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ORIGINAL PAPER

Strength Behavior of Shanghai Clayey Soil Reinforced with Wheat Straw Fibers

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Abstract It is generally recognized that the low strength and high compressibility are the characteristics of soft soil. In addition to other techniques, reinforcement can also be used in increasing the strength and decreasing the deformation of this kind of soil. The results of an investigation into the effects of a natural fiber on the consolidation and shear strength behavior of Shanghai clayey soil reinforced with wheat straw fibers are presented in this paper. A series of one dimensional consolidation and triaxial tests were conducted on samples of unreinforced and reinforced Shanghai clayey soil with different percentages of randomly distributed wheat straw fibers. The results show that the preconsolidation pressure decreases and the coefficient of swelling and compression generally increase with increasing the fiber content until a optimum content value. Furthermore, the addition of wheat straw fiber leads to a significant increase in shear strength and friction angle of the natural soil and there is an optimum wheat fiber content that makes this increase maximal.

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1 Introduction

Reinforced soil technique is one of the ground improvement methods, the concept of which was first given by Vidal of France in 1966. In general, the reinforcing elements in reinforced soil can be divided into oriented and randomly distributed. In the former case, the inclusions are placed in the soil at strategic locations, whereas in the latter, reinforcement elements, usually fibers, are randomly mixed with the soil and may be placed within the problematic shear zone. Compared with oriented or aligned reinforced soil, fiber reinforced soils with random distribution of fibers exhibit some advantages. One of the main advantages of using randomly distributed fibers is the maintenance of strength isotropy and the absence of potential planes of weakness that can develop in soils with oriented reinforcement (Gray and Maher 1982; Maher 1988). Although the concept of randomly reinforced soil is relatively new in geotechnical engineering but the reinforcement of clayey soils with natural fibers has been practiced from ancient China for more than 2000 years. Recently soil reinforcement with short, discrete, randomly oriented natural fibers is getting more attention from many researchers around the world. Many investigators have used natural or artificial fiber to improve various mechanical properties of sandy soil. (e.g. Gray and Ohashi 1983; Maher and Gray 1990; Al-Rafeai 1991; Wei et al. 2005; Consoli et al. 2009; Yetimoglu and Salbas 2003; Ahmad et al. 2010; Jiang et al. 2010; Li et al. 2011; Wang et al. 2011). These investigations have indicated that the strength of reinforced soil increases with increase in fiber content, aspect ratio and friction between soil and fiber. Even though most of the published literature on randomly oriented fiber focus on reinforcement cohesionless or granular soil, results from a limited number of studies have indicated that cohesive soils can also be reinforced and the such reinforced soils can be beneficial in practice (e.g. Andersland and Khattak 1979; Freitag 1986; Maher and Ho 1994; Consoli et al. 2002; Mesbah et al. 2004; Kumar et al. 2006; Tang et al. 2007; Attom et al. 2009). At the same time, although the predominance of reinforcing elements is artificial fibers, the trend of using natural fibers as reinforcing elements is emerging in some specific status due to its unique features: inexpensive, plenty of presence and advantages in environmental protection etc. (e.g. Wei et al. 2005; Li et al. 2011; Wang et al. 2011). It is resulted from the above studies that addition of fibers can affect the behavior of the reinforced soil in different ways. The key factors governing the mechanical behavior of randomly reinforced soil are mainly the size and quantity of fibers. Nevertheless, it should be noted that natural fibers are biodegradable and may not last for many years. Plastic or nylon fibers are not affected by the presence of salts in soils, biological degradation and ultraviolet degradation. Kumar and Tabor (2003) indicated that the tensile strength of nylon fiber is greater than many of the other materials such as paper and rubber from used tires. Li et al. (2011) studied the stress–strain behavior of lime soil reinforced with wheat straw fibers based on laboratory investigation under different conditions of reinforcement and arrived at the strength growth of reinforced soil depends on reinforced condition. Yu et al. (2010) studied the reinforcement effects and engineering application of coast salinized soil reinforced with wheat straw and concluded that there was a significant growth of shear strength with reinforced coast salinized soil compared to unreinforced soil. Wang et al. (2011) analyzed the governing factors of heavy compaction test for wheat straw-reinforced saline soil and concluded that maximum dry density of reinforced soil decreases compared to unreinforced saline soil. Andersland and Khattak (1979) conducted triaxial tests on kaolinite clay reinforced with paper pulp (cellulose) fiber. The samples were consolidated from a slurry mix and tested under two different cell pressures. On the basis of the test results it was concluded that the addition of fibers increased both the stiffness and undrained strength of clay. The results of triaxial tests were used on mixture of kaolinite/fiber to calculate the safety factor of an excavated slope in consolidated fibrous paper mill sludge with properties very similar to the fiber/kaolinite mixture and achieved very good agreement with field data.

Wei et al. (2010) studied physical and mechanical properties of wheat straw and unconfined compressive strength of inshore saline soil reinforced with wheat straw and the test results show that the strength of reinforced inshore saline soil with wheat straw and lime is higher than that of soil with lime only. The strength of the reinforced soil is maximal when the fiber content is 0.25 % and the optimum length of reinforcing element is 10 mm (50 mm in diameter of specimen). The strength of soil reinforced with wheat straw marinated in SH agent (a type of preservative) in moist condition is higher than that in dry condition, and the strength can be effectively increased by adding four equal quarters of wheat straw. The integrality and strength of reinforced soil can not only be enhanced by inclusion of randomly distributed wheat straw, but the deformation can also be restrained. The results from this study had partly been used in local highway projects.

If suitable reinforcements and construction technique can be adapted to use cohesive fill particularly in areas where cohesionless fill is in short supply many widespread benefits and applications could arise. The present study is focused on the effects of wheat straw fibers on improving the mechanical behavior of Shanghai cohesive soil. The reasons of choosing wheat straw fiber as reinforcing element is due to that it is inexpensive, plenty of presence in locality, relatively high tensile strength compared to other natural fibers, of environmental protection function (avoiding burning in field that pollutes air) etc. Therefore it is possible to use wheat straw fiber as the primary reinforcement and an alternative low cost material for soil reinforcement. In order to better understand the effects of using wheat straw fibers as clayey soil reinforcement an experimental program was undertaken to investigate the effects of wheat straw fibers on improving the mechanical behavior of Shanghai cohesive soil. The main objective of this study is to investigate the contribution of wheat fibers to the consolidation and shear strength behavior of the local soil. The results of this study can be used for design of suitable mixture of reinforced soil, for analysis of short- and long-term stability of such reinforced soils and for field applications concerning soils that have properties similar to the fiber-clay mixture.

2 Experimental Study

2.1 Soil Properties

A fine grained soil, a classic Shanghai clayey soil, was used in the testing program. The program was mainly completed in laboratory. The specific gravity, liquid limit (LL), plastic limit (PL), maximum dry density (MDD), optimum moisture content (OMC) based on Standard Proctor compaction were determined according to the ASTM standards. Table 1 summarizes the various index and engineering properties of the soil. The soil can be classified as clay with low plasticity (CL) according to the Unified Classification System (USCS).

2.2 Fiber Properties

The local wheat straw fibers were used as the reinforcement in the present work. Wheat straw fibers have resistance against corrosion or deterioration in the soil in certain period of time even though they are not specially processed. Wheat straw fibers with different lengths were obtained by selecting wheat fibers with approximately equal diameter, removing wheat straw's peel, scissoring it into specified length. The dimensions of straw fiber that was used were about 10.0 mm length, 4.0 mm or so in diameter. Selecting 10.0 mm length was due to that this length has optimum reinforcement effect on soil (Li et al. 2011). The tensile strength of wheat straw fiber was determined through tensile strength tests. The physical and mechanical properties of wheat straw fiber used in this work are shown in Table 2.

Table 1 Physical and mechanical properties of soil

Soil properties	Values
Specific gravity	2.73
Liquid limit (LL)	42 %
Plastic limit (PL)	21 %
Plastic index (PI)	21 %
USCS classification	CL
Optimum water content	20 %
Maximum dry density	1.6 Mg/m^3
Cohesion	37.9 kPa
Angle of internal friction	22°

2.3 Sample Preparation

The conventional consolidation and triaxial compression tests were conducted on saturated samples. In order to prepare the samples, the slurry technique was considered as used by other researchers such as Estabragh et al. (2011), Marto (1996) and Andersland and Khattak (1979). When saturated samples are tested in triaxial apparatus by applying back pressure, the procedure may take a long time for clay soils particularly if the dimensions of the sample are large. This could make triaxial testing of soils time demanding and costly. As a result, some researchers such as Marto (1996) and Andersland and Khattak (1979) have suggested and used the slurry technique for preparation of soil samples. This technique of sample preparation provides reasonably homogeneous and reproducible samples with near saturation conditions. Unreinforced samples and wheat straw fiber-reinforced samples with different percentages of fiber content (0.1, 0.2, 0.3, 0.4, 0.5, 0.6 %) were mixed with distilled water to a water content above the liquid limit (LL) to form a slurry. The exact amount of water was weighted and slowly added to the mixture of soil and fiber. The resultant slurry was mixed by hand steer for

Table 2 Properties of wheat straw fibers (internode)

Properties	Values
Natural ultimate tensile strength (N)	110
Natural elongation ultimate (%)	22
Natural density (Mg/m^3)	0.1
Wall thickness (mm)	0.55
Outer diameter (mm)	4.0
Inner diameter (mm)	3.45

Provided by YiYing Testing Co. Shanghai, China about 1 h until a smooth liquid resulted. The percentage of wheat straw fiber was measured after 15 min of mixing by taking a sample. This was regularly done to ensure an even distribution of fiber at the time of sampling. A number of cylindrical tubes with 150 mm diameter and 300 mm height (referred to as consolidation tubes) were filled with slurry for consolidation. The slurry was then consolidated by loading, using a hydraulic jack, to the maximum consolidation pressure of 50 kPa, while drainage was allowed from the top and bottom of the tube. Consolidation was generally completed within about 7 days. After consolidation the samples were extruded into 38 mm diameter thin walled stainless steel tube and also the conventional consolidation mould. They were waxed at both ends to retain the initial water content. The samples were then stored in a controlled temperature of 20 °C ± 1 before being used for testing.

2.4 Experimental Testing

The samples prepared were used in one dimensional consolidation (oedometer) and consolidated undrained (CU) triaxial tests. The consolidation behaviors of the unreinforced and wheat straw fiber-reinforced soils with different fiber contents were studied through a series of standard oedometer tests under zero lateral strain conditions. A number of consolidated undrained (CU) triaxial tests were performed on the unreinforced samples and samples reinforced with different percentages of wheat straw fiber inclusions in order to study the effect of fiber on shear strength of clay. Each sample was isotropically consolidated to an effective confining pressure ranging from 200 to 400 kPa. During the consolidation test, the plot of the sample volume change against time was plotted. The consolidation stage was considered to be completed when there was no further volume change occurring. In this work, the time for consolidation was about 20–24 h. The triaxial tests were performed with initial pore pressure equal to zero under constant cell pressures of 200, 300, and 400 kPa at a constant rate of axial strain. An axial rate of 7 mm/h was selected giving a strain rate of 0.15 % per minute as suggested by Bishop and Henkel (1969) and Smith and Smith (1990). The slow rate was chosen to ensure the equilibrium of pore water pressure throughout the sample during the test. The undrained triaxial test also allowed the pore pressure response of the soil samples to be studied. Verification tests were also performed by repeating the tests in order to examine the repeatability of the experiments.

3 Results

Figure 1 shows that the peak deviator stresses of reinforced soils with 5, 10, and 15 mm long wheat straw fibers under different confining pressures. Either it is at confining pressure of 200, 300 or 400 kPa, the optimum fiber content of the three different aspect ratios for consolidation is between 0.2 and 0.3 %. This is maybe due to that an appropriate fiber content can not only play fully with soil, but also can maintain the integrity of the soil. From the viewpoint of the aspect ratio, the peak deviator stress of reinforced soil with 10 mm long wheat straw fibers is greater than those for 5 and 15 mm. The main reason is that when aspect ratio is small, the contact area between fibers and soil particles is small, which can't produce the enough friction. But when aspect ratio is too large, the absolute number of wheat fibers is relatively small under same fiber content, which may result in uneven mixing situation, therefore providing insufficient friction. If the fiber content is too large, overlapping may occur, and because frictional resistance between fibers is smaller than that between soil particles and fibers, too large fiber content may lower the strength of reinforced soil. Therefore, an appropriate aspect ratio can enhance the shear strength of reinforced soil in most magnitude. To study the strength behavior of Shanghai

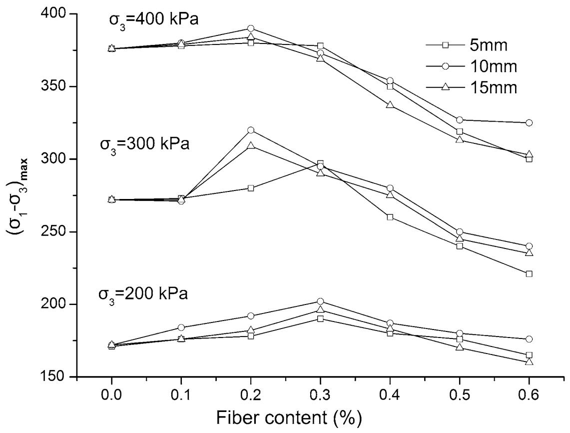

Fig. 1 Strength behaviors of soil reinforced with wheat straw fiber under different confining pressures

clayey soil reinforced with wheat straw fibers with triaxial experiment, (the optimum aspect ratio 10 mm) was selected for further study.

Figure 2 shows the results of the one dimensional consolidation tests as $v - \ln p'$ plots where v is specific volume ($v = 1 + \mathrm{e}$) and p' is the applied pressure. The intersection of the two linear segments of the curve is used to determine the preconsolidation pressure (p'_c) as defined by Cui and Delage (1996) and the results are shown in Table 3. The slopes C_s in the elastic zone (zone before preconsolidation pressure) and C_c in the elastoplastic zone (zone after preconsolidation pressure) were determined and the values are shown in Table 3.

A total of 21 consolidated undrained (CU) triaxial shear tests with constant cell pressure were conducted on samples of unreinforced soil and soil reinforced with 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 % fiber. The tests were conducted at three different cell pressures of 200, 300 and 400 kPa. The variations of the deviator stress $\sigma_1 - \sigma_3$ and pore water pressure u_w with axial strain ε_1 at different cell pressures for the unreinforced and reinforced samples were shown in Figs. 3, 4 and 5. The results of the tests on the unreinforced soil and soils reinforced with different percentages of wheat straw fiber under cell pressure of 200 kPa are shown in Fig. 3. The deviator stress increased until 15–20 % axial strain for the unreinforced soil and reinforced samples (Fig. 3a). It is resulted by comparing the strengths at 15 % axial strain for the unreinforced and reinforced samples that almost all the reinforced soils are increased in strengths to some degree, including 15 % maximum increase in strength attained from soil reinforced with 0.3 % fiber. It is obvious from this figure that the strength curves due to 0.1, 0.2, 0.4, 0.6 % are close to each other, and the increase in

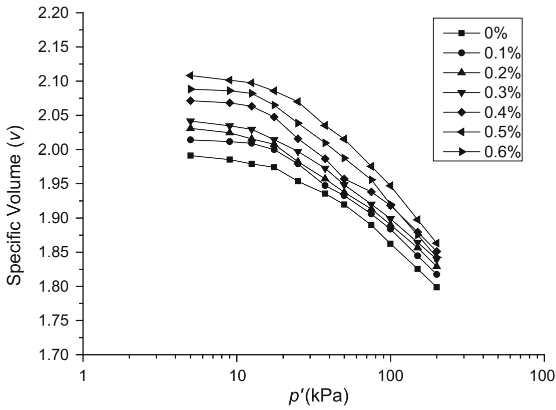

Fig. 2 Consolidation curves for unreinforced soil and soil with 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 % wheat straw fiber

Table 3 Consolidation and shear strength parameters of the unreinforced and fiber reinforced soils

Condition of soil	p'_c (kPa)	C_c	C_s	ϕ (°)	ϕ' (°)
Unreinforced soil	30	0.180	0.045	17	22
Soil + 0.1 % fiber	28.2	0.195	0.049	19	23
Soil + 0.2 % fiber	26.5	0.205	0.053	20	23.5
Soil + 0.3 % fiber	25	0.210	0.055	19.5	30
Soil + 0.4 % fiber	22	0.214	0.056	19	24
Soil + 0.5 % fiber	19.5	0.235	0.084	17	25
Soil + 0.6 % fiber	20	0.220	0.073	16	24

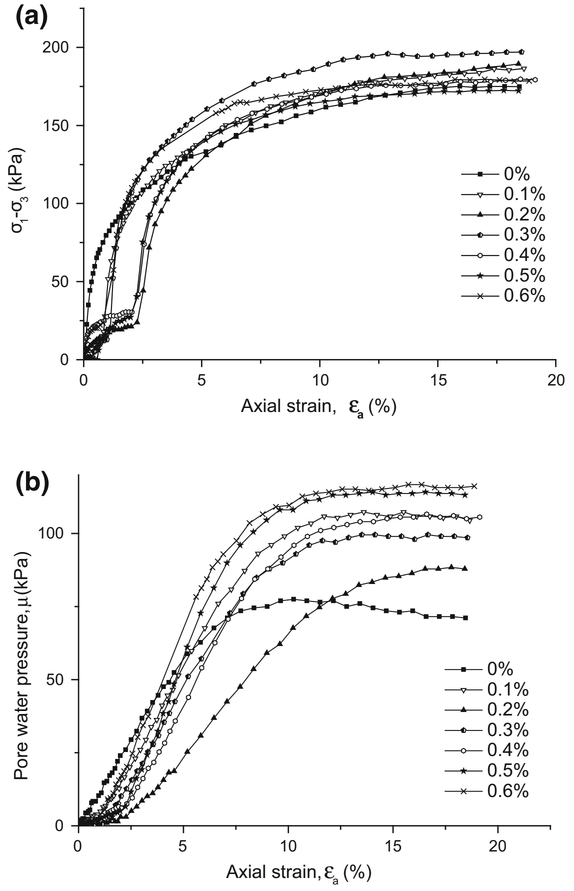

Fig. 3 **a** Deviator stress versus axial strain, **b** pore water pressure versus axial strain under cell pressure of 200 kPa for unreinforced soil and soil reinforced with 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 % fiber

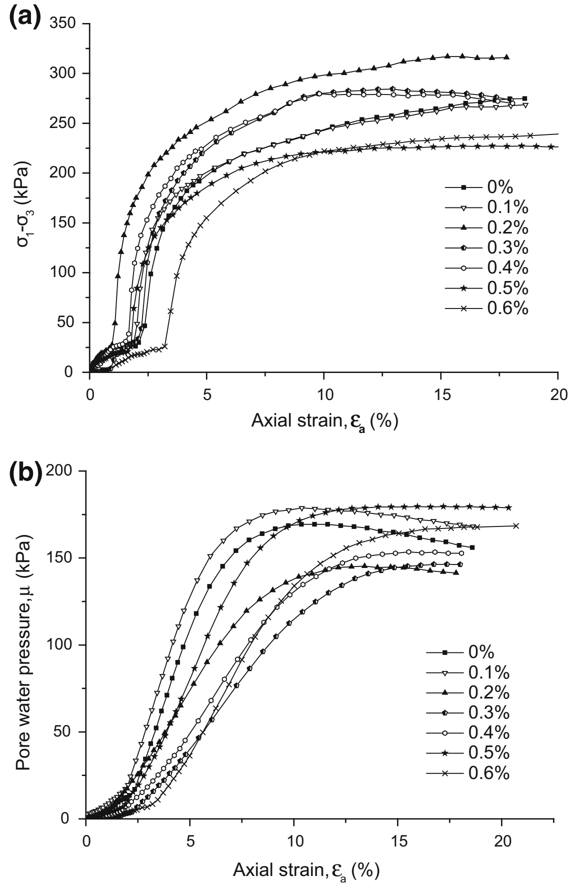

Fig. 4 **a** Deviator stress versus axial strain, **b** pore water pressure versus axial strain under cell pressure of 300 kPa for unreinforced soil and soil reinforced with 0.1, 0.2, 0.3, 0.4 0.5, and 0.6 % fiber

strength for the soil with 0.2 % fiber is only about 2 % in comparison with the soil with 0.1 % fiber, the same as the strength curves with 0.4 and 0.6 % fiber. These results show that at a given confining pressure, increasing the amount of fiber increases the strength of the soil. The variation of pore water pressure against axial strain was shown in Fig. 3b. It is presented that the pore water pressure increased by reinforcing the soil. The increase in the pore water pressure at 15 % axial strain was nearly 53 % by reinforcing the sample with 0.5–0.6 % fiber. It is resulted that the fiber increases the porosity of the soil and the water can be collected in the pores. It can be seen that by increasing the axial strain the pore water pressure increases and at around 10 % axial strain the pore water pressure remains almost constant.

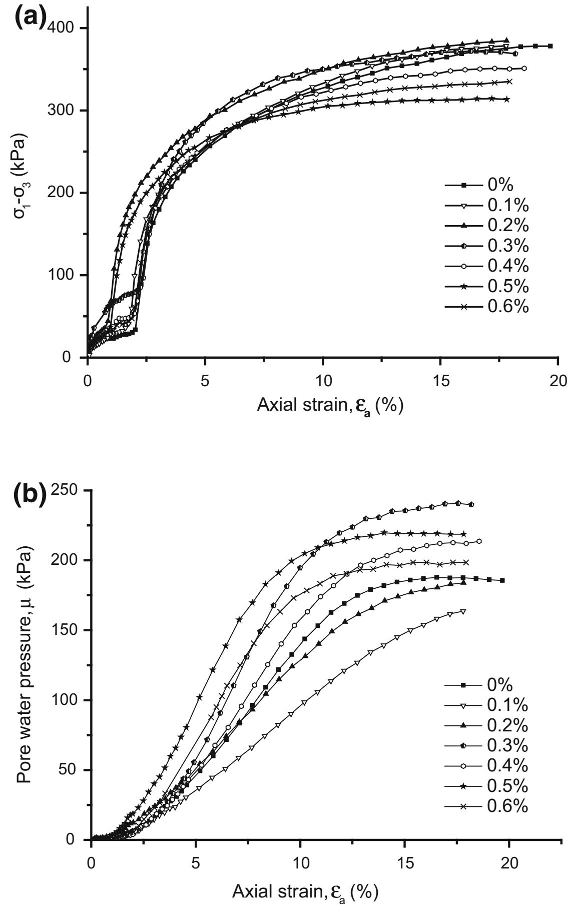

Fig. 5 **a** Deviator stress versus axial strain, **b** pore water pressure versus axial strain under cell pressure of 400 kPa for unreinforced soil and soil reinforced with 0.1, 0.2, 0.3, 0.4 0.5, and 0.6 % fiber

Figure 5 shows the results of shear tests on the unreinforced and reinforced samples under cell pressure of 300 kPa. The tests were continued up to about 20 % axial strain. The deviator stress varied with the variation of the fiber content. The increase of strength at 15 % axial strain is about 20, 11 and 10 % by reinforcing the samples with 0.2, 0.3 and 0.4 % fiber respectively, while the decrease of strength at 15 % axial strain can also be observed by reinforcing the samples with 0.1, 0.5 and 0.6 % fiber respectively. The maximum increase of strength is observed with sample of 0.2 % fiber (Fig. 5a). The variation of pore water pressure with axial strain for the unreinforced sample and the samples with different percentages of fiber is shown in Fig. 5b. The amount of increase in pore water pressure is more compared with the sample tested under confining pressure of 200 kPa.

Figure 5 shows the results of shear tests at confining pressure of 400 kPa. The tests were continued up to axial strain of 20 %. Samples under this confining pressure showed more variations of strength and pore water pressure than the confining pressures 200 and 300 kPa. The maximum increase in strength at 15 % axial strain is 6 % by reinforcing the soil with 0.2 % fiber, while the maximum increase in pore water pressure is about 32 % by reinforcing the sample with 0.3 % fiber. It can be concluded that by increasing cell pressure the stress–strain and pore water pressure slowly evolved and the initial slope of the curves became steeper at higher cell pressures.

4 Discussion

One dimensional consolidation tests were conducted to investigate the consolidation properties of the mixture of Shanghai clayey soil and local wheat straw fibers. The wheat fiber is relatively light in weight but large in volume. Therefore, The mixture of soil and fiber can be considered as a composite due to the small length of wheat fiber and relatively large percentage of wheat fiber (0.1, 0.2, 0.3, 0.4 0.5 and 0.6 %) that was used in preparing the samples. Based on the results of the oedometer tests on samples of unreinforced and reinforced clay it is concluded that the pre-consolidation pressure decreases and the values of C_c and C_s generally increase with increasing the fiber content of the soil as shown in Table 3. Estabragh et al. (2011) used nylon in reinforcing soils and obtained the similar results. For the soils with 0.5 and 0.6 % fiber the values of C_c and C_s slightly decrease from 0.5 to 0.6 %. This may be due to less uniform distribution of wheat fibers in the samples with 0.6 % fiber. By adding wheat fiber to the soil (or increasing the fiber content) some soil particles are replaced with fibers and they occupy the pores between the soil particles which results in increase in void ratio of soil mass. As a result, the soil becomes more compressible. Therefore both the clay and wheat fiber in the mixture control the porosity. A soil that is more compressible has a lower preconsolidation pressure than a less compressible soil. Also, since the wheat fibers are more compressible than the soil particles the compressibility of the soil and values of C_c and C_s increase with increasing the fiber content (except for 0.6 % the values of C_c and C_s are less than those for 0.5 %). During one-dimensional consolidation, the stiffness of the soil decreases with increasing the wheat fiber content. This is in contrast with the observed increase in stiffness during triaxial shear tests where the stiffness and strength increase by increasing the wheat fiber content. The main reason could be that some wheat straw fibers work in tension during shearing whereas there is no tension during consolidation. These results are supported by the finding of Fukue et al. (1986) who studied the consolidation behavior of sand-bentonite-clay mixtures and showed that as the clay content increase the compression index and therefore compressibility of sample increases. In practical field applications, the clay soil can be treated with a suitable agent such as lime before adding the fiber. Adding lime reduces plasticity of clay which allows the fibers to be more easily mixed into the soil.

The shear characteristics of the mixture of wheat straw fibers and Shanghai cohesive soil were investigated through triaxial tests. The fiber-soil mixture can also be considered as a composite. The results of the triaxial tests on the reinforced and unreinforced samples show that the increase of strength continued up to and beyond 20 % axial strain. The stress–strain curves did not indicate a clear peak of shear stress until the end of the test. The maximum deviator stress increased as the confining pressure increased. The tests were usually terminated at 15–20 % axial strain and at this stage the samples were bulging appreciably. The failure stress in the experiments was taken corresponding to axial strain of 15 and 20 % (Head 1986; Bowles 1987). The pore water pressure increased steadily during shearing and also with increasing the confining pressure. Typical deviator stress-axial strain and pore water pressure-axial strain curves (for cell pressures of 200, 300 and 400 kPa) for the unreinforced samples and samples reinforced with different wheat fiber content are shown in Figs. 3, 4 and 5. It can be observed from these figures that the initial slopes of stress–strain curves of the reinforced soils are steeper in comparison with the unreinforced soil. The stiffness of the soil is increased by increasing the amount of fiber and confining pressure. But the maximum stiffness was observed on curves with 0.2 and 0.3 % fibers no matter what the cell pressures are. The results show that the stress–strain behavior was markedly affected by the wheat straw fiber inclusions.

And there is an optimum inclusion that makes up a maximal effect. Therefore, it can be concluded that the wheat straw fibers have a appreciable influence on the mechanical behavior of the soil and the strength and stiffness of the soil increases with increasing the fiber content up to an optimum inclusion. The results indicate that there is a direct relationship between the strength and the amount of fiber in soil mass, at least in the range of the experimental work carried out in this study. These results are consistent with those reported by Ranjan et al. (1996) who indicated that the amount of increase in strength induced by reinforcement with short fibers depends on many factors such as fiber content and confining pressure.

The pore water pressure also generally increased with increasing the wheat straw fiber content during undrained shearing. The pore water pressures generated within the soil during the CU tests are related to the tendency of the soil to contract or dilate during shearing. The excess pore pressures are generally higher for the reinforced soils than the unreinforced soil (Figs. 3b–5b) especially at cell pressures of 300 and 400 kPa. This higher pore water pressure generated can be related to the effect of fibers on the soil during deformation. Li (2005) explained this increase in pore water pressure on the fibers distributing stresses within soil mass and therefore increasing the tendency for the contractive deformations within the mixture of soil fabric. The tendency to contract or dilate is indicated by the slope of the plot of excess pore water pressure in the post peak portion of the curve, whereby a positive slope indicates contractive behavior and a negative slope indicates dilatancy behavior. The values of the excess pore pressure in this work are generally positive and this indicates the tendency towards contractive behavior. Therefore, since positive pore pressure is associated to the tendency for volumetric contraction it may be concluded that fibers restrain the dilatancy of the mixture of soil and fiber as discussed by researchers such as Peters et al. (2010). This also provides an evidence that the deformation behavior of a soil might indicate how the fabric affects the soil behavior. The results of variation of pore water pressure in this test program are in agreement with the findings of Ahmad et al. (2010) and Li (2005).

Figure 6 shows the Mohr circles of failure at different confining pressures together with the failure envelopes for the unreinforced soil and the soil reinforced with 0.2 % fiber in terms of effective stresses. The failure envelopes pass through the origin, indicating zero apparent cohesion, c = c′ = 0. For the unreinforced soil, the values of friction angles in terms of total and effective stresses (φ and φ′) are 17° and 22° respectively (Table 3). For the reinforced soil with 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 % fibers the friction angles are 19°, 20°, 19.5°, 19°, 17°, 16° in terms of total stresses and 23°, 23.5°, 30°, 24°, 25°, 24° in terms of effective stresses. By adding 0.1–0.6 % fiber to clayey soil, the voids created by fiber are occupied by clay particles and thus the friction angle of the mixture is enhanced. This may be attributed to the contribution of both clay and fiber in clay fiber composite with increasing the percentage of fiber from 0.1 to 0.6 % in the mixture. It can also be seen that there seems to be a maximum effective friction angle corresponding a fiber percentage. It is 0.3 % in this test. More content of fiber may cause inverse effect. At this stage the resistance of clay is attributed to the friction mobilized between clay-fiber, fiber–fiber and clay–clay. This phenomenon causes the friction angle to increase. But excessive content may lead to more contact between fibers, which may cause the decrease in friction angle

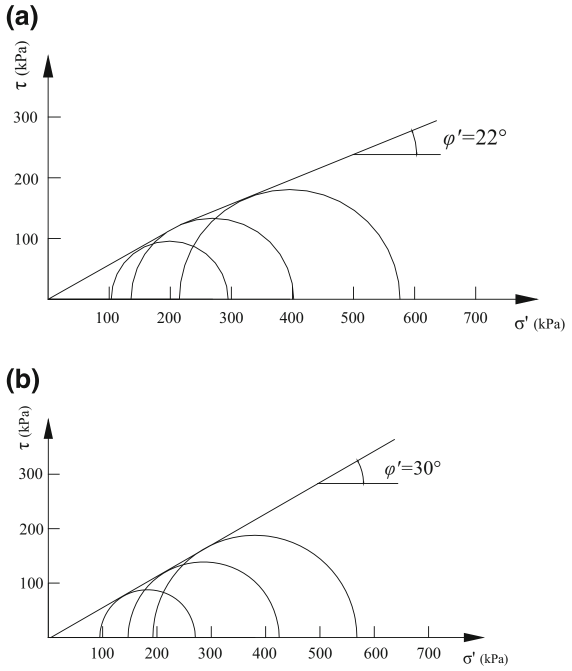

Fig. 6 Mohr circles of effective stresses for **a** unreinforced soil and **b** soil reinforced with 0.3 % wheat straw fiber

as the direct friction among wheat straw fibers is less than that among fibers and clay particles.

Due to the increase in pore water pressure caused by the wheat straw fiber the effective stress within the soil mass decreases. Figure 7 shows the typical stress paths in the space of deviator stress, $q(\sigma_1 - \sigma_3)$ and mean net stress, $p'\left(\frac{\sigma_1+2\sigma_3}{3} - u_w\right)$ or deviator stress and mean total stress, $p\left(\frac{\sigma_1+2\sigma_3}{3}\right)$. The horizontal distance between the effective stress and total stress represents the value of pore water pressure at the desired stress point. The total stress paths (TSP) are straight lines with gradient of 1 vertical to 1 horizontal. Positive pore pressure was produced which caused the effective stress path (ESP) to rise to the left along a curved path. In general, the shape of the stress paths for unreinforced and reinforced samples indicates an increase in pore pressure with deformation (or a tendency towards a contractive volumetric deformation). At critical state, the paths reached the peak value where the samples continued plastic deformation with no change in applied stress or pore pressure. The results of (effective) stress paths show that the critical state line for a given fiber content appears to be a straight line (in the p': q space) given by the following equation:

$$q = Mp' \tag{1}$$

where M is the slope of critical state line.

Figure 8 shows typical effective stress paths and critical state lines for natural soil and soil reinforced with 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 % fiber. The envelop for reinforced soil is located above the one for the unreinforced soil and the envelop for soil reinforced with 0.3 % fiber is located above all other reinforced soil. This increase in strength is due to a combination of an increase in the peak deviator stress, as well as the decrease in effective stress (due to increase in pore pressure) caused by the fibers, resulting in a greater shift to the left in p' value. The results also show that as the effective confining pressure increases, the effect of the fibers on the soil strength increases. It is resulted by comparing the effective stress paths of the unreinforced soil and the soil with 0.3 % fiber that the pore water pressure increases and effective stress decreases with increasing the amount of fiber especially at high confining pressures. It is concluded from the results that the value of M is dependent on the percentage of fiber. The values of M for natural soil and soil with 0.3 % fiber are 0.40 and 0.50 respectively. Table 4 gives the M values of unreinforced soil and soil reinforced with 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 % fiber content. From the Table 4, it can also be seen that M value of soil reinforced with 0.3 % fiber is maximal.

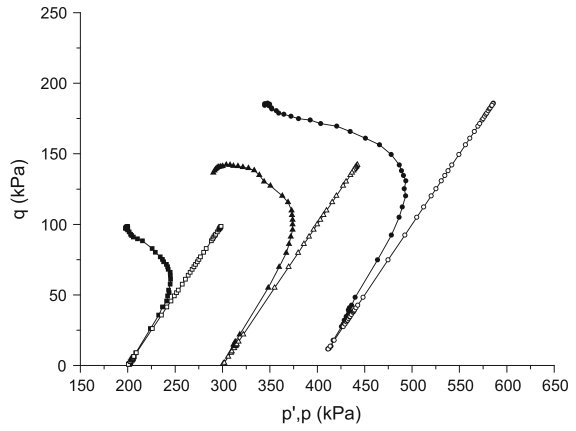

Fig. 7 Stress paths for soil with 0.3 % wheat fiber

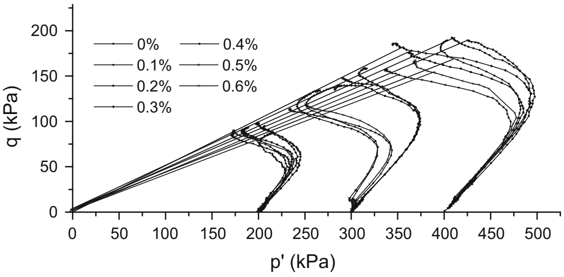

Fig. 8 Typical effective stress paths for unreinforced soil and soil with 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 % wheat straw fiber

The clay particles bond to fiber surfaces which contributes to the bond strength and frictional resistance between the fiber and soil mixture. The distributed discrete fibers act as a spatial three-dimensional network to interlock soil grains, cause grains to form a unitary coherent matrix and restrict the displacement. So within some limit, the strength of soil increases with the increase of fiber content, while excessive fiber content may lead to the decrease of M value. So there is a maximum fiber content that makes the strength highest. In current work, this fiber content

Table 4 The relation between M and fiber content

%	0	0.1	0.2	0.3	0.4	0.5	0.6
M	0.4	0.43	0.49	0.5	0.47	0.42	0.38

is 0.2–0.3 %. with the continual increase of fiber content, there may be direct contact between smooth surfaces of wheat straw fibers whose friction is less than that between fiber and soil particle or between particle and particle. This may be the reason why excessive fiber content may inversely lead to the decrease of soil in strength. The bonding of fiber to soil particle provides resistance against sliding and hence the fibers can bear tensile stresses. It is generally known that within some limits inclusion of fibers with tensile capacity into soils increases the strength of soils. The tensile strength of a fiber is limited to the adhesion/friction developed along the length of fiber and is a function of the length of fiber. The wheat straw fibers that were used in this study had a short length and they were like strips with smaller width and thickness compared to length, with smooth surface outside and rough surface inside. Yu et al. (2010) have used the similar wheat straw fiber in reinforcing salinized soil and the outcome has generally been an increase in strength within some limits. It can be said the addition of wheat straw fibers to clay in the present work leads to a composite soil. The strength of composite soil is usually increased by adding a percent of reinforcing material within some limits as shown by many researchers such as Leelanitkul (1989); Tan et al. (1994); Kumar and Wood (1999) and Wood and Kumar (2000). It is believed that no significant tensile strength could be developed in these fibers. It can be concluded that the interaction of these fibers with soil is not through additional tensile strength that can be developed along the length of long fiber, but through the addition of a stronger substance to the soil. This is evident from the test results as a modest amount of fiber (0.3 %) was required to be used in a soil to make a composite with maximum strength. This composite nature can lead to a modest change in the properties of the soil. As it was indicated the addition of fibers increases the void ratio of composite but with increasing the void ratio the shear strength increases. These findings are consistent with results that were presented by Vallejo and Mawby (2000). They indicated that for the mixture of granular material and clay the peak of shear strength increases with increasing the porosity. Therefore, in this composite the clay and fiber in the mixtures both control not only the porosity but the shear behavior as well. In order to evaluate the effects of wheat straw fibers on the strength of soil during undraind shearing, a strength ratio parameter, R_f, is introduced [similar to the parameter defined by Haeri et al. (2000) and Zhang et al. (2006) for granular soils reinforced with non-random reinforcing elements and Estabragh et al. (2011) for clayey soil reinforced with ramdomly distributed nylon] as:

$$R_f = \frac{(\sigma_1 - \sigma_3)_{rf}}{(\sigma_1 - \sigma_3)_f} \tag{2}$$

where $(\sigma_1 - \sigma_3)_{\mathrm{rf}}$ is deviator stress of reinforced soil at failure and $(\sigma_1 - \sigma_3)_{\mathrm{f}}$ is deviator stress of natural unreinforced soil at failure. Figure 9 shows the strength ratios for different confining pressures and different fiber contents calculated using this definition. The results indicate that in general the strength ratio decreases with increasing the confining pressure for the reinforced soil, but the rate of variation decreases from 300 to 400 kPa confining pressure. When fiber contents are 0.5 and 0.6 %, the strength ratio may be lower than 1, while the strength ratio of soil with 0.2–0.3 % fiber is maximum of all other contents. Therefore, it can be concluded that in general, the value R_f decreases with increasing cell pressure. Upon application of the confining pressure the fibers tend to go temporarily into compression. This compressional prestress has to be overcome by sufficient shear distribution and accompanying tensile elongation in the fibers before any shear strength increase would occur.

In general there are 3 types of triaxial shear tests: UU (unconsolidation undrain), CU (consolidation

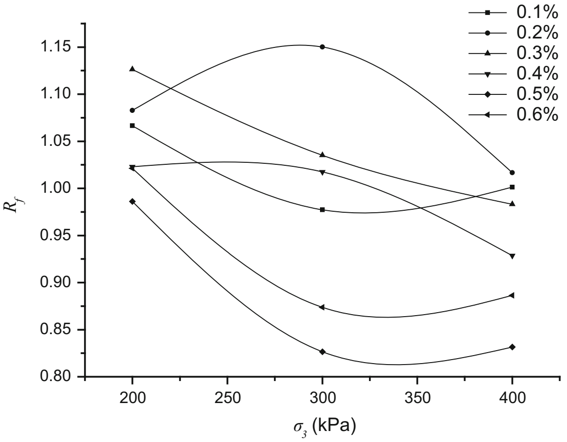

Fig. 9 Variation of strength ratio (R_f) versus confining pressure (σ_3) for soil with 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 % fiber

undrain), and CD (consolidation drain). In our study, we select CU test based on practical loading condition. CU test can be further divided into 2 stages: consolidation stage and compressive (shear) stage. Samples are firstly consolidated under predetermined even confining pressure (200, 300, 400 kPa respectively in this test), until pore water pressure mostly dissipated (above 95 %). In this stage, samples were evenly compressed in all directions, the volume strain was assumed as (delta V/V), while the delta V was just the volume of discharged water from samples, V the volume of samples. It should be said that the volume strain in this stage can be easily calculated because the delta V can be read from instrument. In the 2 stage, which is also our focus, we mainly concern the relationship among axial pressure, axial strain and water pressure because the volume change under undrained conditions was generally assumed to be zero (JTG E40-2007, "Test Methods of Soil for Highway Engineering" issued by Department of Transportation of PRC, 11 July 2007). Therefore in second stage, the axial strain was assumed to increase with the increase of axial pressure, while the volume strain was assumed to be zero, because on the one hand samples are compressed in axial direction, but on the other hand they are swelling in side direction. It should also be mentioned that samples used are completely saturated, and water and soil particles were also assumed to be incompressible. So to sum up, above assumption of unchanged sample volume under undrained condition may be plausible theoretically and reasonable realistically, just from which increasing axial strain and zero volume strain were derived.

The effect of wheat straw fiber-reinforced soil is mainly dependent on the frictional force between fibers and soil particles, which results in changes in stress and deformation of original soil body, so as to increase the strength of soil. Because wheat straw fibers are randomly distributed in soil matrix, the restrained space shaped by crookedly interweaved fibers holds back the displacement produced by soil stresses. Fibers in soil will shrink and curl as fiber-reinforced soil is consolidated. With the development of shear deformation in fiber-reinforced soil, some curved fibers (around shear face) slowly unfold and spread apart until they get back into shape completely when a certain amount of deformation has occurred in soil body, in this moment the fibers start to come into play, while their shapes change from curving to stretching. Natural wheat straw fibers have a certain amount of tensile strength and ductility. As soil body is under external forces, the fibers in soil will produce pressures and frictional forces to soil particles at the concave side of curved fibers, which can consolidate the soil. In addition, because the wheat straw fibers are randomly distributed in soil body, there are certainly a lot of interweaved points of fibers. As soil particles at crossing points are suffered from stresses, they tend to move, while the interweaved wheat fibers will prevent the soil particles from movements. Namely the deformation caused by stresses at any section of fiber may affect other interweaved wheat fibers in all directions, therefore forming a spatially restrained area of stresses to prevent soil movements.

The results of this study indicated that the addition of wheat straw fiber to clay soil can improve its mechanical behavior. The wheat straw fiber may be used in practice to stabilize the subgrades of roads and highways, to increase the stability of highway embankments. In practice, mixing of clay soil with wheat straw fiber in the field could be a problem because of high plasticity of clay soil. It is possible to reduce plasticity of clay by mixing it with lime which will allow the fibers to be more easily mixed into the soil. In this process the decrease in plasticity from the cation exchange of the calcium from lime with the clay minerals allows the fiber to be adequately mixed with clay soil. There is still contention about whether this stabilization technique is applicable to the field implementation. Freed (1990) and Grogan and Johnson (1994) showed that fibers can be successfully mixed with high-plasticity soil stabilized with lime and the mixing could be easy and the uniformity is possible. Since wheat straw fibers are naturally biodegradable after an enough period of time, it can be resulted that no pollution is caused by this technique of soil reinforcement.

5 Conclusion

The effects of wheat straw fiber reinforcement on clayey soil were studied by using results obtained from a series of one dimensional consolidation and CU triaxial tests. The following conclusions can be drawn from the results of this study.

(a) The inclusion of wheat straw fiber with small length and small percentage to Shanghai clayey soil resulted a composite material and the behavior of this composite is dependent on both the soil and the wheat fiber.

(b) The inclusion of wheat straw fibers has a significant effect on the consolidation characteristics of randomly reinforced Shanghai clayey soil. During consolidation, the mechanical properties of reinforced soil change with increasing the fiber content until an optimum content emerges that makes the strength of reinforced soil maximum. In the present work, this content is 0.2–0.3 % wheat fiber.

(c) Reinforcement using wheat straw fibers was found to restrain the volumetric dilation of soil and this leads to an increase of the excess pore water pressure in undrained conditions.

(d) Failure envelopes determined from CU triaxial tests indicate an increase in the effective shear strength of the soil with presence of fibers and there is also an optimum fiber of 0.2–0.3 % that make the effective shear strength of the soil maximum.

(e) The stiffness and shear strength of soil increase with increasing the fiber content. The friction angles in term of total stresses and effective stresses (ϕ and ϕ') also increase with fiber content until an optimum content (0.2–0.3 % fiber). In general, for an increase in fiber content, the increase in ϕ' is greater than the increase in ϕ. The slope of critical state line M is dependent of fiber content of reinforced soil.

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