Impact of Randomly Distributed Hay Fibers on Engineering Properties of Clay Soil

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ABSTRACT

Natural fibers had been used as reinforcing elements since 3000 BC. Recently, reinforcing soil with natural fibers has become of key significance in investigations. Hay fiber has been selected for this study because of its tensile strength and bulk availability. Thus, it is anticipated that the strength of reinforced soil would increase and cracking of the soil would be minimal. To verify that, a series of experimental tests have been performed on natural and hay fiber-reinforced soil specimens. Four different percentages of hay fibers (0.25, 0.5, 1.0 and 1.5% by weight) were used in this study and various experimental test, including unconfined compression test, P-wave velocity test, free swell test, soil-water retention test and microstructural test, were conducted on natural and hay fiber-reinforced soil specimens.

Results show that the strength behavior of soil specimens depends considerably on the hay fiber content. It is found that the unconfined compressive strength (UCS) increases as the hay fiber content increases up to 1.0%, then it decreases for higher hay percentage used in the current study. It is noticed that the interaction between hay fiber and soil compounds could control the mechanism of the reinforcement benefit. Consequently, the swelling potential decreases significantly as the hay percent increases. The water-holding capacity of soil specimens increases with hay content. Furthermore, the parameters of soil water retention curve (SWRC): volumetric water content and corresponding air entry value depend directly on the texture of the hay fiber. Microstructural test explains the variations in SWRC parameters. It is observed that these parameters are significantly affected by the change in the pore size distribution of hay fiber-reinforced soil specimens.

KEYWORDS: Hay fiber, Clay soil, Compressive strength, Microstructure, Water retention behaviour, Soil reinforcement.

INTRODUCTION

Soil reinforcement techniques date back to earlier civilizations. They used straw fibers to enhance the strength and durability of soils (Miller and Rifai, 2004). In fiber-reinforced soil, fibers are embedded in a soil matrix and behave as a composite material (Khatri et al., 2017). During loading, the shear stresses generated in the soil lead to mobilizing the tensile resistance in the fibers, resulting in an increase in the soil strength (Jamshidi et al., 2010). Recently, natural and synthetic fibers have been used to improve the engineering properties of soils (Prabakar and Sridhar, 2002; Cai et al., 2006; Khattab et al., 2011; Mohamed, 2013; Benessalah et al., 2016). Ghavami et al. (1999) showed that natural fibers provide ductility and strength gain to fiber-reinforced soil. Other researchers (Consoli et al., 2009; Ahmad et al., 2010; Zhang et al., 2010) have documented similar results. Zaimoglu (2010) studied the effect of polypropylene fibers on the strength and freeze-thaw durability behavior of fine-grained soil. It was found that during freeze-thaw cycles, the strength properties of soil specimens increased with increasing

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fiber content. It was also found that the initial stiffness of the soil specimens was slightly affected by the fiber content. Mittal and Shukla (2020) investigated the strength properties of two types of soils (silt and clay soils) reinforced by kenaf fibers. The test results indicated that unconfined compressive strength and California Bearing Ratio (CBR) increased with fiber content and small values of peak strength loss and higher failure strain are noticed for reinforced soil specimens. It is worth noting that the use of natural fibers in soil reinforcement and building constructions has remarkably increased because of their availability and low cost (Savastano et al., 2000; Hossein et al., 2014).

Generally, hay fibers are cultivated and harvested annually in most parts of the world. These natural fibers can be used in soil reinforcement and/or in producing composite soil elements with good properties (Li, 2002; Mansour et al., 2007; Mohamed, 2013). Bouhicah et al. (2005) found that the addition of hay fibers reduces shrinkage, decreases curing time and enhances compressive strength of reinforced soil specimens. They also reported that all the advantages of hay fiber reinforcement could be satisfied when an optimum reinforcement ratio is used. Furthermore, more ductility was obtained during the flexural and shear tests for fiber-reinforced specimens. Abtahi et al. (2010) carried out a comparative study between hay and kenaf fibers in order to enhance the shear strength of reinforced soil specimens. They found that hay fibers are better reinforcing elements than kenaf fibers. Alkiki et al. (2012) reported that the addition of hay fibers enhanced tensile strength properties of reinforced soil. Mohamed (2013) studied the engineering properties of hay fiber-reinforced expansive clay soil. It was found that direct shear and indirect tensile strengths of soil specimens increased with hay fiber content, while swell potential decreased to about 20% with 1% hay fiber content. Jili et al. (2013) carried out direct shear test for cohesive soil reinforced with different percentages of wheat straw fiber (varying between 0.1% and 0.4%) with various lengths of 5, 10 and 15 and 20 mm. They found that inclusion of straw fibers enhanced the shear strength of reinforced soil specimens and that the maximum shear strength occurred at 0.3% straw fiber with 15-20 mm in length. Muhammad and Marri (2018) investigated the effect of lime and wheat straw on the consistency properties of high expansive clayey soils. They found that soil plasticity increased with straw fiber content, while linear and volumetric shrinkage values decreased and the number and width of cracks (during shrinkage) drastically decreased with straw fiber addition. The literature mentioned previously have dealt with the influences of fiber length and percentage on the engineering behavior of reinforced soils. To the best of the authors' knowledge, few studies have been conducted on the characterization of hay fiber and the performance of hay fiber as soil reinforcement. Furthermore, hay fiber can be regarded as a waste product and its application in soil reinforcement can be considered environment-friendly and economic for soil improvement. The primary objective of this research paper is to assess the usefulness of hay fiber as a reinforcing element for enhancing the engineering properties of clay soil. A series of experimental tests were performed including unconfined compression test, P-wave velocity test, free swell percent tests, soil-water retention test and microstructural test to assess the behavior of the reinforced soils.

Materials and Testing Program

Materials

Two materials were used in this research work: clay soil and hay fiber. The soil specimens were obtained at a depth of 1.0 m underground surface. The liquid limit (LL) was 37%, the plastic limit (PL) was 17% and the specific gravity of the soil (Gs) was 2.7. The soil was classified as a lean clay soil (CL) based on the Unified Soil Classification System (USCS). The grain size analysis showed that the soil consisted of 15% sand, 56% silt and 29% clay. X-ray diffraction test results revealed that the clay minerals were kaolinite and illite, while the non-clay minerals were quartz and calcite.

Hay fibers (fibers of wheat) used in this study were harvested and ground into small pieces using a Bosch crusher plant (Bocsh AXT 23TC), as shown in Figure 1. The pieces of hay fiber had a length of about 5–30 mm and an approximate thickness ranging between 0.3mm and 0.7 mm. Before use, hay fibers were oven-dried for 2 days at 60°C.

Sample Preparation

Different hay fiber contents of 0, 0.25, 0.5, 1 and 1.5% by weight were used. To prepare non-reinforced samples, the soil was thoroughly mixed with a predetermined amount of water, then kept in plastic bags and left for 24 hours to allow for moisture equilibrium. For fiber-reinforced soil samples, the fibers were mixed randomly with the oven-dried soil by hand, ensuring obtaining a uniform mixture. Then, the required water was added. The mixture was placed in a closed plastic bag and left for 24 hours for homogeneity. After that, the soil samples were statically compacted in a specific mold. All natural and fiber-reinforced soil specimens were compacted at maximum dry unit weight of (18 kN/m^3) and optimum moisture content of (12%) according to an ASTM D-698 standard procedure. It is worth noting that all values of the experimental tests reported in this research were the average of three measurements with a standard deviation of less than 5%.

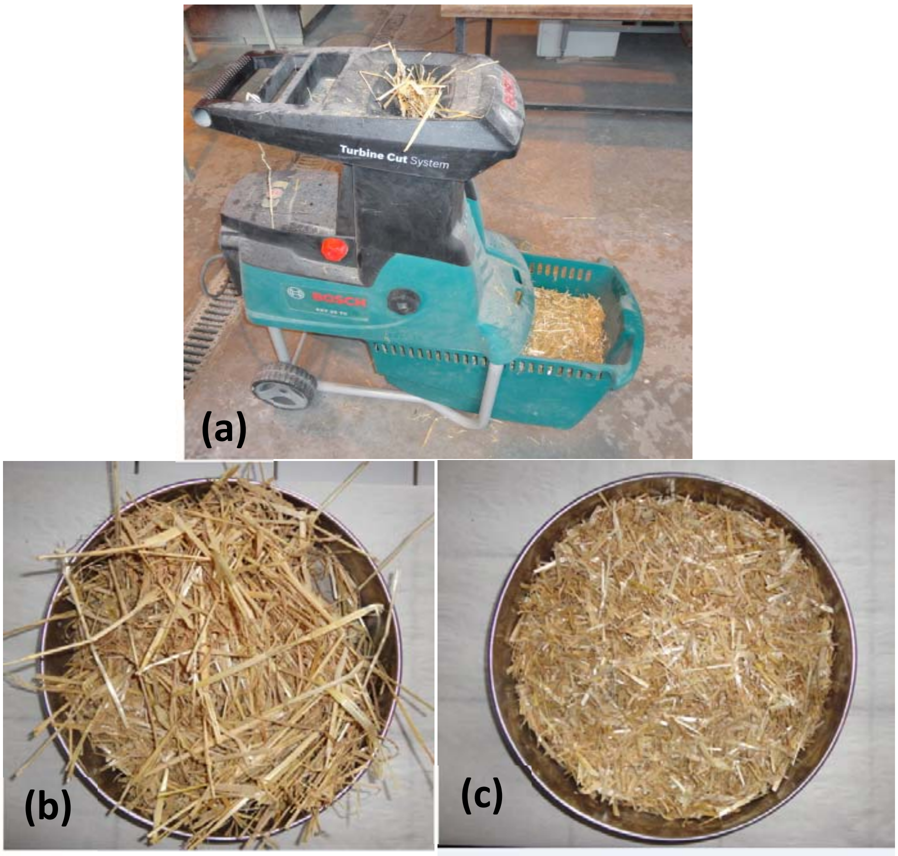

Figure (1): (a) Electrical hay cutter and (b and c) hay fibers before and after cutting

Testing Methods

Unconfined Compression and P-wave Velocity Tests

Unconfined compression test (UCT) was carried out on cylindrical specimens having 50 mm diameter and 100 mm height. UCT was conducted based on the ASTM test procedure (D–2166) and the specimens were tested at constant strain (0.1 mm/min). Before testing, soil specimens were subjected to P-wave velocity test using PUNDIT device with a frequency of 82 kHz.

Free Swell Test

Swell percentages of natural and fiber-reinforced soil specimens were determined based on ASTM standard (D–4546), using a standard Oedometer device. The compacted soil specimens (71 mm in diameter and 20 mm in height) were placed in the Oedometer device. Initial vertical pressure (6.9 kN/m^2) was applied and a sensitive dial gauge was set on top of the specimens to monitor the desired swell percentage. The swell percentage can be estimated by the following equation:

$$\text{Swell Percentage} = \frac{\Delta H}{H_i} \times 100 \qquad (1)$$

where:

ΔH is the difference between the initial and final readings of the dial gauge (in mm).

H_i is the initial height of the soil sample (in mm).

The free swell test was continued depending on time, which considerably varies according to the fiber content.

Micro–structural Test

To determine the micro-structural properties of natural and fiber-reinforced soil specimens, mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) tests were used. A Pore Sizer 9320 device was used to assess the pore size distribution (PSD) of soil specimens. The mercury pressure was raised continuously to values higher than 210 MPa, allowing apparent pore diameters from 0.0036 mm to 350 mm to be measured. In SEM test, the soil specimens, approximately 1 cm^3 in volume with and without hay fibers, were treated by epoxy fix resin, refined, gold-coated and then scanned by using Table Top Microscope–TM 3000 device.

Water Absorption Capacity Test

The coefficient of water absorption capacity (WAC) of hay fibers was evaluated. An oven-dried (48 hours at 60°C) hay fiber sample of 20g was soaked in water at 20°C for different soaking times ranging from 1 minute to 240 minutes. After that, hay fibers were taken out to superficially dry in order to remove the water absorbed on their surface (Bouasker et al., 2014). The coefficient of WAC of hay fibers can be calculated using the equation below:

$$WAC = \frac{W_2 - W_1}{W_1} \times 100 \qquad (2)$$

where:

W_1 is the weight of hay fibers before soaking (dry fibers).

W_2 is the weight of hay fibers after soaking (wet fibers).

Soil–Water Retention Test

The soil–water retention curve (SWRC) of natural and fiber-reinforced soil specimens was evaluated by using indirect methods. Three different methods were used to determine the entire SWRC of soil specimens. These methods are: vapour equilibrium technique, osmotic membrane and tensiometric plates. Tensiometric plates determined the SWRC with a suction range from 10 to 20 kPa. The SWRC in the suction range from 100 to 1500 kPa was determined by the osmotic membrane. The SWRC in the suction ranges of more than 1500 kPa was determined by vapour equilibrium technique. More details about these techniques can be found in Aldaood et al. (2014). Finally, all the previous SWRC determination methods were conducted at room temperature (20°C).

RESULTS AND DISCUSSION

Evolution of Unconfined Compressive Strength (UCS)

UCS of natural and fiber-reinforced soil specimens compacted at maximum dry unit weight and OMC of natural soil was determined. The UCS values of the soil specimens were 0.19, 0.22, 0.23, 0.27 and 0.2 MPa for 0, 0.25, 0.5, 1 and 1.5% hay fiber content, respectively. It was observed that the UCS of soil specimens increased along with the increase of hay fiber content up to 1% of fiber, then decreased. The increase in UCS with hay fiber content could be attributed to the fact that during compaction, the fiber surface attaches to some soil particles (especially clay particles), resulting in an increase of bonding and friction between the fiber and the soil matrix (Figure 2–a). Further, the random distribution of hay fibers in the soil matrix acts as threads between the soil particles and forms a network in all dimensions (Figure 2–b). The binding of the soil particles forms a unitary coherent matrix leading to increased strength and limitation of displacement. Furthermore, during the compaction process, some rigid soil grains (like sand grains) embedded into the body of the fibers and other grains abraded the surface of the fiber, resulting in removing some parts of the surface layer. As shown in (Figure 2–c), the holes and grooves that formed on the surface of the fiber caused an interlock and enhanced the interaction between the soil matrix and the hay fibers. These results agree with the results reported by Tang et al. (2010). They reported that the interfacial shear stresses between soil and polypropylene fiber depend mainly on the roughness of fiber, soil composition and the effective contact area between soil and fiber. Further, Khatri et al. (2017) found that the increase in shear strength of the soil is related to better interaction at soil-fiber interface. The reduction in UCS values of soil specimens having1.5%

hay fiber content is attributed to the difficulty of packing high hay fiber content (i.e., 1.5%) in the soil matrix, forming more air voids (Figure 2–d), resulting in a reduction in compressive strength. Estabragh et al. (2013) documented that as fiber content increases, some soil particles are replaced with fibers, resulting in increasing the void ratio of the reinforced samples in comparison with un-reinforced ones. Further, in comparison with the stiffness of soil particles, hay fiber possesses a soft behavior and causes tensile stresses near the contact surface areas with the soil particles when subjected to compression loads. These tensile stresses form micro-cracks (premature cracks) at the contact areas during loading and reduced the compressive strength. However, the fiber content of 1.5% reduces the effectiveness of the enhancement in the compressive strength properties of soil samples, since fiber clumps adhere to each other to form lumps and do not make full contact with soil particles (Figure 2–e). This finding correlates with the work of Parbakar and Sridhar (2002). Local flooding and clumping of hay fibers are two main problems related to soil reinforced with high hay fiber content. For instance, 1.5% of hay fiber content does not improve the properties of soil and causes more difficulties in the preparation of free swell and SWRC. Thus, these tests were conducted on the samples reinforced with hay fiber content up to 1% only.

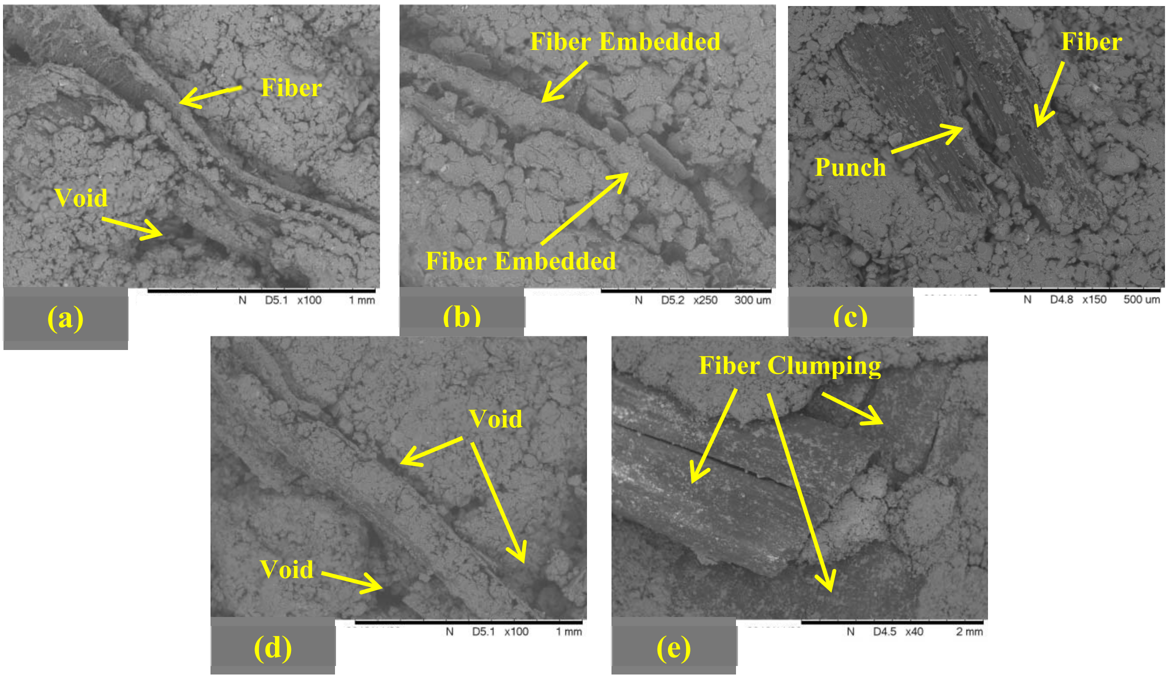

Figure (2): SEM images of fiber-reinforced soil samples (a) soil on fiber surface (b) fiber embedded in soil (c) fiber punching (d) void formation between fibers and soil and (e) fiber clumping

Evolution of P-wave Velocity

The P-wave velocity values of natural and fiber-reinforced soil specimens were determined before conducting the UCS test. P-wave velocity test was carried out to show the variations and to correlate the values of P-wave velocity with hay fiber percentages. The results showed that P-wave velocities decreased with increasing the percentage of hay fibers. The values were 540, 510, 475, 350 and 235 m/sec for 0%, 0.25%, 0.5%, 1% and 1.5% hay fiber percentage, respectively. The addition of hay fibers significantly affected the P-wave velocities of fiber-reinforced soil samples and showed the opposite action to that of the UCS, which increased with higher fiber percentages. The addition of hay fibers results in an increase in the void ratio (as previously reported), which represents a lower P-wave velocity value. Increasing void ratio causes an increase in the travel time between the two transducers (i.e., the transmitter and the receiver), thus the P-wave velocity decreased. Further, in the soil-fiber matrix, the wave transmission occurred in all phases (i.e., solid, liquid and air) and the P-wave velocity was higher in solids compared with other phases. Therefore, a larger percent of voids in the hay fiber-reinforced specimens and the voids in the fiber itself (Figure 3) result in a lower P-wave velocity.

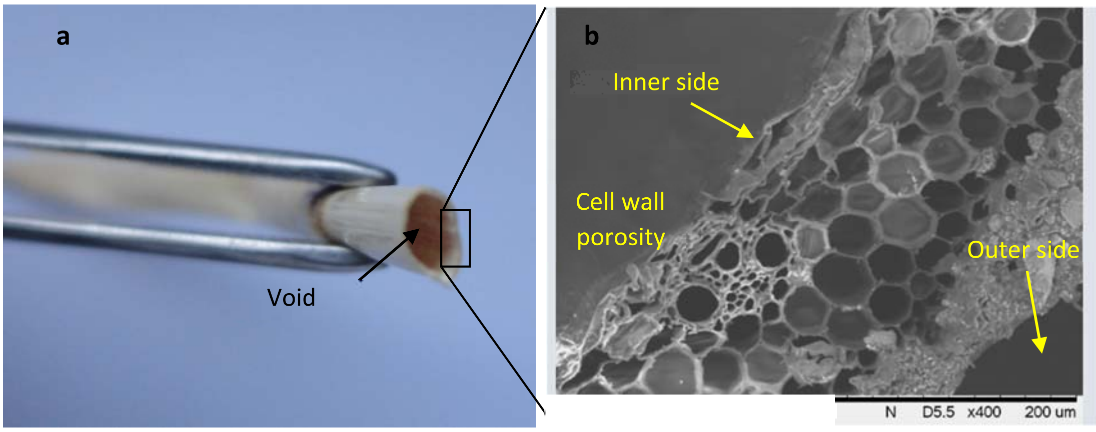

Figure (3): Hay-fiber structure a) voids (macro-porosity) and b) cross-section (cell wall porosity: capillary structure)

Evolution of Free Swell Percent

Figure 4 illustrates the free swell variation of fiber-reinforced soil specimens within all hay fiber percentages. The results showed that the addition of hay fiber causes a reduction in the swell percent, and as the hay fiber percent increased, the reduction in swelling was larger. The maximum reduction in swelling potential value reached 96% for the soil specimens reinforced with 1% hay fiber. Mohamed (2013) reported similar observations during his study on the improvement of soil swelling properties by hay fiber. He found that the swell deformation of soil specimens decreased with increasing hay fiber content. Further, Al-Akhras et al. (2008) studied the effect of two types of fibers (nylon and palmyra fibers) on the swelling pressure of clay soil. They found that fiber addition decreased the swelling pressure values of soils with more reduction for soil samples reinforced with palmyra fibers. In the case of fiber-reinforced clay soil (i.e., swelling soil), the amount of swelling is reduced due to several reasons. These reasons are: (a) Replacement of clay soil, which represents a swelling material, by non-swelling fiber. (b) The interaction (bonding) between soil and fiber, as mentioned in the section of (evolution of unconfined compressive strength). The contact area between hay fibers and soil grains could be more effective and could result in higher resistance to swelling behavior. Therefore, higher fiber percentages produce lower swelling percentage.

Water Absorption Capacity of Hay Fibers

The general shape of water absorption capacity curve (WAC) of hay fibers is presented in Figure 5. This figure describes the sorption process in two phases. The first phase represents a very high value of the coefficient of WAC of the fiber samples and the trend of this coefficient was linear within the capillary zone (attributed to the highly porous structure of the hay fibers), as illustrated in Figure 3. Further, the coefficient of WAC in this phase reached 290% during the first 10 minutes of soaking. In the second phase, the coefficient of WAC increased slightly with the soaking period and reached 350% after 60 minutes. This feature is harmful to straw fiber itself and causes many problems for straw fiber construction. In general, highly moist is a problem in all types of construction. Lawrence et al. (2009) reported that straw will decay when it is kept in a highly moist environment (moisture level exceeding 25% of the dry weight of straw). The increase of WAC of hay fiber could be attributed to macro-porosity (i.e., the voids) of the hay fibers enabling them to absorb a quantity of water more than their own weight at the initial period of soaking. After that, water could penetrate the hay fibers only through the micro-pores, resulting in a small increase in the coefficient of WAC of fiber samples. In addition, the structure of hay fibers could be changed under the effect of water soaking, causing internal stress that could enable the hay fibers to absorb more water (Bouasker et al., 2014). It worth noting that there was no volume increase in the hay fibers during water soaking.

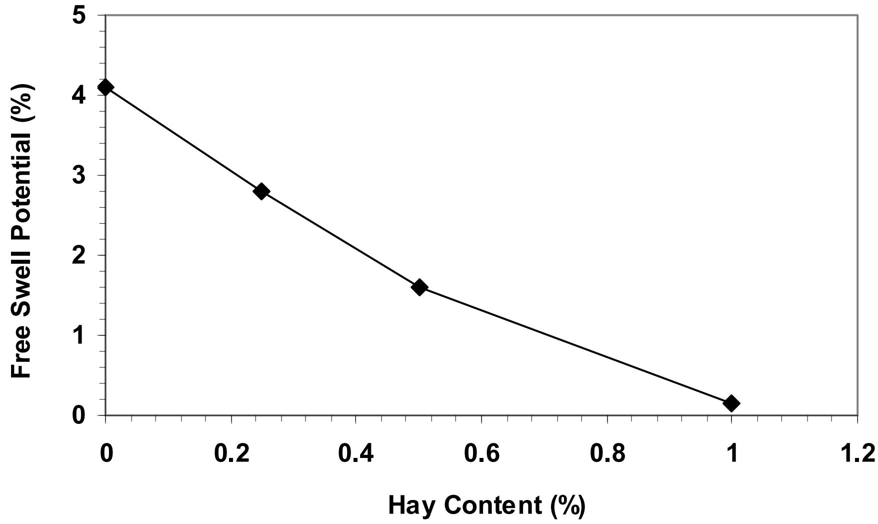

Figure (4): Free swell potential of soil samples with hay fiber addition

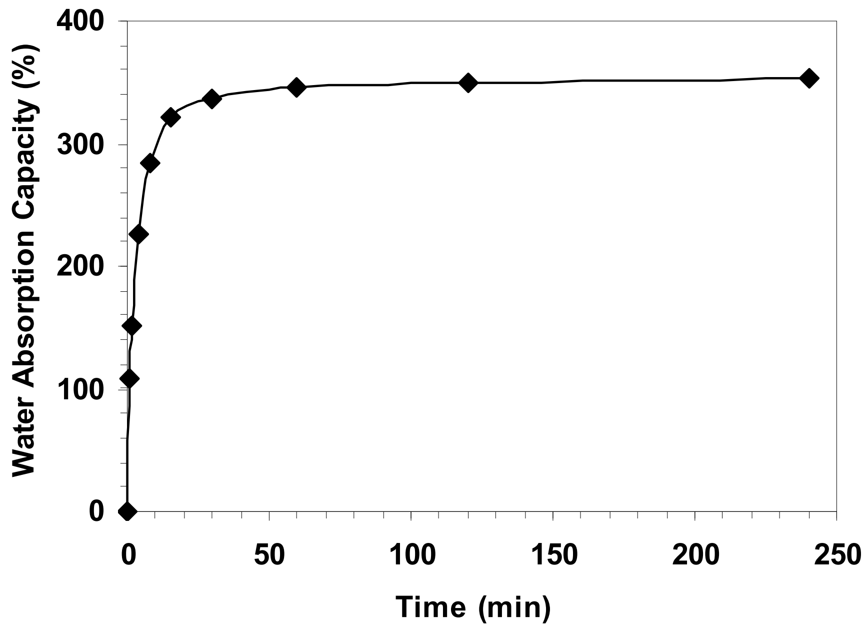

Figure (5): Water absorption capacity of hay fibers

Table 1. Porosity variation with hay fiber addition

Hay Content (%)	Total Intrusion Volume (mL/g)	Porosity (%)
0	0.204	33.5
0.25	0.128	23.8
0.5	0.134	25
1	0.137	25.4

Table 2. Key parameters of SWRC of soil samples with hay fiber addition

Hay Content (%)	Saturation State		Residual State	
	Ψ_a , AEV (kPa)	θ_a (%)	Ψ_r (kPa)	θ_r (%)
0	200	30.5	6600	10
0.25	200	33.6	5750	11
0.5	190	37	4100	12
1	180	42	4400	13

Soil-Water Retention Behavior

The soil-water retention curve (SWRC), which is a relationship between volumetric water content and suction pressure for natural and hay fiber-reinforced soil specimens, is shown in Figure 6. SWRCs are similar and have an S-shape. The trend of these curves was similar, representing a suction pressure decrease as the volumetric water content increased (Aldaood, 2020). Further, increasing the percentages of hay fibers caused an increase in volumetric water content. This behavior is expected due to hay fiber texture, which is represented as a porous material. SEM images and photos of hay fibers illustrated multi-scale porosities in the structure of hay fibers. These porosities could be divided into two categories: macro porosity (also called internode porosity), as presented in (Figure 3-a), and micro-porosity of cell walls as shown in (Figure 3-b) (Zhang, Ghaly and Li, 2012). The cell wall contains pores with a diameter of 150 μm in the outer surface of the fiber wall and constitutes a hexagonal vessel, whose dimensions increase from the inner surface to the outer one (Figure 3-b). Thus, hay fibers act as suction tubes, which absorb water and keep it in their pores.

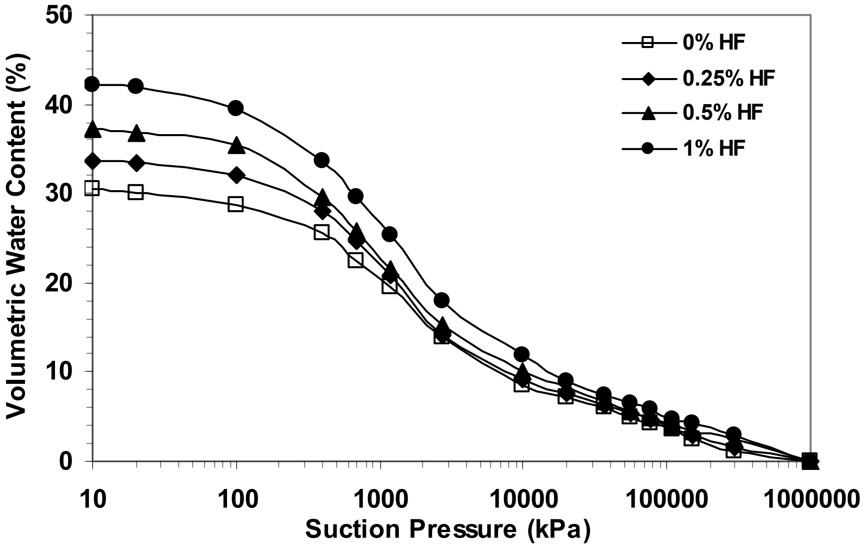

Figure (6): Soil-water retention curve of soil samples with hay fiber addition

Further, hay fibers influenced the porosity and pore size distribution of soil specimens, as presented in Figure 7 and Table 1, by occupying the original voids of soil and by binding the soil particles. From Figure 7, it was observed that the pores with (1 and 10μm) decreased with increasing hay fiber content, while there was an insignificant change in pores with a diameter of less than (1μm). This behavior is attributed to the coarser particles of hay fiber as compared with soil particles (especially clay particles). Such coarse particles did not influence the pores with a diameter of less than1μm. Further, the smaller surface area of fiber, as compared to soil particles, affected the porosity of fiber-reinforced soil, which decreased with increasing fiber content

(Kodicherla et al., 2018). The SWRC elements are air-entry value AEV (Ψ_a), saturation volumetric water content (θ_a) which corresponds to the AEV, residual suction pressure (Ψ_r) and residual volumetric water content (θ_r) which corresponds to residual suction pressure. The first two parameters represented the saturation zone, while the other parameters represented the de-saturation (residual) zone. The saturation and de-saturation zone values are illustrated in Table 2. The results showed that a slight decrease in AEV occurred with an increase in hay fiber percentage, while the saturation of volumetric water content increased with hay fibers. Similar observations (trends) were noticed for the parameters of de-saturation zone (i.e., Ψ_r and θ_r) with the addition of hay fibers. Malekzadeh and Bilsel (2014) found that AEV markedly increased with the increase in polypropylene fiber, which indicates a good bonding between soil and fiber. The differences between the findings of the current study and those obtained by Malekzadeh and Bilsel (2014) are attributed to the fiber properties, including composition, texture and length. The variations in the parameters of the saturated and de-saturated (residual) zones could be attributed to the variations in the values of porosity and the changes in the distribution of pore size of the fiber-reinforced soil specimens, as previously mentioned.

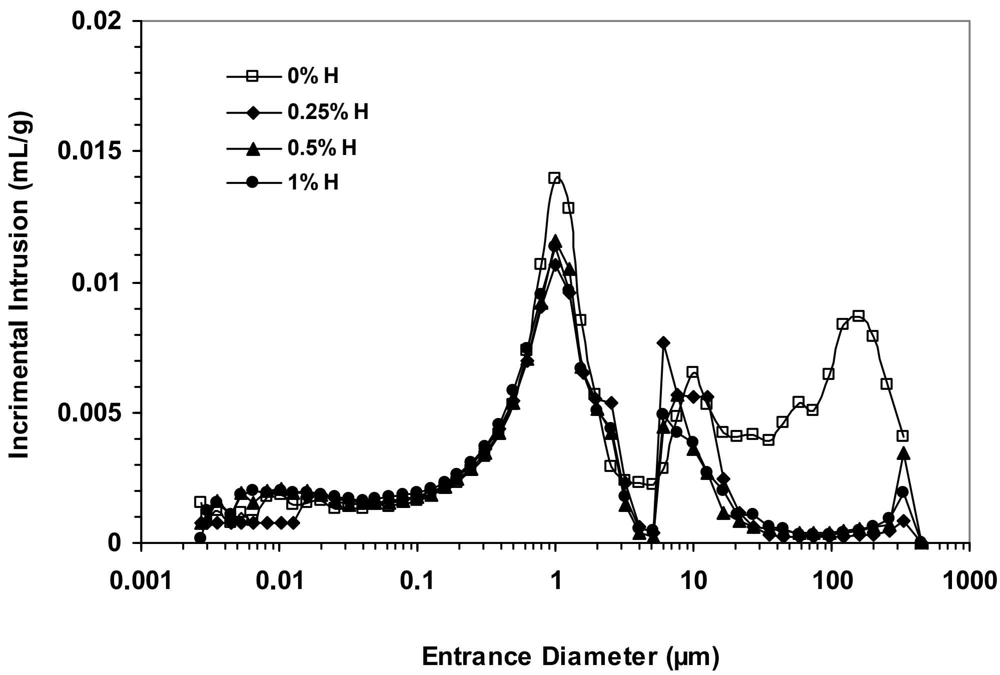

Figure (7): Pore size distribution of fiber-reinforced soil samples

CONCLUSIONS

The feasibility of using hay fibers to enhance the engineering properties of clay soil has been investigated. The main conclusions drawn from the research work are as follows:

1. Randomly distributed hay fiber caused a significant increase in the UCS of soil specimens.
2. The P-wave velocity of soil specimens decreased with hay fiber, which is related to the structure of the fiber that contains multi-scale porosities (macro-and micro-porosities).
3. Marked enhancement can be noticed in the swelling behavior of soil specimens reinforced with hay fiber. Therefore, hay fiber-reinforcement is a favorable technique for reducing possible damages on roads (especially roads with light traffic) and buildings due to swelling potential.
4. The hay fiber texture controlled the water retention behavior of soil specimens and the water holding capacity of soil specimens increased with hay-fiber addition.
5. SEM images of fiber-reinforced soil specimens showed a significant bonding between hay fibers and

soil grains, resulting in strength and swelling enhancements. Moreover, the insignificant effect of hay fiber on the soil fabric was noticed.

These conclusions will be helpful for civil engineering construction, mainly for infrastructure projects (i.e., roads). The application of hay fiber in clay soils and its use as a sub-base layer may considerably reduce the requirement of pavement thickness, thus saving road materials (especially aggregates) which are depleting every day. Further, it is important to study other dimensions (more than 30 mm used in this work), in order to determine the optimum length, which gives the maximum strength. Along with that, chemical treatment of hay fiber should be studied to reduce the attack of microorganisms on the fiber itself, which causes negative effects on the engineering properties of soils. Further research works are required to examine the influence of durability (chemical and/or mechanical) of hay fiber-reinforced soils.

REFERENCES

Abtahi, M., Okhovat, N., Pourhosseini, R., and Hejazi, M. (2010). "Improvement of soil strength by natural fibers". From RES to DES Europ. Prac., Bratislava, Slovak Republic, 2-4.

Ahmad, F., Bateni, F., and Azmi, M. (2010). "Performance evaluation of silty sand reinforced with fibres." Geotextiles and Geomembranes, 28 (5), 93-99.

Al-Akhras, N.M., Attom, M.F., Al-Akhras, K.M., and Malkawi, A.I.H. (2008). "Influence of fibers on swelling properties of clayey soil." Geosynthetics International, 15 (4), 304-309.

Aldaood, A. (2020). "Impact of fine materials on saturated and unsaturated behaviors of silty sand soil." Ain Shams Engineering Journal; doi.org/10.1016/ j.asej.2019.11.005.

Aldaood, A., Bouasker, M., and Al-Mukhtar, M. (2014). "Geotechnical properties of lime-treated gypseous soil." Applied Clay Science, 39-48, 88-89.

Alkiki, I. M., Al-Zubaydi, A. H., and Al-Atalla, M. A. (2012). "Compressive and tensile strength of fibrous clayey soil stabilized with lime." Journal of Al-Rafidain Engineering, 20 (2), 66-77.

Benessalah, I., Arab, A., Villard, P., Sadek, M., and Kadri, A. (2016). "Laboratory study on shear strength behaviour of reinforced sandy soil: effect of glass-fibre content and other parameters." Arabian Journal for Science and Engineering, 41 (4), 1343-1353.

Bouasker, M., Belayachi, N., Hoxha, D., and Al-Mukhtar, M. (2014). "Physical characterization of natural straw fibers as aggregates for construction material applications." Materials, 7, 3034-3048.

Bouhicha, M., Aouissi, F., and Kenai, S. (2005). "Performance of composite soil reinforced with barley straw." Journal of Cement and Concrete Composites, 27 (5), 617-621.

Cai, Y., Shi, B., Ng, C. W. W., and Tang, C.-S. (2006). "Effect of polypropylene fiber and lime admixture on engineering properties of clayey soil." Engineering Geology, 87, 230-240.

Consoli, C., Vendruscolo, A., Fonini, A., and Rosa, D. (2009). "Fiber reinforcement effects on sand considering a wide cementation range." Geotextiles and Geomembranes, 27, 196-203.

Estabragh, A.R., Bordbar, A.T., and Javadi, A.A. (2013). "A study on the mechanical behavior of a fiber-clay composite with natural fiber." Geotechnical and Geological Engineering, 31, 501-510.

Ghavami, K., Filho, R. D. T., and Barbosa, N. P. (1999). "Behaviour of composite soil reinforced with natural fibres." Cement and Concrete Composites, 21 (1), 39-48.

Hossein, S., Hossein, G., and Ali, A. H. (2014) "CBR strength of reinforced soil with natural fibres considering environmental conditions." International Journal of Pavement Engineering, 15 (7), 577-583.

Jamshidi, R., Towhata, I., Ghiassian, H., and Tabarsa, R. (2010). "Experimental evaluation of dynamic deformation characteristics of sheet pile retaining walls with fiber-reinforced backfill." Soil Dynamics and Earthquake Engineering, 30, 438-446.

Jili, Q., Chencai, L., Baoshi, L., Xinxing, C., Ming, L., and Zhaowei Y. (2013). "Effect of random inclusion of wheat straw fibers on shear strength characteristics of Shanghai cohesive soil." Geotechnical and Geological Engineering, 31, 511-518.

Khatri, V.N., Dutta, R.K., and Katre, S. (2017). "Shear strength, bearing ratio and settlement behavior of clay reinforced with chemically treated coir fibres." Jordan Journal of Civil Engineering, 11 (4), 659-679.

Khattab, S. A., Alkiki, I. M., and Al-Zubaydi, A. H. (2011). "Effect of fibers on some engineering properties of cement- and lime-stabilized soils." Engineering and Technology Journal, 29 (5), 886-905.

Kodicherla, S.P.K., Muktinuthalapati, J., and Revanna, N. (2018). "Effect of randomly distributed fibre reinforcements on engineering properties of beach sand." Jordan Journal of Civil Engineering, 12 (1), 99-108.

Lawrence, M., Heath, A., and Walker, P. (2009). "Determining moisture levels in straw bale construction." Construction and Building Materials, 23, 2763-2768.

Li, V.C. (2002). "Large-volume, high-performance applications of fibers in civil engineering." Journal of Applied Polymer Science, 83, 660-686.

Malekzadeh, M., and Bilsel, H. (2014). "Hydro-mechanical behavior of polypropylene fiber-reinforced expansive soils." KSCE Journal of Civil Engineering, 18 (7), 2028-2033.

Mansour, A., Srebric, J., and Burley, J. (2007). "Development of straw-cement composite sustainable building material for low-cost housing in Egypt." Journal of Applied Sciences Research, 3 (11), 1571-1580.

Miller, C. J., and Rifai, S. (2004). "Fiber reinforcement for waste containment soil liners." Journal of Environmental Engineering, 130 (8), 891-985.

Mittal, A., and Shukla S. (2020). "Effect of random inclusion of kenaf fibres on strength behaviour of poor subgrade soils." Jordan Journal of Civil Engineering, 14 (1), 43-56.

Mohamed, A. E. M. K. (2013). "Improvement of swelling clay properties using hay fiber." Construction and Building Materials, 38, 242-247.

Muhammad, G., and Marria, A. (2018) "Immediate and long-term effects of lime and wheat straw on consistency characteristics of clayey soil." Geomechanics and Engineering, 16 (3), 217-231.

Prabakar, J., and Sridhar, R. S. (2002). "Effect of random inclusion of sisal fibre on strength behavior of soil." Construction and Building Materials, 16, 123-131.

Savastano, H., Warden, G. and Coutts, P. (2000). "Brazilian waste fibers as reinforcement for cement-based composites." Cement and Concrete Composite, 22, 379-384.

Tang, C., Shi, B., and Zhao, L. (2010). "Interfacial shear strength of fiber-reinforced soil." Geotextiles and Geomembranes, 28, 54-62.

Zaimoglu, A. S. (2010). "Freezing-thawing behavior of fine-grained soils reinforced with polypropylene fibers." Cold Regions Science and Technology, 60, 63-65.

Zhang, C. B., Chen, L. H., Liu, Y. P., Ji, X. D., and Liu, X. P. (2010). "Triaxial compression test of soil–root composites to evaluate the influence of roots on soil shear strength." Journal of Ecological Engineering, 36 (1), 19-26.

Zhang, Y., Ghaly, A. E., and Bingxi, Li. (2012). "Physical properties of wheat straw varieties cultivated under different climatic and soil conditions in three continents." American Journal of Engineering and Applied Sciences, 5 (2), 98-106.