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Strength and Ductility of Randomly Distributed Palm Fibers Reinforced Silty-Sand Soils

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Abstract: This paper investigates the resultant strength and ductility behavior when randomly distributed palm fibers are used to reinforce silty-sand soils. The composite soils were tested under laboratory conditions and examined for unconfined compression strength (UCS), California Bearing Ratio (CBR) and compaction test. The results indicated that; the maximum and residual strengths, orientation of surface failures, ductility and the stress-strain relationship of the specimens were substantially affected by the inclusion of palm fibers. A significant result was the determination that the sliding failure strength controlled the failure of the specimens rather than the rupture failure strength. Overall it was found that reinforced soil using palm fibers as the primary reinforcement are beneficial engineering materials and could potentially be used more often, though additional field use and testing should be carried out. Given the current concern over the environment and greenhouse gas emissions, strengthening soil through the use of natural materials (in this case palm fibers) and the promotion of the cultivation of palm groves is one way that engineers and designers can contribute to a greener earth. Add to this the fact that the date palm is one of the most cultivated tree crops in the world with a worldwide distribution of around 100 million palms distributed in 30 countries including the Middle East, Asia, Africa, North America, Mediterranean countries and Australia in a bountiful resource that is available in many places where high technology engineering practices are either not available or too expensive. The use of the date palm for soil reinforcement means that in many areas of the world there is a readily available, effective local source of material for road foundation construction.

Keywords: Clinker, microstructure

INTRODUCTION

The southern Iranian city of Bam with 100,000 in population was practically destroyed on December 26, 2003 at 1:56 AM UTC (5:26 AM local time) when a series of devastating earthquakes flattened much of the city resulting in the deaths of over 40,000 people. In the aftermath of the earthquakes the city had to be rebuilt. Among the numerous projects, road and foundation construction figured heavily. It was during this reconstruction phase that the use of date palm fibers as a soil reinforcement element to replace traditional and expensive soil reinforcement options was first postulated.

The main agricultural crop in southern Iran, particularly in the vicinity of the southern city of Bam, is the cultivation of date palms which; inhabit more than 183,000 hectares which is approximately 17% of the worlds total date palm plantations. The palm fibers in date production have filament textures with special properties such as: low costs, plenitude in the region, durability, lightweight, tension capacity and relative strength against deterioration. Thus, it is possible to use the palm fibers as an alternative low cost natural material for soil reinforcement.

In order to better understand the effects of using palm fibers as soil reinforcement an experimental program was undertaken to investigate the effect of including randomly spaced palm fibers in a soil matrix and then testing against established soil strength characteristics.

Objectives and scope:

The primary objectives of the work presented in this paper were:

1. To investigate the behavior of the stress-strain relationship, stiffness, ultimate strength, residual strength and ductility of silty-sandy soils reinforced with date palm fibers.

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2. To examine the effect of palm fiber length (two cases) of wet and saturated soil/fiber matrix on unconfined compression and California bearing ratio tests.
3. To improve the earth quaked soil of city of Bam with its own cheap, environmentally sensitive and waste recycling local date palm grove.

There have been numerous past papers published on the topic of fiber strengthening of soils. Examples include Lee et al. [19], Hoare [14], Andersland and Khattac [2], Freitag [8], Gray and Ohashi [12], Gray and Rafeai [11], Arenzic and Chowdhury [3], Shewbridge and Sitar [30], Maher and Gray [20], Lawton et al. [18], Maher and Ho [21], Benson and khire [4], Michalowski and Zhao [24], Oliver and El-Gharbi [26], Ranjan et al. [27], Consoli et al. [6], Frost and Han [9], Ghavami et al. [10], Wang et al. [32], Kaniraj and Havanagi [16], Michalowski and Cermak [24], Consoli et al. [7] , Mesbah et al. [23], Vildal [31] and Zare [32].

All of the papers listed above have generally shown that; strength and stiffness of the soil was improved by fiber reinforcement. The increase in strength and stiffness was reported to be a function of:

- Fiber characteristics; such as; aspect ratio, skin friction, weight fraction; and modulus of elasticity;
- Sand characteristics; such as shape, particle size and gradation; and
- Test condition; such as; confining stress.

Maher and Gray [20] and Al-Rafeai [1] reported that the strength of reinforced sand increases with increase in aspect ratio, fiber content, and soil fiber surface friction.

Hoare [14] found both increases and decreases in strength for specimens compacted with the same energy using two different types of reinforcement. An extensive field study of the performance of fiber-reinforced roadway soils by Hoover et al. [15] produced inconsistent results. McGown et al. [22] and Gray and Al-Rafeai [11] found that their reinforced soil was stiffer at all deformations than the un-reinforced soil.

In contrast are the direct shear data of Gray and Ohashi [12], the load settlement data from model footing tests by McGown et al. [22] and the data from unconfined compression tests by Freitag [8], which indicated lower stiffness for reinforced soils at small strains. Setty and Rao [28] and Setty and Murthy [29] carried out tri-axial tests, CBR tests and tensile strength tests on silty sand and black cotton soil, reinforced with randomly distributed polypropylene fibers. The test results indicated that both of the soils showed a significant increase in the cohesion intercept and a slight decrease in the angle of internal friction with an increase in fiber content up to 3% by weight.

The results from tri-axial tests presented by Al-Rafeai [1] were mixed; in some cases the reinforced soils were stiffer at all strains, but in other cases the reinforced soils were less stiff at small strains. Consoli et al. [7] studied the influence of fiber and cement addition on behavior of sandy soil. They reported that; the fiber reinforcement increased the peak and residual triaxial strength and; decreased stiffness; however, the increase in residual strength was more efficacious when the fiber was added to cemented soil. Ghavami et al. [10] found that inclusion of 4% sisal, or coconut fiber, imparted considerable ductility and slightly increased the compressive strength. It was also found that introduction of bitumen emulsion did not improve the bonding between the soil and fibers; but did significantly improve soil durability.

Frost and Han [9] reported the characteristics of FRP (fiber reinforced polymer)- sand and steel-sand. They found that; the interface shear behavior between FRP composites and granular materials depended on the relative roughness, normal stress level, initial density of the soil mass and the angularity of the particles. The experimental results obtained by Kaniraj and Havanagi [16] revealed that; depending on the type of fly ash-soil mixture and curing period, the increase in strength caused by the combined action of cement and fibers is either more than or nearly equal to the sum of the increase caused by them individually.

Consoli et al. [6] worked on engineering behavior of sand reinforced with plastic waste. They found that, the polyethylene terephthalate fiber reinforcement improved the peak and ultimate strength of both cemented and un-cemented soil and somewhat reduced the brittleness of the cemented sand. In addition, the initial stiffness was not significantly altered by the inclusion of fibers. Mesbah et al. [20], proposed development of a direct tensile test for compacted earth blocks reinforced with natural fibers. By using the direct tensile test, it was possible to quantify the tensile reinforcing effects of randomly distributed sisal fibers in earth blocks. Benefits of the inclusion of the natural fiber reinforcement include both improved ductility in tension in comparison with plain earth blocks and the inhibition of tensile crack propagation after initial formation. Prior to cracking, the fibers appeared to have no noticeable effect on the material behavior.

In spite of the quantity of research conducted into the resultant characteristics of using fiber and shavings for soil improvement there are still no standard scientific outcomes or techniques and additional experimental data is needed. Throughout the examination of published data information regarding the specific application of palm fiber as reinforcement for silty-sand was found to be scarce.

MATERIALS

Soil characteristics: The soil used in the investigation was sourced from the earth quaked city of Bam situated in southeast of Iran. Characteristics of the soil; including the particle grading, standard Proctor values; plasticity, sand equivalent and specific gravity were determined using ASTM D 422-87 and ASTM D 421-58, ASTM D 1775-70, ASTM D 4318-87, ASTM D 2419-87 and ASTM C 128-79 standards respectively. The results are presented in Table 1 and Figure 1. Based on the soil characteristics, the soil was classified as SM (as per the Unified Soil Classification System [USCS]).

Palm fibers: Palm fibers with different lengths were obtained by threading long filaments of palm trees obtained mainly from Bam palm grove. The fibers were threaded into pieces and stretched to a specified length and width.

The shear resistance, cohesive properties and compressive friction forces appearing on the surface of the reinforcing fiber due to shrinkage of the soil are the three main factors that affect the adhesion between the reinforcing fibers and the soil. As the palm fibers undergo dimensional change (shrink and swell) due to changes in moisture content, this influences the adhesion factors. At the micro level the swelling of the fibers pushes the soil away. Subsequent drying shrinks the fibers back almost to their original dimensions leaving small (micro level) voids between the fiber and the surrounding soil. The swelling of palm fiber is shown in Figure 2. To improve the adhesion between the fibers and soil, an effective water repellent treatment, such as bituminous materials, should be used which; however, this examination was not within the scope of this study.

The moisture absorption characteristics of the palm fibers were examined by soaking the fiber samples and weighing two hours intervals. The average results are shown in Figure 3. The results indicate that the maximum water absorption of 187% was achieved after a period of 24 hours (there was insignificant increase in water content above this level).

The transversal and longitudinal changes in fiber dimensions at 24 hours also measured. The average increase in length and transversal section after 24 hours were 2.51% and 11.11% respectively. The results showed similarity with 0.84% (transversal) and 12.90% (longitudinal) for sisal; and were higher than 0.12% (transversal) and 9.80% (longitudinal) for coconut fibers found by Ghavami et al. [10] after 96 hours water absorption time. The dimensional changes are most likely the result of the fiber type and the process of preparing the fibers. From results it can be observed that; a significant increase occurs in the transversal section.

The fiber strength characteristics were obtained through tensile strength tests. The stress-strain plot curve of the test fibers is shown in Figure 4. The results show that; the maximum tensile strength of 63.32 MPa was achieved at a strain of 11%.

Other significant characteristics identified were: fiber specific gravity (of solids) of 0.92, elastic modulus of 600.8 MPa and average diameter of 0.35mm.

SAMPLE PREPARATION

Based on historical laboratory and theoretical investigations, relative density and its resultant void ratio is one of the effective factors on soil mechanical behavior and shear strength. It is clear that; in practical scale, the soil properties depend on the formation of the soil layers and are related to the laboratory sampling. Although the tested samples in this study were made at optimum compaction, due to the small dimension of the laboratory samples, the compaction uniformity is important to the validity of the experimentation. For this purpose, and to provide samples with relatively uniform compaction, the method of under-compaction introduced by Ladd [17] was used in this investigation. Using this method the specimen was compacted in layers with tamping (of a specified number of blows) to a rate less than the ultimate compaction. The compaction of each layer results in greater compaction of the preceding layer (i.e. a greater density). In order to achieve a compacted state uniform layer thickness, the pre-compaction layer thicknesses varied depending on the sequence in the compaction sequence. The thickness of the compacted layers was determined by the following:

$$d_i = i \times \left[h + (j - i)\left(\frac{\Delta h_1}{j-1} \right) \right] \quad (1)$$

Where: di = the circle distance of i layer from the base circle, i = the layer number, h = final determined thickness of the layers, j = total layers chosen for sampling and Δh1 = the increase in first layer thickness.

The compaction apparatus consisted of a solid high density Teflon cylinder with height of 250mm and diameter slightly smaller than the internal diameter of the unconfined compression test mould (50mm). The inner surface of the cylinder was marked with parallel circles indicating the final compacted layer thickness with thicknesses pre-determined by the under-compaction theory. The optimal number of compaction layers was determined to be five and the maximum increase in layer height was 1.9mm, equivalent to 9.2% decrease in compaction. It is important to note that; the decrease in percentages of compaction was determined by experimentation to control the compacted layers thickness. The final sample height was 103mm.

COMPACTION TESTS

The compaction curves of palm fiber-silty sand mixtures with, and without, the fiber reinforcement are given in Figure 5. The values of maximum dry density and optimum moisture content for the palm fiber-soil mixture mixed with 0.5% and 1.0% palm fiber content are summarized in Table 2. The results show that as the palm fiber content increases, the maximum dry density decreases and optimum moisture content increases. With 1% palm fiber added to the soil mixture, the maximum dry unit weight of the matrix decreased approximately 2% and optimum moisture content increased by approximately 7%.

Table 1: Soil characteristics

Characteristics	Value
Sand content (0.075-2*mm*)	83.6%
Silt content (0.002-0.075*mm*)	13%
Clay content (<0.002*mm*)	3.4%
D_{50}	0.18*mm*
D_{10}	0.048*mm*
C_U	4.16
C_C	1.76
Optimum moisture content	12.42%
Maximum dry density	19.36 kN/m^3
Plasticity	*NP*
Sand equivalent (*SE*)	51%
Specific gravity of solids (G_S)	2.72

The decreased in density is most likely a result of the fiber filaments having less specific weight in comparison with the soil grains and the fibers prevent the soil particles approaching on another. The increase in moisture content is most likely the result of the fibers having a greater water absorption capacity than the surrounding soil. Sliding between the fibers and the soil particles is related to the size of the fibers, which in turn is influenced by the moisture content. From the results it was found that sliding between the soil particles in the un-reinforced soil occurred at optimum water content of 12.42%, while, adding 1% fiber resulted in sliding occurring at moisture content of 13.30%.

Table 2: Compaction test results of un-reinforced and Palm fiber / silty-sand mixtures

Mix Designation	Maximum dry unit weight (kN/m^3)		Optimum moisture content (%)	
	Reinforced	Un-reinforced	Reinforced	Un-reinforced
0.00% Palm fiber	-	19.36	-	12.42
0.50% Palm fiber	19.19	-	13.00	-
1.00% Palm fiber	18.95	-	13.30	-

The results obtained were somewhat different from the trend observed by Setty and Rao [28] where both maximum dry density and optimum moisture content increased with increase in fiber content (polypropylene fibers) in silty sand. The results also contradict that of Kaniraj and Havanagi [16] who studied the behavior of cement-stabilized fiber-reinforced fly ash-soil mixtures. For fiber inclusion they found a decrease in optimum moisture content and increase in maximum dry density.

As can be seen, the addition of fiber reinforcement into a soil, influences the compaction and moisture characteristics of the soil. The type of influence is dependent on the available moisture and the properties of the fibers. The effect of fiber content on compaction characteristics requires further research using various types of fibers and different fiber contents.

UNCONFINED COMPRESSION TEST

Test procedure: Unconfined compression tests were carried out on cylindrical specimens, of maximum dry unit weight and optimum moisture content state, prepared by static compaction. A 50mm inner diameter and 103mm long mould with detachable collars at both ends was used. To ensure uniform compaction, the samples were compacted in five layers using the under-compaction method discussed previously. A minimum of three specimens was tested for each combination of variables.

For making each specimen, the dry soil and the palm fibers were weighed to a resolution of 0.1 gram and 0.01 gram respectively and were laid in separate containers. To ensure that effective mixing between the soil and fibers was achieved the process was staged. Initially all of the soil and half of the water and palm fibers were mixed, after which the proportions of water and fiber were gradually increasing up to optimal water content and the prescribed fiber percentage. For uniform distribution of water into the soil-fiber mixture, the mixture kept in a covered container for 18 hours.

The mixed samples were tested by unconfined compression test equipment supplied by the soil mechanics laboratory of the University of Shahid Bahonar in Kerman (Iran). The loading velocity was equivalent to 1% of axial strain per minute.

RESULTS

The stress-strain curves of un-reinforced and reinforced palm fiber-soil specimens are shown in Figures 6 and 7. The specimen's palm-fiber contents were 0.25%, 0.50%, 0.75%, 1.00%, 1.5%, 2.00% and 2.50% by dry total weight and the fiber lengths rested were 20mm and 40mm. The results showed that the stress-strain behavior was markedly affected by the palm fiber inclusions. In specimens without palm fibers; a distinct failure axial stress was reached at an axial strain of approximately 1.23%. Whereas, the palm fiber reinforced specimens exhibited more ductile behavior.

The results also showed that an increase in UCS with the inclusion of the palm fiber and with the length of the fiber. The results of the UCS testing are shown in Table 3.

The relative increase in UCS between two consecutive palm fiber lengths, IL is defined as:

$$I_L = \frac{(UCS)_{L_2} - (UCS)_{L_1}}{(UCS)_{L_1}} \times 100 \qquad (2)$$

Where: $(UCS)_{L_1}$, and $(UCS)_{L_2}$ = unconfined compression strength of the palm fiber reinforced specimens with lengths L1 and L2 respectively. The correlation between IL and L is found to be:

$$I_L = -7.7141L^2 + 17.459L + 21.84 \qquad (3)$$

The coefficient of determination R2 of the correlation for derived equation above is 0.9173. The plot curve in Figure 8 indicates that, the behavior of the soil is mainly influenced by the existence of the palm fibers and is a function of the length. In summary, the inclusion of fibers has a positive effect on the maximum UCS and increases the ductility of the specimens.

Furthermore; the results presented in Table 3 and Figures 6 and 7 show that at a constant palm fiber length (Lf), with increase in fiber inclusion (W_f), the maximum strength and residual strength increase, while; the difference between the two decreases. The same trend is true for the effect of increasing the palm fiber length at a constant fiber inclusion percentage. With increase in fiber length, with constant fiber inclusion, both maximum and residual strengths increase in the specimens.

The strengths results confirm the strength behavior trends found by Ranjan et al. [27] and Kaniraj and Havanagi [16], while, contradicting their ductile behavior results. Ranjan et al. [27] carried out extensive experimental tests using probabilistic analysis of randomly distributed fiber-reinforced sands and did not find any exhibition of peak stress even at an axial strain of 20%. Kaniraj and Havanagi [16] who worked on behavior of cement-stabilized fiber reinforced fly ash-soil mixtures found no distinct reduction in axial stress even at 15% of axial strain. The contradiction in the results regarding ductile behavior may be due to the characteristics of the fiber type or characteristics of the composite material especially cement inclusion used in Kaniraj and Havanagi [16] experimental specimens. However, the failure stress in the experiments were taken corresponding to a strain of 20% which is suggested by Head [13] and Bowles [5].

Analysis and Discussion of the Effects of Palm Fibers on the Ultimate UCS: The results of variation of maximum strength versus palm fiber inclusion for two series of tests, with fiber lengths of 20mm and 40mm, are shown in Figure 9. The results show that the specimen strength increases with increasing fiber strength and increasing fiber length. The rate of strength increase decreases with fiber inclusion and for the fiber length of 40mm the peak strength appears to be at a fiber ratio of 2-2.5%. This confirms the report of Wang et al. [32], who working with sandy clay soils reported that; using more than 2% fiber decreased the UCS.

Based on the above results it is clear that, in reinforced soils, where the soil grains are replaced by fibers, it is the fibers that control the behavior of the specimen. Furthermore; Figure 9 indicates that; at a constant fiber length; with increase in W_f, the material strength increases and has a direct relationship with the existence of the fibers in soil mixture. Also, it can be observed from Figure 8 that, at a constant W_f, an increase in the fiber length results in a higher composite strength. It appears that; the fiber length is more effective in strength increase in comparison with W_f. In other words, the fiber sliding strength in comparison with their failure strengths controls the increase of the strength and bearing capacity of the specimens. In all experimental tests it was observed that; the behavior of elements at failure surface was sliding type and no rupture was observed.

Table 3: Average unconfined compression strength (*kPa*) of un-reinforced and reinforced palm fiber-soil specimens

Mix Palm Fiber %	$L_f = 20mm$ Axial Strain (%)	$L_f = 20mm$ *UCS* (*kPa*)	$L_f = 40mm$ Axial Strain (%)	$L_f = 40mm$ *UCS* (*kPa*)	I_L
0.00	1.23	31.4	1.23	31.4	
0.25	2.47	77.4	2.71	97.0	25.3
0.50	2.71	120.0	3.21	156.5	30.4
0.75	3.21	151.7	3.70	198.2	30.6
1.00	3.70	227.2	4.19	293.0	28.9
1.50	4.69	308.2	5.43	404.7	31.3
2.00	5.92	387.9	6.66	494.0	27.3
2.50	6.66	449.1	7.40	523.1	16.5

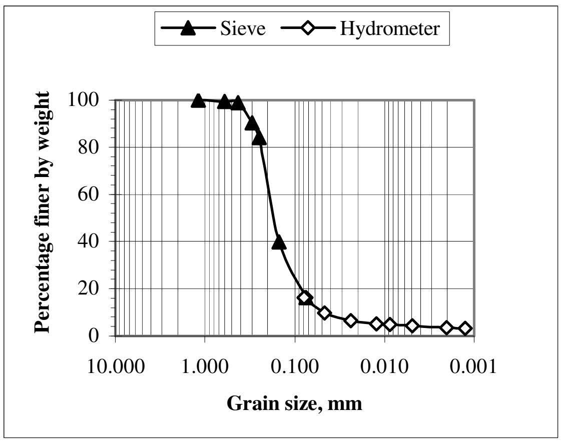

Fig. 1: Grain size distribution

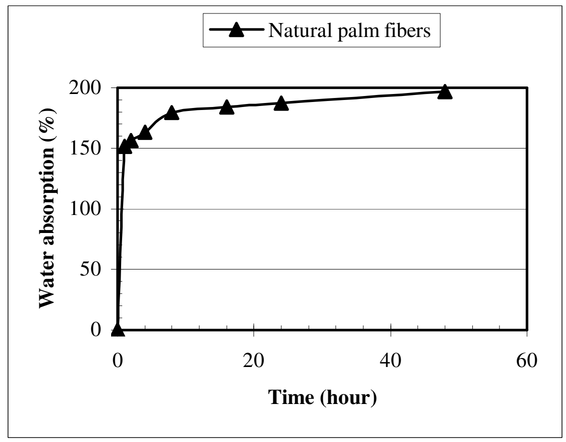

Fig. 3: Palm fiber water absorption

Fig. 2: Typical palm fibers

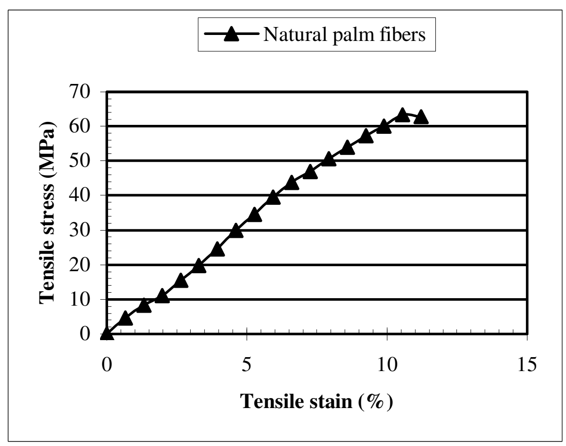

Fig. 4: Palm fiber stress-strain curve

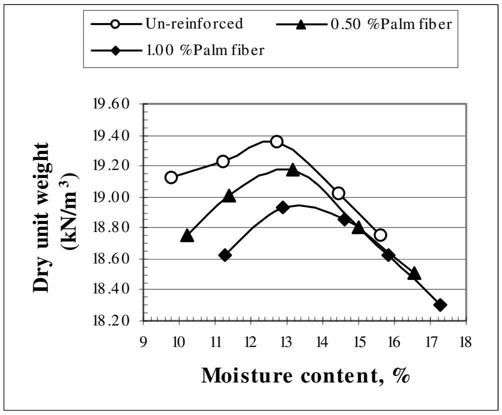

Fig. 5: Compaction curves of un-reinforced, and Reinforced, palm fiber / silty-sand mixture

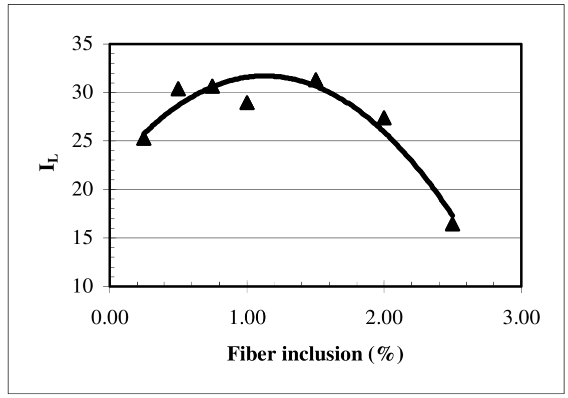

Fig. 8: Relative increase in *UCS* between two consecutive palm fiber lengths, I_L

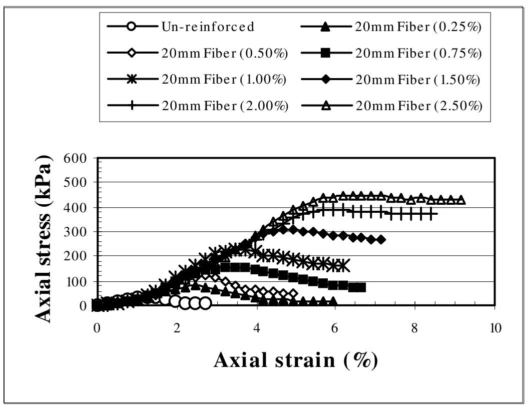

Fig. 6: Stress-strain curves of un-reinforced and reinforced soil specimens in unconfined compression tests

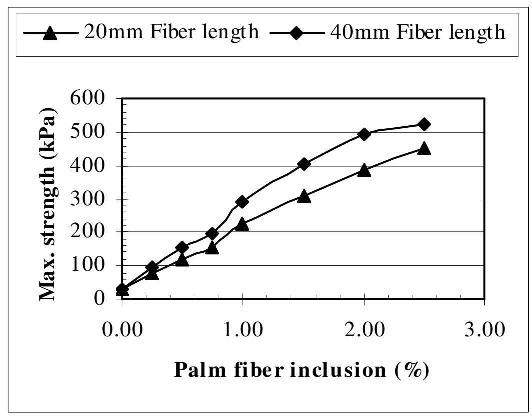

Fig. 9: Maximum strength versus palm fiber inclusion

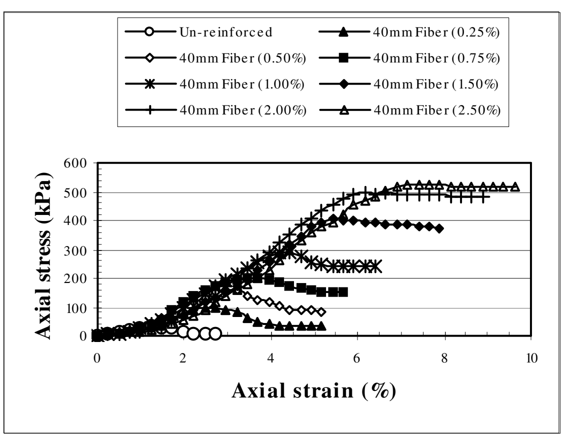

Fig. 7: Stress-strain curves of unreinforced and reinforced soil specimens in unconfined compression tests

Fig. 10: Position and orientation of failure plane in failed Un-reinforced specimen

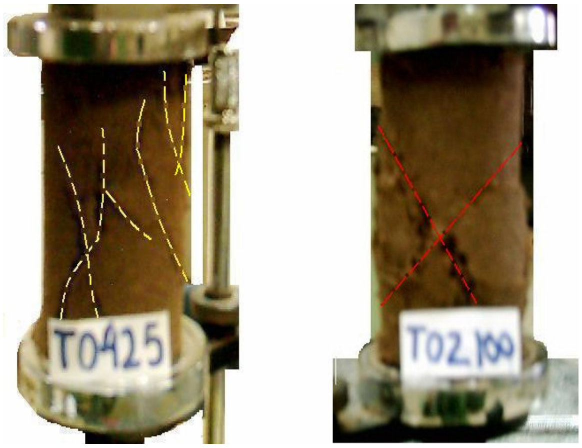

Fig. 11: Position and orientation of failure plane in failed palm fiber silty-sand soil mixture samples

Fig. 12: *CBR* test frame and saturating reservoir

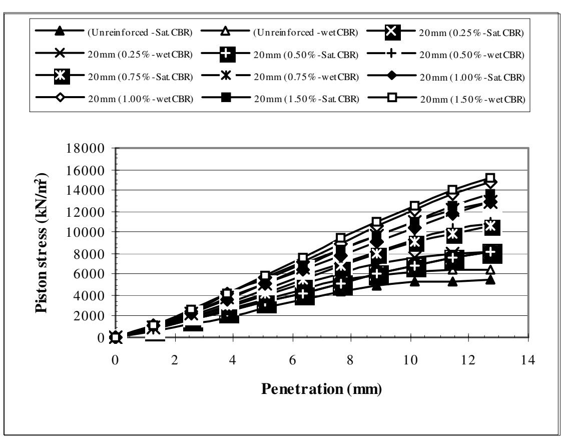

Fig. 13: Wet and saturated *CBR* tests (fiber length = 20*mm*)

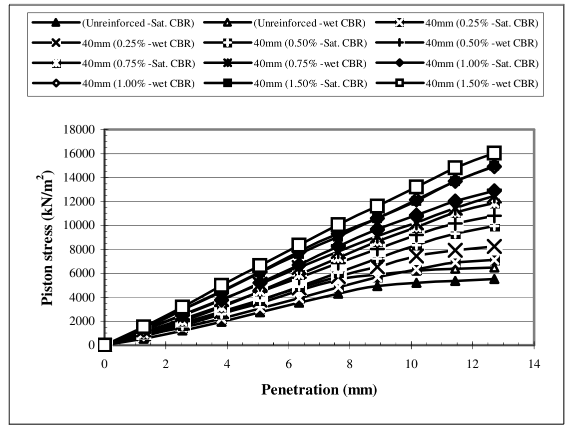

Fig. 14: Wet and saturated *CBR* tests (fiber length = 40*mm*)

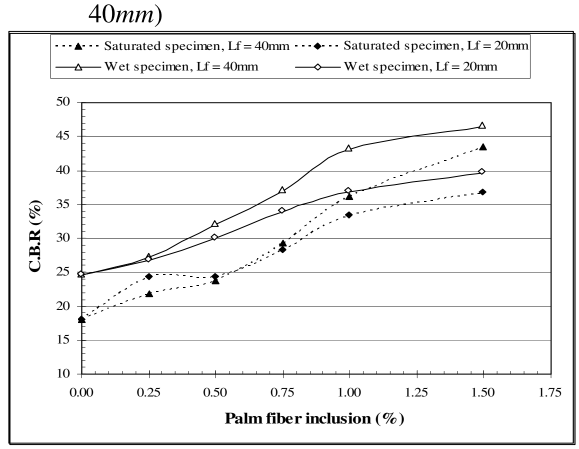

Fig. 15: Wet and saturated *CBR* values with, and without, reinforcement

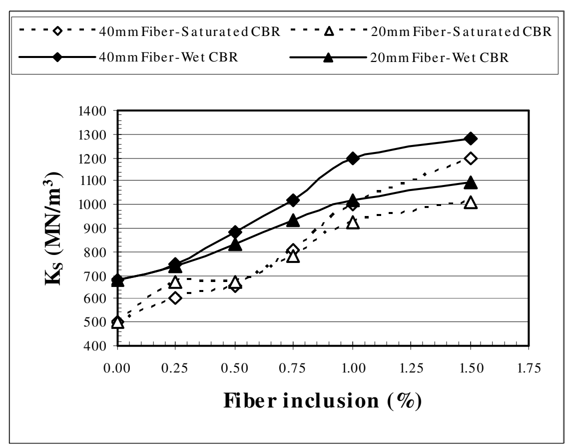

Fig. 16: Wet and saturated secant modulus

Analysis and Discussion of the Effects of Palm Fibers on Specimen Ductility: As can be observed from Figures 6 and 7, the slopes of the stress-strain curves of un-reinforced soil are steeper in comparison with reinforced soil and reach a maximum at a failure strain of about 1.3%. While the reinforced soils reach maximum values at between 2% to 6% strain (with palm inclusion percentages of 0.25% to 2.50%). The rapid reduction in strength of the un-reinforced soil combined with the initial rapid (relatively) increase to the maximum strength is suggestive of a brittle material, as observed in the compaction of granular and over-consolidated fine-grained soils. It can also be observed that, with an increase in fiber length (W_f), the strain failure increases and the stiffness (maximum modulus of elasticity) decreases, or ductility increases. This trend suggests that; adding fibers to a soil medium that exhibits brittle material properties results in greater fiber connection and replacement of a portion of soil by elastic material. The soil becomes softer, the elasticity of the medium increases and as a result; the specimens fail at higher axial strains.

Analysis and Discussion of the Effects of Palm Fibers on the Failure Surface: The soil mass shearing strength is the strength of internal unit cross sectional area; which acts against failure or sliding along every internal plane. Adding elements with tensile properties such as fibers, to the soil medium effects the surface failure direction and the shear zone through the activation of tensile forces in the fibers under load. The reflection of these stresses causes higher compression between the solid grains and increases the soil compressive stress. These phenomena combine to have the dual benefit of increasing the shearing strength, and ductility, of the soil medium. Since these two properties are the most distinct parameters for soil medium failure criteria, the failure geometry and shear zone are affected by existence of the fibers.

A close examination of the failed un-reinforced samples revealed that; in most cases, the failure surfaces were planar and oriented closely to the surface (refer to Figure 10). As predicted by the Coulomb theory, the failure occurred at, the angle of obliquity or ($45^\circ + \varphi/2$). In contrast, the behavior of the reinforced palm fiber specimens showed that; the trends of surface failures were distinguishable but irregular (refer to Figure 11).

Observation during the experimental tests showed that; at a constant palm fiber length; with increase in fiber inclusion, there were a greater number of failure surfaces and the surface orientations were regular with higher angle in respect to the horizontal line. The reason for this behavior suggests that increasing the palm fiber inclusion (i.e. the number of filaments per unit volume) the greater the homogenous and isotropic properties of the soil medium or the soil medium becomes more uniform. It was also observed that, increasing the palm fiber length, at a constant W_f, the shear surfaces were more irregular but with a higher angle in respect to horizontal line. This suggests that an increase in palm fiber length, at a specific W_f, decreases the number of filaments per unit weight which; decreases the homogeneous and isotropic nature of the soil medium resulting in irregularity in surface failures. Conversely, the soil medium shearing strength increases and results in the increase in the surface failure angle in respect to the maximum principal plane.

California bearing ratio:

Test procedure: California Bearing Ratio (CBR) tests were carried out to examine the effects of palm fiber on the ultimate strength of fiber-soil medium. Testing was conducted on specimens with fiber inclusion of 0.25%, 0.50%, 0.75%, 1.00% and 1.50%, for fiber lengths of 20mm and 40mm and for wet and saturated states. The CBR tests were carried out as per ASTM D 1883. Specimens were molded in a steel CBR mould with an inside diameter of 152mm and height of 172mm. The samples were compacted as per the ASTM D 1557 standards, consisting of five layers with optimum moisture content of 12.42%.

The soil-fiber mixing was carried out as previously described. The wet samples were tested immediately after the compaction phase, while the saturated samples were submerged in drinking water for 24 hours and then tested within 10 minutes of removal from the soaking reservoir.

A surcharge plate providing a pressure of 2.44 kPa was placed on the specimen prior to testing. The specimen was placed in a load frame and dial gauges were mounted to measure deformation of the specimen and penetration of the loading piston. A loading piston with cross-sectional area of 1940mm2 was used. All tests were conducted at a penetration rate of 1.27mm/min. until a penetration of 12.5mm was achieved. The test frame and saturated reservoir used for experimental tests is shown in Figure 12. All testing was carried out at the geo-technical laboratory of the University of Shahid Bahonar (Iran).

The test results for both wet and saturated specimens, with palm fiber lengths of 20mm and 40mm, presented in the form of load-penetration relationships, are shown in Figures 13 and 14. The CBR values were calculated by dividing the piston stress at a displacement of 2.5mm by 6,900kPa and then multiplying by 100 (ASTM D 1883). The results are presented in Figure 15.

Analysis and Discussion of results: Figures 13 and 14 indicate that, at a constant penetration, with increase in fiber inclusion, the piston stress value increases and the incremental difference in stress between every two consecutive curves increases with increase in penetration. Also, it can be observed that; for the un-reinforced soil, and samples with lower fiber inclusion, the piston stress reaches its maximum at about 12.5mm penetration. The samples with higher fiber inclusion exhibited a higher piston stress and the maximum stresses were achieved at a penetration greater than 12.5mm. The behavior suggests that the deformation in the soil medium causes the fibers elongate and create tensile stresses in the fibers resulting in greater localized compression of the soil grains (as for the compressive strength). Thus, as a result of this process, the required stress for the displacement and plunger penetration increases.

The CBR values calculated for both wet and saturated specimens with various fiber inclusion and lengths are shown in Figure 15. From the plot curves; it can be observed that; the CBR values are affected by both increases in fiber inclusion and fiber length. The average increase between saturated and wet specimens, for 20mm and 40mm fiber lengths, are 18% and 24.8% respectively. Similar differences were found between the results for the wet specimens with increase, for 20mm and 40mm fiber lengths, 8.6% and 2.9% respectively. It can be concluded that; the increase in fiber length effectively increases the CBR, and this trend is more increases with increasing fiber inclusion. Saturating specimens decrease the CBR values considerably.

The secant modulus (K_S, MN/m^3) for wet and saturated CBR specimens is shown in Figure 16. The secant modulus was determined by the following equation:

$$K_S = \frac{\sigma_{2.5mm}}{0.0025m} \quad (4)$$

The results indicate that; the K_S values are higher for the wet CBR and lower fiber lengths in comparison with the saturated, higher fiber lengths. The increase in fiber inclusion also results in an increase in K_S (for both states of wet and saturated samples). Furthermore, the plot curves show that with an increase in the fiber inclusion; the K_S differences between the 20mm and 40mm fiber length samples increase; however, the differences between the saturated and wet states decrease. It can be concluded that; the secant modulus substantially affected by increase in fiber inclusion and length.

CONCLUSIONS

This paper has analyzed the change in soil characteristics when adding palm fibers as reinforcement effects on the reinforcement. Palm fibers of varying lengths, mixed in varying proportions, were mixed with silty-sand and tested to determine the UCS, residual strength, ductility and CBR values. Based on the test results and analysis, the following conclusions are drawn:

1. Water absorbed by palm fibers influenced the optimum moisture content of the palm fiber / sandy silt soil mixture
2. At a constant palm fiber length, with increase in fiber inclusion, the maximum and residual strengths increased, while; the difference between the residual and maximum strengths decreased. A similar trend was observed for constant palm fiber inclusion and increase in palm fiber length
3. With increase in palm fiber length, and fiber inclusion, the ductility increased and the stiffness decreased
4. In the palm fiber / silty sand soil mixture; the sliding failure strength controlled the breaking phenomena of the specimens rather than rupture failure strength; however, in all experimental tests no rupture failure was observed (within the limits of the testing regime)
5. Increase in the fiber inclusion rate resulted in the soil being more soft and elastic (ductile). This behavior motivated the soil specimens to fail at higher axial strains
6. At a constant fiber inclusion rate, an increase in the palm fiber length resulted in the decrease of the degree of homogeneity and isotropy causing irregularity in the failure shear surface
7. The increase in fiber length effectively increased CBR values, and this trend was more effective when the fiber inclusion increased. However, saturating the specimens decreased the CBR values considerably
8. The secant modulus of the wet and saturated specimens was substantially affected by increase in fiber inclusion and length
9. The results suggested that the use of palm fiber reinforcement provided beneficial properties to the

silty sand soil and that the use of palm fibers would be an effective soil reinforcement method

10. This paper examined the effectiveness of 20mm and 400mm palm fibers. Additional research is required to examine the characteristics of other fiber dimensions. Also, the effectiveness of adding a water repellant to the fibers to reduce the dimensional variations with moisture content should be investigated.

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