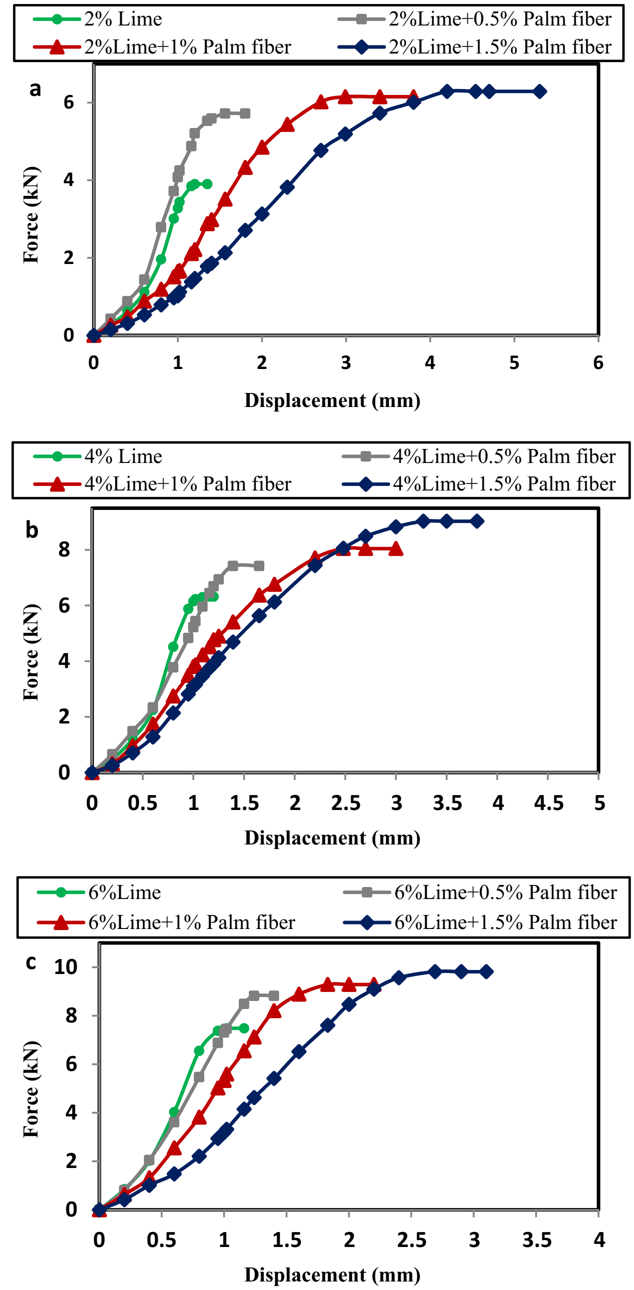


Fig. 14 Force–displacement curves for specimens with different lime and palm fiber contents obtained from UCS tests after 56 days

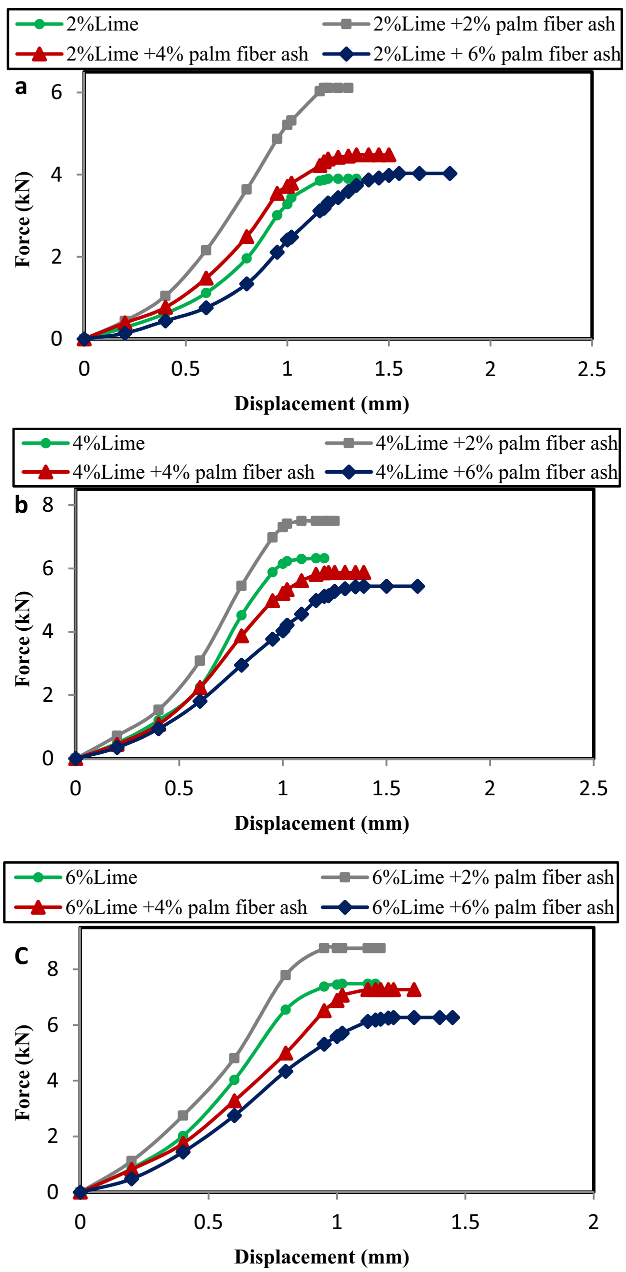


Fig. 15 Force–displacement curves for specimens with different lime and palm fiber ash content obtained from UCS tests after 56 days

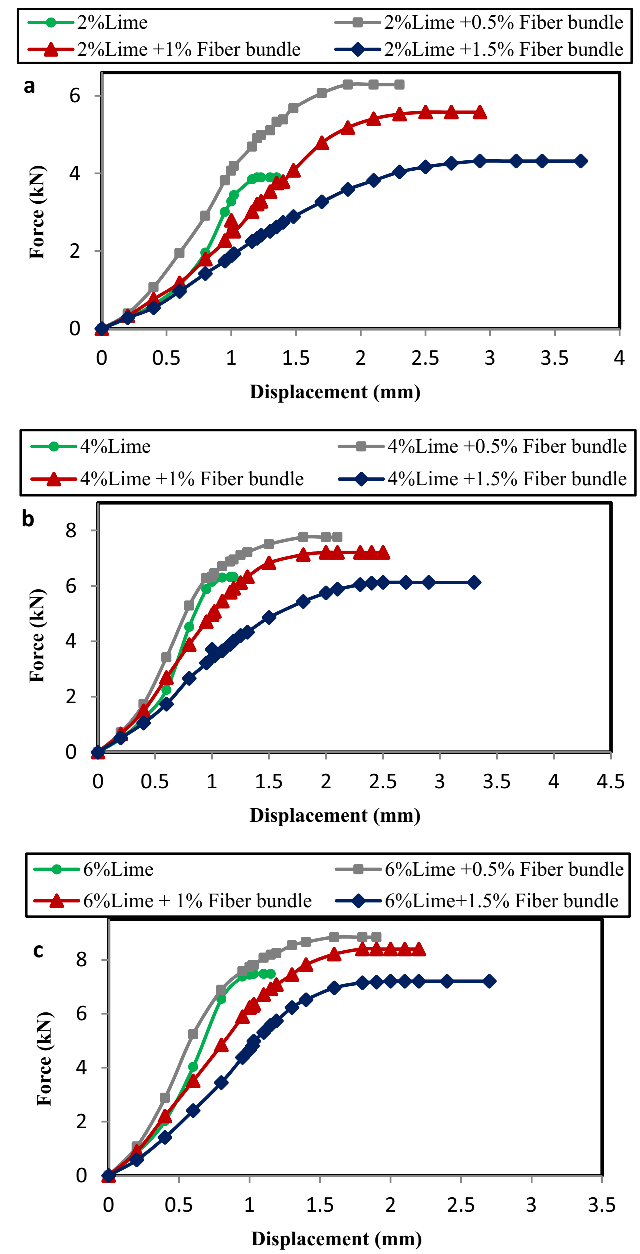


Fig. 16 Force–displacement curves for specimens with different lime and fiber bundles content obtained from UCS tests after 56 days

3.3 The effect of additives on failure characteristics

Figure 13 presents the force–displacement curves obtained from unconfined compression tests for lime-treated specimens after 56 days of curing. As shown in Fig. 13, the maximum strength increased with increasing the lime content, while the specimens seem to be more brittle. Increasing lime content resulted in increasing force and reducing displacement at failure. Figures 14a–c, 15a–c and 16a–c illustrate force–displacement curves obtained from unconfined compression tests after 56 days of curing with different lime contents for palm fiber, palm fiber ash and fiber bundles, respectively. According to the figures, specimens with higher additive contents took a longer time to reach their ultimate strength than others. Figures 17, 18 and

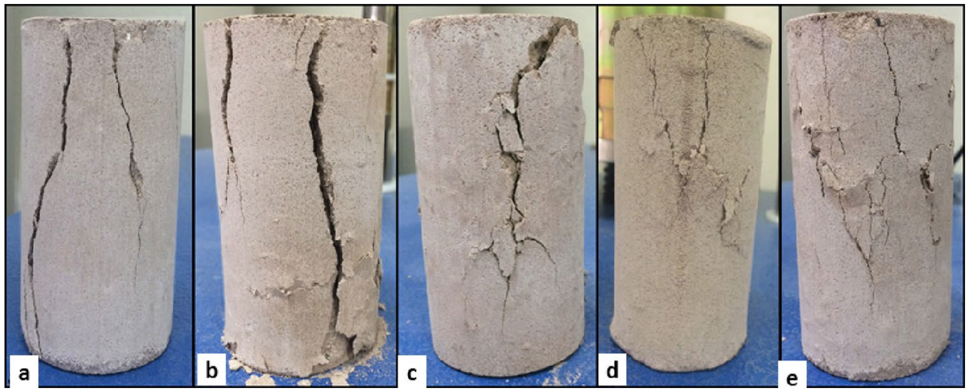


Fig. 17 Effects of lime and palm fiber ash on the failure characteristics; **a** natural soil, **b** stabilized soil with 6% lime, **c** 2% palm fiber ash and 6% lime, **d** 4% palm fiber ash and 6% lime and **e** 6% palm fiber ash and 6% lime

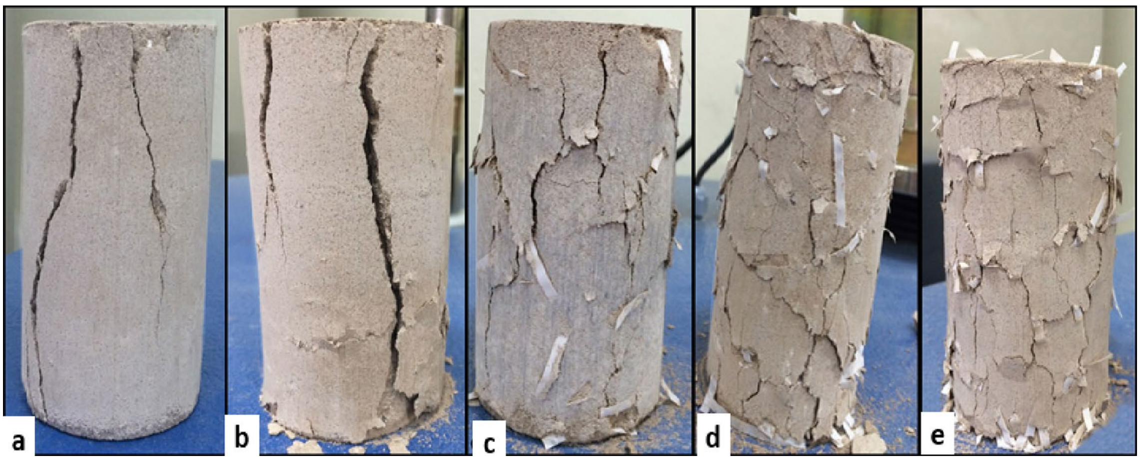


Fig. 18 Effects of lime and fiber bundles on the failure characteristics; **a** natural soil, **b** stabilized soil with 6% lime, **c** 0.5% fiber bundles and 6% lime, **d** 1% fiber bundles and 6% lime and **e** 1.5% fiber bundles and 6% lime

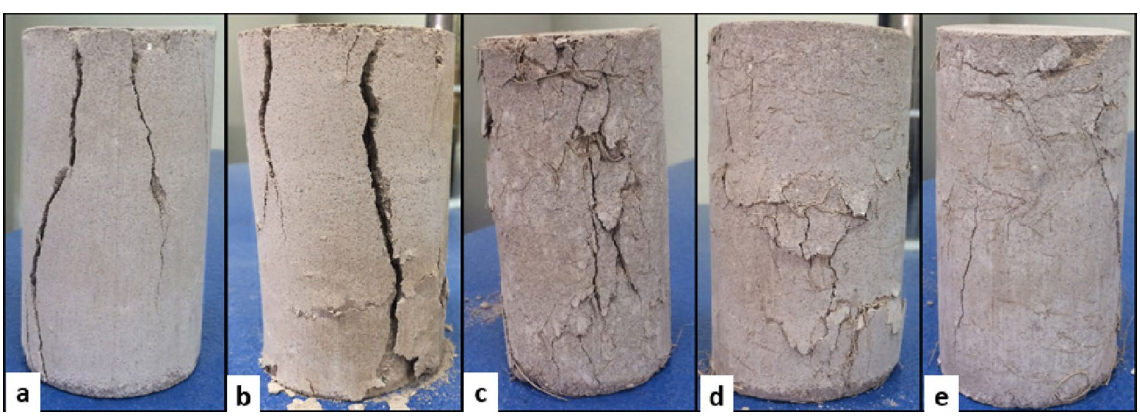


Fig. 19 Effects of lime and palm fiber on the failure characteristics; **a** natural soil, **b** stabilized soil with 6% lime, **c** 0.5% palm fiber and 6% lime, **d** 1% palm fiber and 6% lime and **e** 1.5% fiber and 6% lime

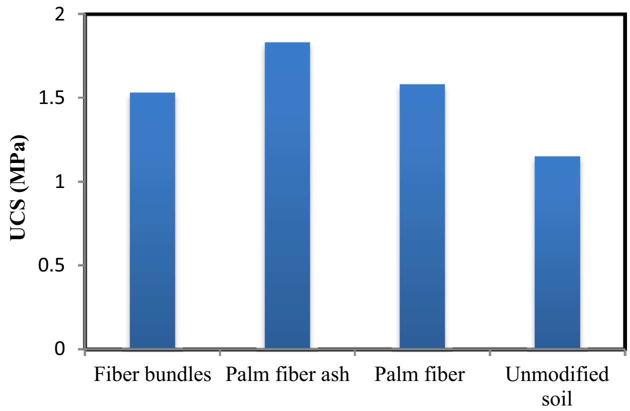


Fig. 20 Comparison of UCS of reinforced samples with optimum content of additives

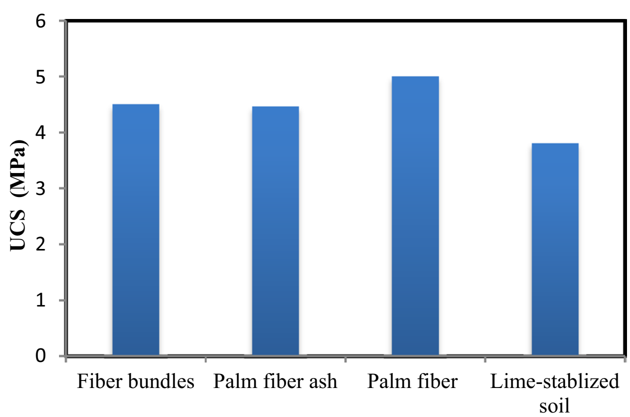


Fig. 21 Comparison of UCS of reinforced–stabilized samples with 6% lime and optimum content of additives

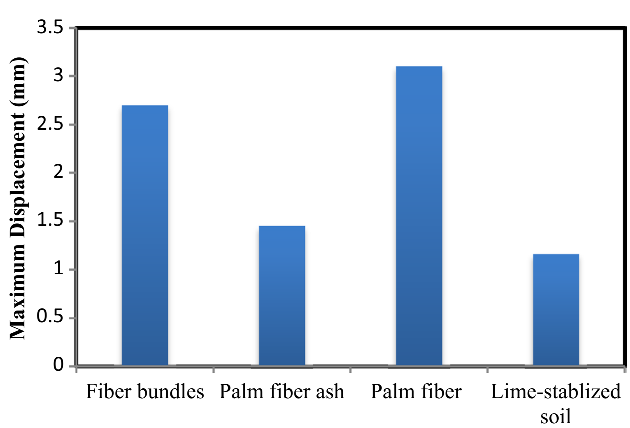


Fig. 22 Comparison maximum displacement of reinforced–stabilized samples with 6% lime and optimum content of additives

19 demonstrate cracked specimens, after conducting unconfined compression tests, consisting of 6% lime and different contents of palm fiber, palm fiber ash and fiber bundles, respectively. As shown in the figures, in the specimen treated with 6% lime, the cracks were wider and fewer than unmodified soil. In reinforced specimens with increasing the waste materials content, the cracks became gradually narrower and shorter, and the number of cracks also increased compared to untreated soil and lime-treated soil.

3.4 Comparison between additives

Figures 20 and 21 compare the maximum UCS of samples treated with 6% lime and optimum contents of other additives after 56 days of curing, respectively. The UCS of treated specimens with palm fiber ash is higher than that of other specimens, but the difference is less than 4%. By using 6% lime and 2% palm fiber ash, the UCS increases by 4.24 times for the curing period of 56 days. The addition of 6% lime with 0.5% fiber bundles increases UCS up to 4.28 times, and the addition of 6% lime with 1.5% palm fiber increases UCS up to 4.76 times after 56 days of curing. The palm fiber works better than the fiber bundles and palm fiber in lime-treated specimens, but the difference is less than 6%. By adding 6% lime alone, the UCS of the soil increases by 3.62 times for the curing period of 56 days. It was found that the lime and additives mixture performed better compared to additives alone. Figure 22 presents the comparison of maximum displacement of reinforced–stabilized specimens with 6% lime and optimum contents of other additives after 56 days of curing. According to the figure, to evaluate the effect of additives on failure patterns, the palm fiber performs better than the palm fiber ash and fiber bundles. The variations in the compaction properties are almost at the same rate for palm fiber ash and palm fiber, while the effect of lime and fiber bundles inclusion is more noticeable.

Table 3 presents the UCS results of reinforced soil with different percentages of lime and optimum percentage of fiber bundles, palm fiber and palm fiber ash after 56 days of curing. The results revealed that adding 0% to 6% lime increased the UCS of soil from 1.50 to 3.81 MPa, while the combined use of 4% lime and 1.5% palm fiber increased the UCS of untreated soil from 1.50 to 4.60 MPa. In other words, by reducing the percentage of lime from 6% to 4% and including 1.5% palm fiber, the UCS of specimens increases from 3.81 to 4.60 MPa. The specimen treated with 2% lime and 0.5% fiber bundles developed the same UCS compared to the specimen with 4% lime after 56 days of curing. However, the experimental results indicate the feasibility of using these waste materials as a substitute for lime in soil stabilization projects to achieve the desired strength.

Table 3 UCS results after 56 days of curing

	Lime content (by weight of dry soil)			
	0% (Mpa)	2% (Mpa)	4% (Mpa)	6% (Mpa)
UCS of natural soil	1.50	1.98	3.22	3.81
UCS of natural soil + 2% palm fiber ash	1.86	3.11	3.82	4.46
UCS of natural soil + 0.5% fiber bundles	1.55	3.20	3.95	4.50
UCS of natural soil + 1.5% palm fiber	1.71	3.58	4.60	5.00

4 Conclusions

A series of laboratory tests were conducted to study the influence of palm fiber, palm fiber ash and fiber bundles inclusion on the compaction, compression and failure patterns of lime-treated and untreated clayey sand. From the test results, the following main conclusions can be drawn:

1. The additives content, fiber length, curing time and lime content are among the most important factors that significantly affect the strength, density and ductility of the improved clayey sand.
2. The addition of lime, palm fiber and palm fiber ash to the clayey sand increases the optimum moisture content (OMC) and decreases the maximum dry density (MDD) values compared to the samples without additives, while adding fiber bundles decreases both MDD and OMC values.
3. UCS of samples increased with increasing the curing period. The highest UCS value was recorded after 56-day-curing period for all samples. Maximum strength was attained at palm fiber ash content of 2% and fiber bundle content of 0.5%, while further addition of these additives led to a decrease in the UCS of lime-treated and untreated soil. Moreover, the UCS increased with the increase in the lime and palm fiber content.
4. The strength of the clayey sand also varies with the changes in palm fiber and fiber bundles lengths. The increase in the length of fiber increases the UCS of specimens.
5. The addition of palm fibers, fiber bundles and palm fiber ash increases maximum strength and displacement at failure and results in a noticeably ductile behavior of both lime-treated and untreated soil. On the contrary, the inclusion of lime leads to a more brittle behavior and reduces the ductility of the clayey sand.
6. It can be concluded that the application of palm fiber, palm fiber ash and fiber bundles increases the strength of lime-treated and untreated clayey sand, and the use of these waste materials as useful and economic additives for soil stabilization projects is highly recommended.

Compliance with ethical standards

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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