Soils and Foundations 2012;52(2):228–238

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

Feasibility of saline soil reinforced with treated wheat straw and lime

Min Li[a,*], Shou Xi Chai[b], Hu Yuan Zhang[a], Hong Pu Du[c], Li Wei[b]

[a]*Key Laboratory of Mechanics on Disaster and Environment in Western China, Lanzhou University, Ministry of Education, Lanzhou 730000, China*
[b]*Tianjin Key Laboratory of Soft Soil Characteristics and Engineering Environment, Tianjin Institute of Urban Construction, Tianjin 300384, China*
[c]*College of Civil Engineering, Hebei University of Technology, Tianjin 300401, China*

Available online 22 March 2012

Abstract

Saline soils in inshore areas have characteristics that are problematic to engineering such as salt expansion, dissolution and water absorption; therefore, these soils cannot meet the requirements of strength and anti-deformation in construction. A method of reinforcing saline soil with wheat straw and lime was investigated in this study. Specifically, the feasibility of using wheat straw treated with an SH (modified polyvinyl alcohol) agent as reinforcement and the compaction and strength of saline soil reinforced with wheat straw and lime were investigated. The results indicated that wheat straw treated with SH agent is suitable for use as a reinforced material owing to its higher corrosion resistance, tensile force and elongation. Additionally, reinforcement with wheat straw and lime was found to have a positive effect on the mechanical properties of soil. Reinforcement with wheat straw fiber enhanced the strength of soil during the early curing period and reduced the brittle failure problem associated with lime soil. Reinforcing soil with wheat straw and lime is an effective method for improving soil in the geotechnical field.

Keywords: Reinforced soil; Anticorrosion; Maximum tension; Maximum elongation; Compaction; Strength; Wheat straw; SH agent; Lime; Saline soil

1. Introduction

Chlorine saline soil is widely distributed on the surface of soil in Bohai Bay and Southeast coastal areas of China. Saline soils are composed of air, crystallized salt grains, soil grains and salt solution, which results in engineering problems, such as salt expansion, dissolution and water absorption (Szabolcs, 1989). Accordingly, it cannot meet the requirements for strength and anti-deformation for use in construction without treatment (China Standard GB 50021, 2001). Therefore, it is necessary to improve the load bearing capacity of saline soil through ground improvement techniques such as reinforcement, cushioning, admixtures, grouting, compaction, and dewatering.

Lime is commonly used to change the properties of soils due to its more stable performance, lower prices and abundance (Rajasekaran and Rao, 1997). Lime is most effective for treating soils capable of holding large amounts of water (Kamal uddin and Buensuceso, 2002). However, soils treated with lime are subject to brittleness (Kavak and Akyarlı, 2007; Ninov and Donchev, 2008). Therefore, it is better to amend with the technique of reinforcement (Ziegler et al., 1998; Ranjan et al., 1996, Yetimoglu and Salbas, 2003).

In China, plant fiber materials such as wheat straw, reeds, hemp, grass, bamboo chips and willow branches have historically been used as additives in soil buildings (Li, 2006). For example, the Rammed Residence, Ancient Great Wall, Mogao Grottoes Mural, and Hakkas Earth Buildings were all constructed with soils that had been reinforced with plant materials (Fig. 1) (Xie, 2004; Zhang et al., 2008). Furthermore,

*Corresponding author. Tel.: +13919965868.
E-mail addresses: limin-0409@163.com (M. Li), chaishouxi@163.com (S. Xi Chai), zhanghuyuan@lzu.edu.cn (H. Yuan Zhang), d_hongpu@163.com (H. Pu Du), weili_79@126.com (L. Wei).

Peer review under responsibility of The Japanese Geotechnical Society
doi:10.1016/j.sandf.2012.02.003

Production and hosting by Elsevier

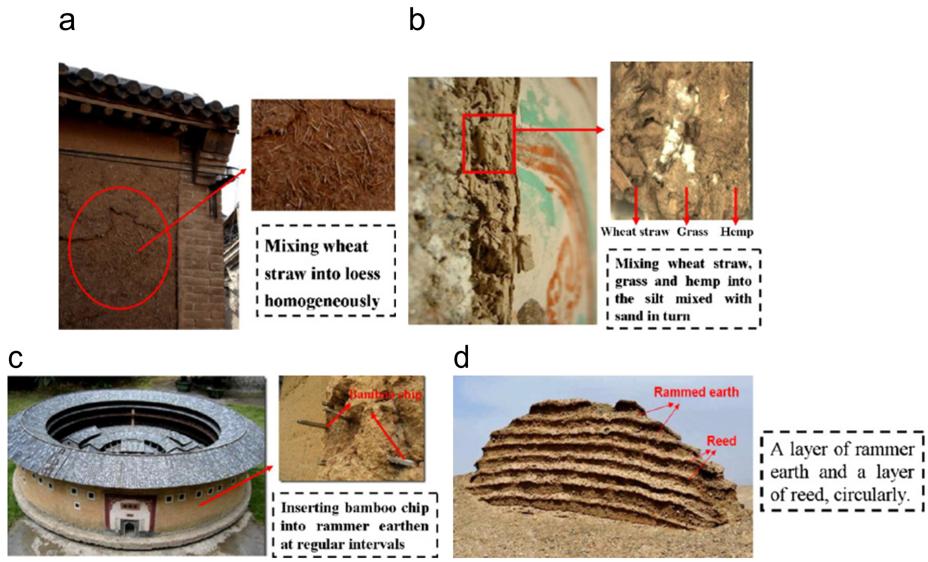

Fig. 1. Traditional buildings constructed of reinforced soil. (a) Rammed Residence, (b) Mogao Grottoes Mural, (c) Hakkas Earth Buildings, (d) Han Great Wall.

Table 1
Physical properties of saline soil.

Specific gravity	Consistency index			Compaction test		Granulometric distribution (%)		
	Liquid limit (%)	Plastic limit (%)	Plasticity index	Maximum dry density (g cm^{-3})	Optimum moisture content (%)	0.074–0.038 (mm)	0.038–0.005 (mm)	≤0.005 (mm)
2.72	32.6	16.8	15.8	1.81	17.7	22.7	56.6	20.7

the reinforcement of soils with natural fibers such as roots, sisal, coir, and palm has recently received a great deal of attention (Ramanatha Ayyar et al., 1988; Mandal and Murti, 1989; De Baets et al., 2008; Prabhakara and Sridhar, 2002; Marandi et al., 2008; Sivakumar Babu and Vasudevan, 2008). The soils that are treated with fibers include loess, sand, silt, and some consolidated soil.

Wheat straw is an agricultural waste that is produced in high volumes every year. Owing to its low cost, good mechanics and environmentally friendly nature, there is great potential for the use of wheat straw and lime to reinforce saline soil. To evaluate the feasibility of using wheat straw to reinforce saline soil, a series of experiments were conducted to investigate the anticorrosion features of wheat straw treated with SH agent. In addition, the effectiveness of reinforcing soil with a combination of wheat straw and lime was verified by comparing the compaction characteristics, compressive strength, shear strength and failure pattern of soils subjected to different treatments.

2. Materials and methods

2.1. Materials

2.1.1. Soil

The soil (chlorine saline soil) used in this investigation was collected from Tianjin coastal areas and had a salt content of 2.64%. The specific gravity, consistency, particle grading, maximum dry density and optimum moisture content of the soil used in this study are presented in Table 1. The soil was air dried, sieved (2 mm) and set aside until use.

2.1.2. Wheat straw fibers

Wheat straw fibers were obtained from a farm in Xiqing District, Tianjin. The fibers were subjected to the following pretreatment steps: (i) air drying to remove moisture; (ii) selection of a homogenous group of fibers with a uniform thickness; (iii) removing the surface leaves; (iv) cutting to the same length (5 cm) and labeling.

Celluloses, hemicelluloses and lignin are the major chemical constituents of wheat straw, and its total inorganic content is only about 15%. As shown in Fig. 2, a cross section of raw wheat straw has a honeycomb pattern with evenly distributed pores. The physical and mechanical properties of raw wheat straw are shown in Table 2.

2.1.3. SH agent

The SH agent (modified polyvinyl alcohol) is a novel water-soluble polymer material developed by the Lanzhou University. The agent is composed of a hydrophobic C–C bond based macromolecular main chain, with hydrophilic components such as hydroxyl and carboxyl groups. The SH agent is non-toxic, environmentally friendly and has

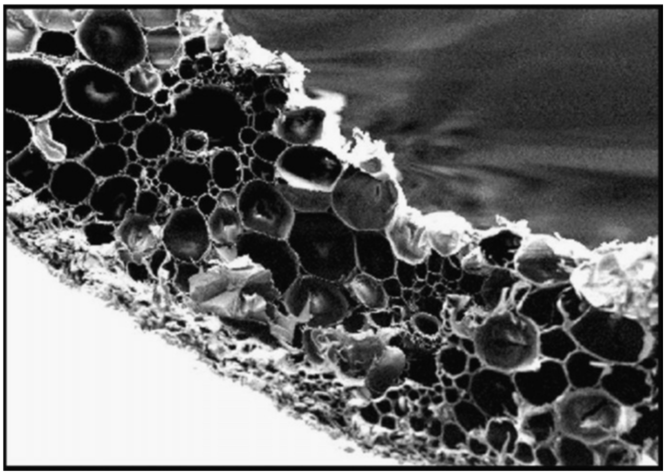

Fig. 2. Cross section of raw wheat straw.

Table 2
Physical and mechanical properties of raw wheat straw.

SL. no.	Properties	Values
1	Average diameter	2–3 mm
2	Whole length	50–70 mm
3	Wall thickness	0.498–0.665 mm
4	Maximum tensile strength	53 N
5	Maximum elongation	1.13%

Table 3
Properties of SH agent.

SL. no.	Properties	Values
1	Solid content	6%
2	Density	1.09 g/cm
3	Molecular weight	> 20000
4	Character	Colorless, transparent, liquid
5	Viscosity	Low
6	Cost	800 RMB/ton

low viscosity; therefore, it has been used in the field of sand fixation, loess solidification and saline soil improvement. It had been confirmed that coating soil particles with an SH membrane produces stronger elasticity and aging resistance (Wang et al., 2003). In addition, the solidified membrane formed by the SH agent can effectively improve the stability and anticorrosivity of treated materials (Wang et al., 2005; Chai et al., 2007). Properties of SH agent are shown in Table 3.

2.1.4. Lime

The bagged lime powder used in study was directly purchased from lime plants in Tianjin, China. The properties of the lime powder used in this study are shown in Table 4. Prior to use, all lime was sieved (2 mm) to remove impurities.

Table 4
Characteristics of lime used in this study.

SL. no.	Properties	Values
1	Available calcium and magnesium content	82%
2	No digestion residue (residue weight after 5 mm screen)	5%
3	Water content	2%
4	CO_2 content	6%

Fig. 3. CMT 6104 electrical universal material machine.

2.2. Methods

The test site was located at the Tianjin Key Laboratory of Soft Soil Characteristics and Engineering Environment, Tianjin Institute of Urban Construction, China. The experiment was composed of two parts: an investigation of the anticorrosion of wheat straw treated with SH agent, and the compaction and strength characteristics of soil reinforced with wheat straw fiber and lime.

2.2.1. Anticorrosion test of wheat straw

According to the section regarding wood preservation and wood preservatives in the British Standard Code of Practice for Preservation of timber (British Standard BS 5589, 1989), anticorrosion agents must be safe, widely available and durable. The SH agent is non-toxic and environmentally friendly, and wheat straw is an agricultural waste; therefore, this reinforced material is investigated based on its (i) permeability, (ii) water absorption, (iii) mechanics (maximum tensile force and elongation) and (iv) microstructure.

The samples investigated herein included raw wheat straw, wheat straw soaked in water for varying lengths of time, wheat straw soaked in the SH agent for varying lengths of time and wheat straw treated with the SH agent soaked in water for different lengths of time. The mechanical properties (maximum tension and maximum elongation) were measured with the aid of the SANS CMT 6104 material testing machine (Fig. 3) from MTS Co. (Shenzhen, China) at RT and a strain rate of 10^{-2} N/S. CMT 6104 electrical universal material machine is suitable for experiments like tensile, compression and bending on nonmetal materials, and its main specifications include a maximum force of 10 kN, an effective tensile space of 700 mm and a valid test width of 340 mm.

2.2.2. *Tests of reinforced soil*

Sisal fiber was applied as a reinforcement material at percentages of 0.25, 0.50, 0.75 and 1.00% of the weight of the soil and lengths of 10, 15, 20 and 25 mm. Maximum cohesion was observed when the fiber was applied at 0.75% and 20 mm to a 102 mm diameter sample (Prabhakara and Sridhar, 2002). An optimum coir fiber content of 1.00% (by weight) was recommended to strengthen black cotton soil (Ramesh et al., 2010). Additionally, palm-fiber contents of 0.25, 0.50, 0.75, 1.00, 1.50, 2.00 and 2.50% and lengths of 20 and 40 mm were applied to a 50 mm diameter specimen and the soil strength improved as the fiber length increased, with the peak strength occurring at a fiber ratio of 2.00–2.50% and a fiber length of 40 mm (Marandi et al., 2008). In addition, preliminary pilot experiments indicated that the maximum compression strength of soil reinforced with wheat straw was observed when fibers 10–20 mm long were applied to a 50 mm diameter sample at 0.20–0.30%.

Based on these findings, five different lengths of fiber (30, 40, 50, 60 and 70 mm) were selected for the compaction and unconfined compression strength test (152 mm diameter sample), while fibers 15, 20 and 25 mm long were used for the triaxial test (61.8 mm diameter sample). Fibers of each length were added to the soil at 0.20, 0.25 and 0.30%.

This study primarily investigated the effects of (a) reinforced length, (b) reinforced ratio and (c) curing time on (i) compaction, (ii) compression strength, and (iii) shear strength of the soil. To provide an accurate comparison, all experiments included an un-reinforced soil specimen as a control.

2.2.2.1. Compaction test. The compaction test was conducted using cylindrical specimens prepared by the heavy compaction method. Each sample was prepared by mixing soil and corresponding fibers, and then weighed to an accuracy of 0.01 g. To ensure uniformity, samples were compacted in five layers. The optimum moisture content and maximum dry density were then determined. In addition, the water content was measured using the oven drying method according to the Standard Soil Test Method (China Standard GB/T 50123, 1999). For this study, the drying temperature was controlled at 65 °C based on the characteristics of wheat straw and the SH membrane. A DJ standard electric compaction apparatus produced by Nanjing Soil Instrument Factory was used in this test (hammer weight of 4.5 kg and falling distance of 457 mm). The sample had a diameter of 152 mm and a height of 116 mm.

2.2.2.2. Unconfined compressive strength test. A compression strength test was conducted using an improved CBR apparatus at a strain rate of 0.10 mm/min using a load cell of 10 kN. The disturbed soil specimens with and without reinforced materials were prepared by heavy compaction and the amount of fiber added was equal to that in the compaction test. Furthermore, to enable a discussion of the effects of the SH agent treatment on the mechanical properties of the reinforced soil, the compressive strength of (a) reinforced soil with wheat straw treated with the SH agent, (b) reinforced soil with raw wheat straw, and (c) lime soil in (i) the soaking water condition and (ii) un-soaking water condition were compared. All tests were conducted using a 0.25% reinforced ratio and length of 10 mm in a 50 mm diameter sample.

2.2.2.3. Unconsolidated and un-drained triaxial test. Unconsolidated and un-drained triaxial tests were conducted using a SJ-1A.G desktop triaxial shear apparatus at a strain rate of 0.828 mm/min and confining pressures (σ_3) of 100, 200, 300 and 400 kPa. Soil specimens with and without wheat straw were prepared by the standard static compaction method, and samples were compacted in three layers to ensure uniformity. The cylindrical specimens were 61.8 mm in diameter and 125 mm in length.

3. Results and discussion

3.1. *Feasibility of using treated wheat straw as reinforced material*

3.1.1. *Permeability of SH agent on wheat straw*

The weight variation (Fig. 4) and microstructure of wheat straw soaked in the SH agent for different lengths of time (Fig. 5) are considered in this evaluation. The weight variation is the ratio of the weight of the SH agent adsorbed over the weight of air-dried wheat straw, and the equation can be expressed as follows:

$$w_v = \frac{m_i - m_0}{m_0} \times 100$$

where w_v is the weight variation (%); m_0 is the weight of untreated wheat straw (g); m_i is the weight of wheat straw soaked in SH agent for different lengths of time (g).

The SH agent can easily permeate wheat straw, attach to the surfaces and then fill its pores. The absorption rate showed a rapid increasing trend during the first three days and then slowed. The adsorption equilibrium time was seven days. However, from the construction and technology perspective, it is better to use wheat straw that has been soaked in the SH agent for three days as the

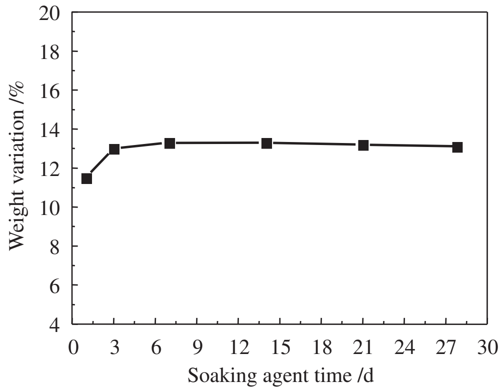

Fig. 4. Weight variation curve of wheat straw vs. soaking time.

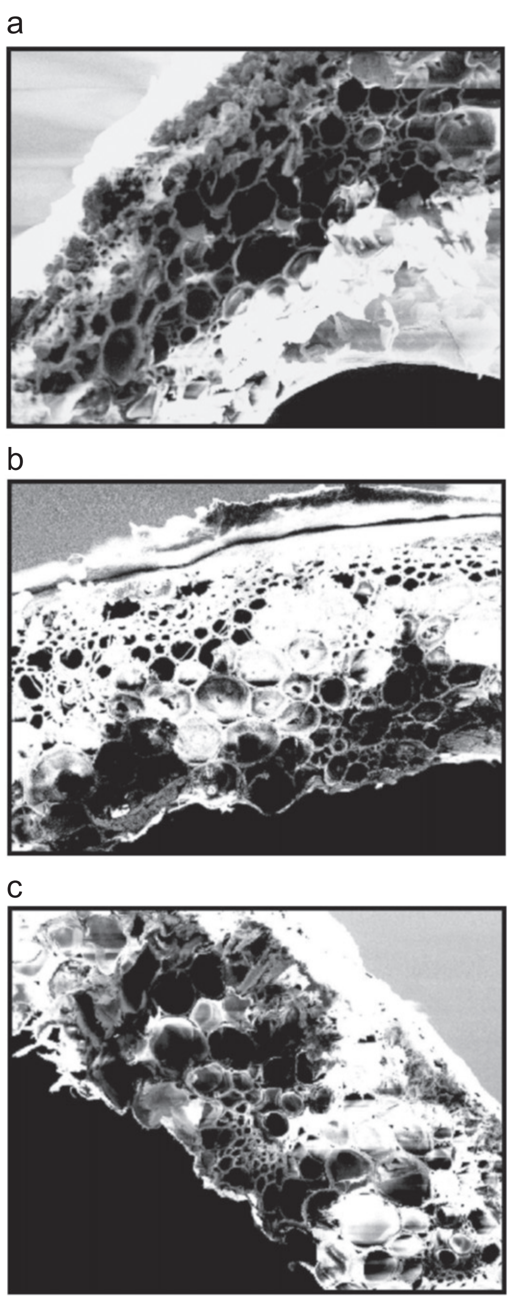

Fig. 5. SEM of wheat straw soaked in SH agent for different lengths of time (× 500). (a) 3 days, (b) 7 days, (c) 28 days.

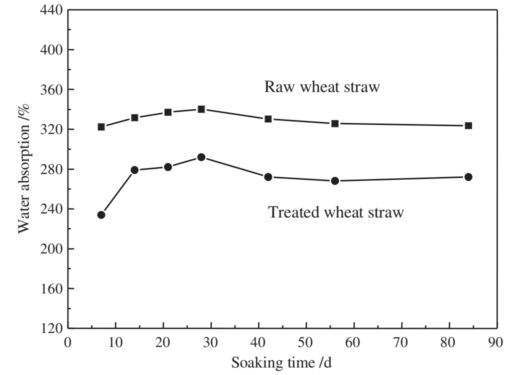

Fig. 6. Water absorption by raw wheat straw and treated wheat straw.

reinforced material because there is a little weight variation between straw soaked for three and seven days (Fig. 4).

3.1.2. *Effects of the SH membrane on the water absorption of wheat straw*

Wheat straw soaked in the agent for three days was selected for subsequent testing (Fig. 4). The water absorption of raw wheat straw and treated wheat straw and SEM photos taken after soaking in water for 28 days and 56 days were compared (Figs. 6 and 7). The results revealed that the attachment of the SH membrane was irreversible, and that the filling and coating function of the SH membrane effectively decreased the infiltration of water, as indicated by the water absorption of treated wheat straw being less than that of raw wheat straw. Therefore, the SH membrane plays a positive role in the water resistance of wheat straw, even when it is fully immersed.

3.1.3. *Effects of SH agent on the mechanics of wheat straw*

The maximum tensile force and elongation of raw wheat straw is 63–68 kN and 1.24–1.38%, respectively, and these factors are consistent with each other. The use of raw wheat straw as a reinforcing material has been well documented based on the intact remains of historical sites. Therefore, as long as the mechanics of wheat straw treated in soaked water are greater than those of raw wheat straw, the use of treated wheat straw as a reinforcing material is advantageous.

The maximum tensile force and elongation of wheat straw (i) directly soaked in water and (ii) treated with SH agent for three days and then soaked in water were compared (Figs. 8 and 9).

The maximum tensile force and elongation of wheat straw declined linearly as the water soaking time increased, with values of 43 N and 0.80%, respectively, being observed after soaking for four weeks. However, the tensile force and elongation of wheat straw treated with the SH agent for three days changed only slightly with soaking time, with a slight decrease occurring initially and then leveling off at 71.2 N and 1.52%, respectively. Based on these findings, treated wheat straw can meet the

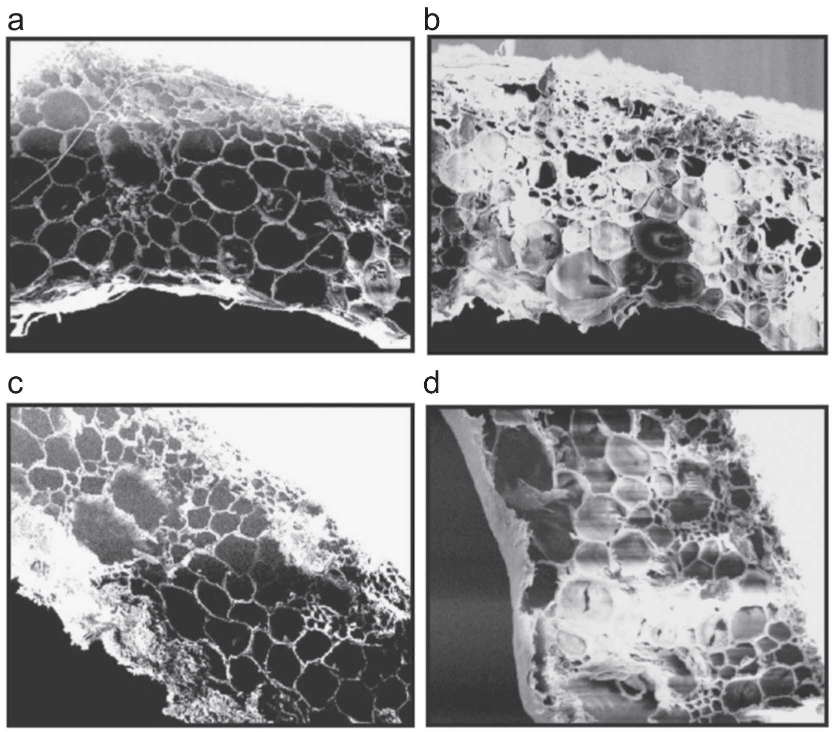

Fig. 7. SEM photos of raw wheat straw and treated wheat straw after soaking in water for different lengths of time. (a) SEM photos of raw wheat straw after immersion in water for 28 days, (b) SEM photos of treated wheat straw after immersion in water for 28 days, (c) SEM photos of raw wheat straw after immersion in water for 56 days, (d) SEM photos of treated wheat straw after immersion in water for 56 days.

Fig. 8. Tensile force variation curves of wheat straw subject to different conditions.

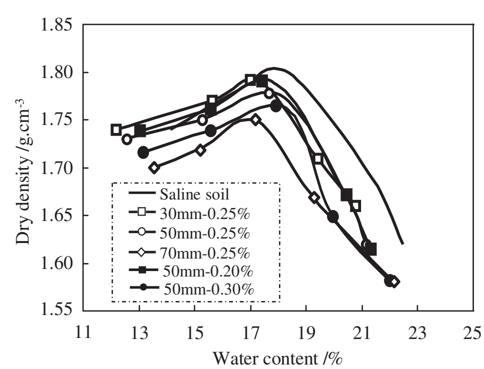

Fig. 10. Compacting curve of saline soil and reinforced soil.

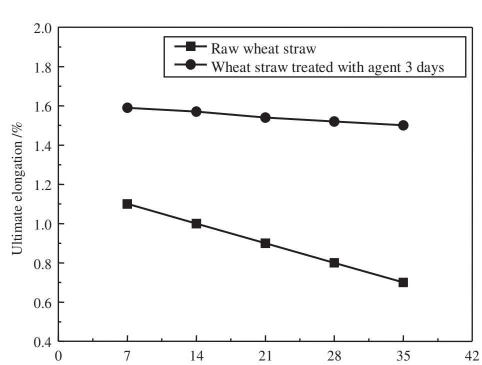

Fig. 9. Elongation variation curves of wheat straw under different conditions.

mechanical requirements for construction, even in higher water content condition.

3.2. Compaction characteristics

The variation in compaction curves for reinforced soil was similar to that of un-reinforced samples (Fig. 10). For all samples, the dry density increased as the water content increased, but beyond the optimum moisture content the opposite occurred.

Dry density decreased as the reinforced length increased for all reinforced ratios (Fig. 10). The maximum dry density of soil reinforced with 30 mm wheat ranged from 1.77 to 1.81 g/cm^3, while that of soil reinforced with 70 mm

Table 5
Maximum dry density and optimum water content.

Reinforced condition	Maximum dry density ($g\,cm^{-3}$)	Optimum water content (%)
Saline soil	1.81	17.7
30 mm–0.20%	1.81	17.8
30 mm–0.25%	1.79	17.2
30 mm–0.30%	1.77	17.4
40 mm–0.20%	1.80	17.1
40 mm–0.25%	1.78	17.4
40 mm–0.30%	1.77	17.5
50 mm–0.20%	1.79	17.5
50 mm–0.25%	1.78	17.6
50 mm–0.30%	1.76	17.7
60 mm–0.20%	1.78	17.4
60 mm–0.25%	1.77	17.5
60 mm–0.30%	1.76	17.6
70 mm–0.20%	1.76	17.2
70 mm–0.25%	1.75	17.3
70 mm–0.30%	1.74	17.4

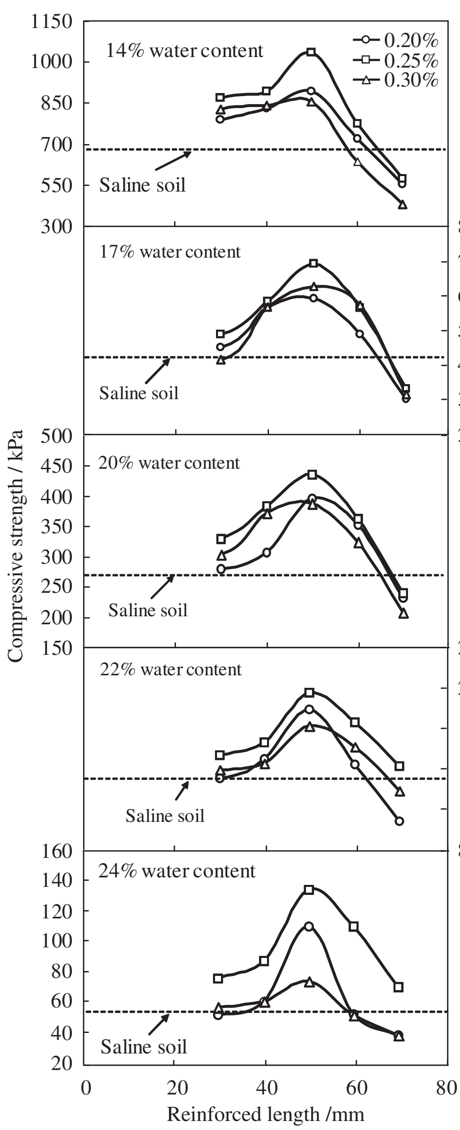

Fig. 11. Compressive strength of reinforced soil.

wheat was the lowest (1.74–1.76 g/cm^3). As shown in Table 5, the maximum dry density of reinforced soil decreased by nearly 3.87% when compared to that of un-reinforced soil (1.81 g/cm^3).

The increase in the reinforced ratio also caused a reduction in dry density (Table 5). For example, soil reinforced with 50 mm wheat showed a decrease in the maximum dry density from 1.79 g/cm^3 in the 0.20% ratio samples to 1.76 g/cm^3 in the 0.30% ratio samples.

Generally speaking, reinforcement primarily affects the maximum dry density, but has little effect on the optimum water content. The following factors are responsible for this phenomenon: (i) the friction between soil particles and wheat straw can prevent the approach among soil particles and then reduce the average unit weight, and (ii) the momentary action of compaction can only remove air from the soil body.

3.3. Compressive strength test

The results of compressive strengths of saline soil and reinforced soil with different water contents are shown in Fig. 11. Compressive strength can be effectively improved by reinforcement. The compressive strength of saline soil and reinforced soil decreased as the water content increased. The values observed for water contents of 14, 17, 20, 22 and 24% were 688.2, 439.2, 280.6, 137.6 and 48.4 kPa, respectively, for untreated saline soil, but it is 1037.0, 693.0, 437.0, 196.4 and 134.2 kPa, respectively, for reinforced soil (50 mm length and 0.25% ratio).

The length of the straw used to reinforce the soil has a great influence on the compressive strength of the soil. The improvement in response to treatment increases until a length of 50 mm is reached, after which the strength decreases. The reinforced ratio also plays a significant role on the improvement of compressive strength, which increased until a ratio of 0.25% was reached. Owing to the smooth surface of wheat straw, the integrity of reinforced soil decreased as the length and ratio of added wheat increased in excess of a range.

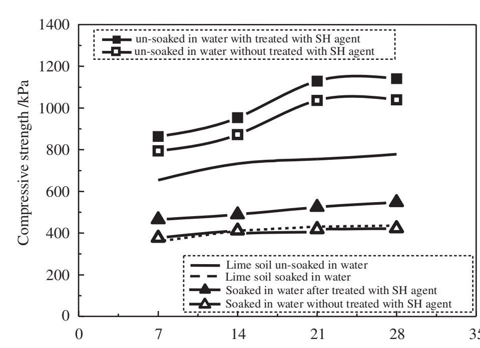

Fig. 12. Compressive strength of lime soil and lime soil reinforced with treated and untreated straw under soaked and un-soaked water conditions.

Based on these findings, the optimum conditions were a length of 50 mm and a ratio of 0.25% for samples 152 mm in diameter.

The effects of SH treatment on the mechanical properties are shown in Fig. 12. The strength of lime soil reinforced with straw that had been treated with SH was greater than that of lime soil reinforced with untreated wheat straw. Under soaking water conditions, the compressive strength of lime soil reinforced with untreated fiber was nearly equal to that of lime soil. These findings indicate that the reinforcement of untreated wheat straw will be invalid after soaking in water. However, the compressive strength of reinforced lime soil containing treated fiber was higher than that of lime soil, regardless of the soaking conditions. Taken together, these findings indicate that wheat straw treatment can work well, even under high water content conditions.

3.4. Shear strength test

3.4.1. Saline soil and soil reinforced with wheat straw

Varying the reinforced length and ratio can greatly improve the shear strength of the soil. The cohesion (C) and internal friction angle (φ) of saline soil and reinforced soil are shown in Fig. 13 and Fig. 14, respectively. The trend regarding cohesion presents a parabola as the length and the ratio increase. The peak corresponds to a length of 20 mm and a ratio of 0.25% (61.8 mm diameter sample). The maximum cohesion was 43 kPa, which is 1.86 times greater than that of saline soil.

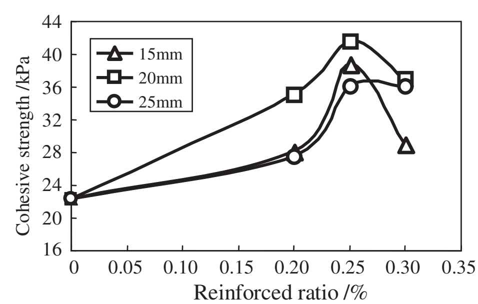

Fig. 13. Cohesive strength of saline soil and reinforced soil under different conditions.

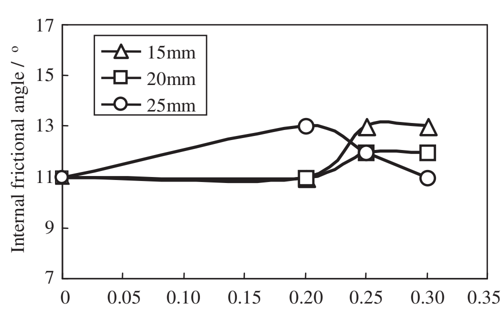

Fig. 14. Internal frictional angle of saline soil and reinforced soil under different conditions.

There was not much variation in the internal fraction angle, which ranged from 11° to 13°. It is generally agreed that reinforcement does not have an obvious influence on the angle of shearing resistance (Prabhakara and Sridhar, 2002; Ramesh et al., 2010).

The improvement of cohesion caused by reinforcement was primarily a result of the additional confining pressure produced by the friction between wheat straw fibers and soil particles. The confining pressure of un-reinforced soil was (σ_3), but that of the reinforced soil was ($\sigma_3+\Delta\sigma_3$). The stronger the fiber tension is the higher $\Delta\sigma_3$ will be.

Comparison of Figs. 11 and 13 reveals that fiber length has an obvious effect on soil strength. The optimum fiber length is closely related to the sample size, especially the diameter. Within a certain length scope, longer reinforced materials have a greater contact area and greater friction between soil and reinforced materials, which results in a higher strength. However, once the length is beyond a certain range, as the length increases, the reinforced material overlaps easily, and then has an adverse effect on the structural integrity. Based on the compressive strength (50 mm in length to 152 mm in diameter) and shear strength (20 mm in length to 61.8 mm in diameter) tests, the optimum reinforced length is about one-third of the sample diameter.

The general trend of stress–strain curves of reinforced soil was similar to those of saline soil, and all soils showed strain hardening behavior (Figs. 15 and 16). However, the shear stress of the reinforced soil was higher than that of un-reinforced soil, as was the strain corresponding to the maximum shear strength.

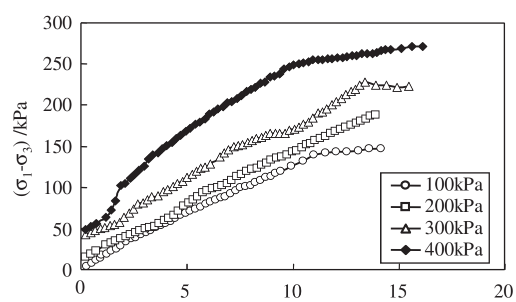

Fig. 15. Stress–strain curves of saline soil.

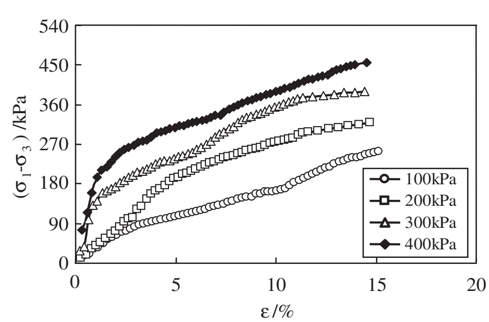

Fig. 16. Stress–strain curves of reinforced soil.

3.4.2. Lime soil and reinforced lime soil with wheat straw

The cohesion of lime soil and reinforced lime soil increases as the curing-day increases, but the change in the internal fraction angle is not as strongly correlated with curing-day (Figs. 17 and 18). The effect of length and ratio on reinforced lime soil is concordant with that of reinforced saline soil, and the optimum reinforced condition is also wheat straw with a length of 20 mm at a ratio of 0.25% (61.8 mm diameter sample). The cohesion of reinforced lime soil at curing-day 21 was found to be 1.23 times greater than that of lime soil and 8.34 times that of saline soil.

The reinforcement function of wheat straw is more obvious in the early curing period (Fig. 17). Reinforced materials will help improve the strength of soil in the early stage, and be good for the soil stability.

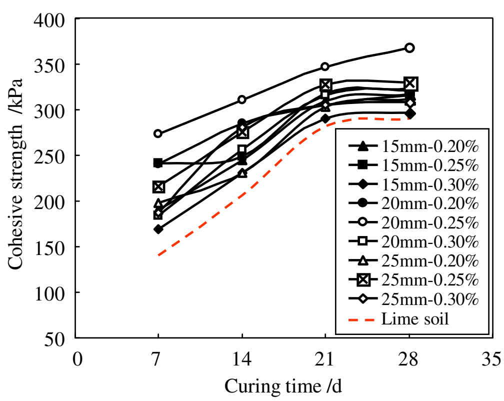

Fig. 17. Cohesive strength of reinforced soil vs. curing time.

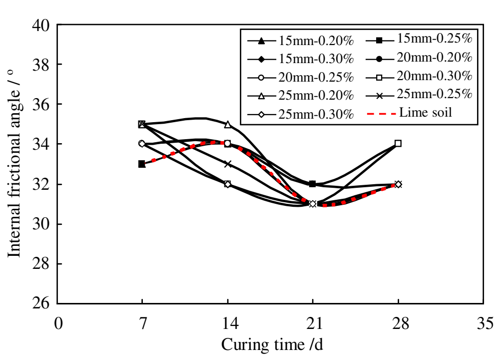

Fig. 18. Internal frictional angle of reinforced soil vs. curing time.

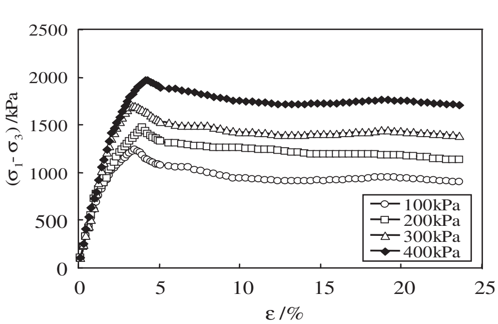

Fig. 19. Stress–strain curves of lime soil (21d).

Lime soil (curing-day 21) shows strain softening behavior (Fig. 19), but strain hardening was observed in reinforced lime soil (curing-day 21) (Fig. 20). Wheat straw fiber enhances the plasticity of lime soil. The stress–strain curves of lime soil and reinforced lime soil approached each other at the beginning of the curing period, and then gradually grew apart. These findings confirm that reinforcement does occur until a higher strain is reached.

3.5. Failure pattern

Saline soil displays plastic failure, in which a typical swelling morphology that is larger in the middle and smaller at both ends is observed (Fig. 21). A pattern of plastic failure was also observed in saline soil reinforced with wheat straw. However, the lateral deformation of reinforced soil is much lower than that of saline soil (Fig. 22). These findings further demonstrate that reinforcement of wheat straw can offer additional confined pressure ($\Delta\sigma_3$) to a soil sample. The tensile strength of wheat straw will be mobilized and work together with soil particles under certain loads.

Lime-soil showed plastic failure, and there were many micro-cracks on the surface during the early curing period; however, brittleness and a crack of $45^\circ+\varphi/2$ were observed in the later period. In addition, as the curing-day increased, the failure pattern varied from multiple cracks to one crack (Fig. 23). This phenomenon also occurred in

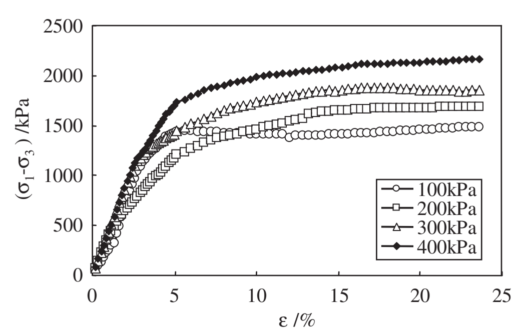

Fig. 20. Stress–strain curves of reinforced lime soil (21d).

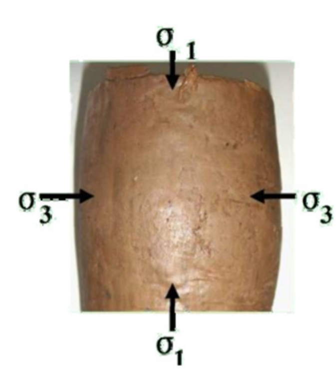

Fig. 21. Failure pattern of saline soil.

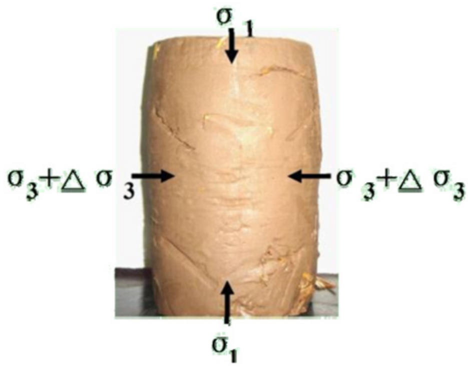

Fig. 22. Failure pattern of saline soil reinforced with wheat straw.

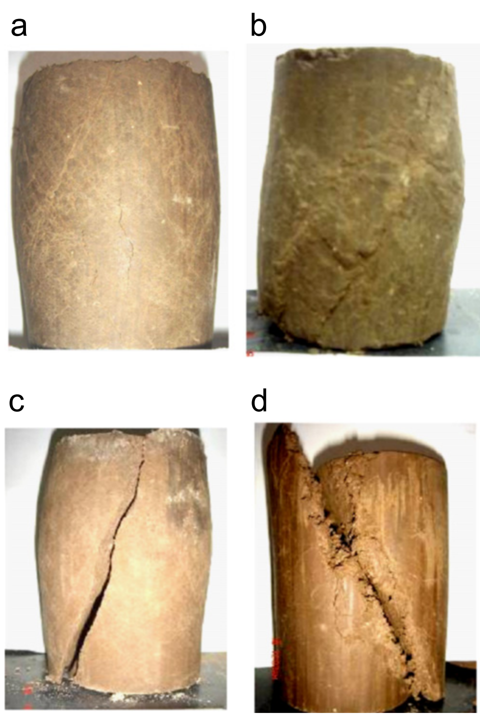

Fig. 23. Failure pattern of lime-soil. (a) curing-day 7, (b) curing-day 14, (c) curing-day 21, (d) curing-day 28.

lime soil reinforced with wheat straw (Fig. 24), but the fractures in its surface were more irregular.

The addition of lime to saline soil in the presence of water initiates several reactions. The primary reactions, cation exchange, flocculation–agglomeration and carbonation occur and produce improvements in soil plasticity, strength, and deformation properties (Diamond and Kinter, 1965). The effects of lime treatment or stabilization on pertinent soil properties can be classified as immediate and long-term. Immediate modification effects are of interest primarily during the construction stage. These effects are attributed to the cation exchange and flocculation–agglomeration reactions. Long-term stabilization effects are important from a strength and durability standpoint. These effects are generated to an extent by cation exchange and flocculation–agglomeration, and are

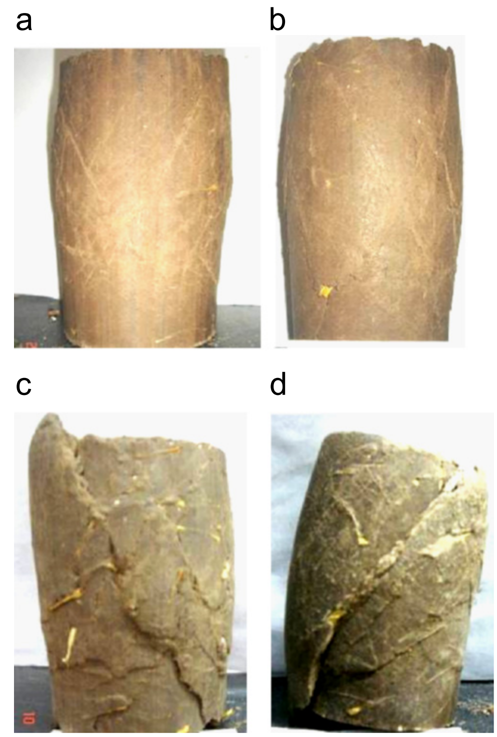

Fig. 24. Failure pattern of lime-soil reinforced with wheat straw. (a) curing-day 7, (b) curing-day 14, (c) curing-day 21, (d) curing-day 28.

primarily the result of carbonation. Accordingly, the reduction in PI is associated with curing time.

Figs. 23 and 24 show a comparison of lime soil and lime soil reinforced with wheat straw. The results demonstrate that combined physical and chemical treatment can improve the strength and anti-deformation of soil, as well as overcome the brittleness associated with lime soil.

4. Conclusions

Based on the experiments conducted to investigate the anticorrosion of wheat straw treated with an SH agent and the influence of wheat straw fiber inclusion on the compaction and strength behavior of soil under various test conditions, the following conclusions can be drawn:

Wheat straw treated with the SH agent showed better anticorrosion performance and higher maximum tensile and elongation; therefore, it is suitable for use to reinforce soil, even under high water content conditions.

The reinforcements have a remarkable influence on dry density, but little effect on water content. In the light of the results of strength tests conducted on samples of different dimensions, the optimum reinforcement is application of wheat straw with a length of 50 mm at a ratio of 0.25% to 152 mm diameter samples and 20 mm at a ratio of 0.25% to 61.8 mm diameter samples. The fiber length should be one-third of the diameter of the sample and applied at a ratio of 0.25%.

Saline soil reinforced with wheat straw and lime showed enhanced strength during the early curing period and was not subject to the brittle failure problem commonly associated with lime-soil. Overall, these findings indicate that reinforcement with wheat straw fiber treated with the SH agent and lime is an effective treatment of saline soil.

The mechanics of reinforcement with wheat straw and lime lie in the friction between wheat straw and soil particles and the carbonation of lime. Accordingly, there is great potential for reinforcing soil using a combination of fiber and chemical treatment.

Acknowledgments

This project was supported by the National Natural Science Foundation of China (Grant no. 41140024) and the Tianjin City High School Science & Technology Planning Foundation (Grant no. 20090901). The authors are grateful to the Key Laboratory of Mechanics on Disaster and Environment in Western China of Lanzhou University and Tianjin Key Laboratory of Soft Soil Characteristics and Engineering Environment of Tianjin Institute of Urban Construction for their support.

References

British Standard BS 5589, 1989. Code of Practice for Preservation of Timber. British Standards Institute.

Chai, S.X., Wang, P., Han, W.F., Li, F., Wei, L., Wang, X.Y., 2007. Research on strength and microstructure feature of solidified saline soil in inshore with polymer. Rock and Soil Mechanics 28 (6), 1067–1072.

China Standard GB 50021, 2001. Code for Investigation of Geotechnical Engineering. China Architecture & Building Press.

China Standard GB/T 50123, 1999. Standard for Soil Test Method. China Planning Press.

De Baets, S., Poesen, J., Reubens, B., Wemans, K., De Baerdemaeker, J., Muys, J., 2008. Root tensile strength and root distribution of typical mediterranean plant species and their contribution to soil shear strength. Plant Soil 305 (1–2), 207–226.

Diamond, S., Kinter, E.B., 1965. Mechanisms of soil-lime stabilization. Highway Research Record 92, 83–102.

Kamal uddin, M., Buensuceso, B.R., 2002. Lime treated clay: salient engineering properties and a conceptual model. Soil and Foundations 42 (5), 79–89.

Kavak, A., Akyarlı, A., 2007. A field application for lime stabilization. A Field Application for Lime Stabilization 15 (6), 987–997.

Li, Z., 2006. Shapes and Technology of Traditional Chinese Architecture. Tongji University Electronic Audio and Video Press, Shanghai.

Mandal, J.N., Murti, M.V.R., 1989. Potential for use of natural fibers in geotextile engineering. In: Proceedings of the International Workshop on Geotextiles. Bangalore, India, pp. 251–254.

Marandi, S.M., Bagheripour, M.H., Rahgozar, R., Zare, H., 2008. Strength and ductility of randomly distributed palm fibers reinforced silty-sand soils. American Journal of Applied Sciences 5 (3), 209–220.

Ninov, J., Donchev, I., 2008. Lime stabilization of clay from the 'Mirkovo' deposit. Journal of Thermal Analysis and Calorimetry 19 (2), 487–490.

Prabhakara, J., Sridhar, R.S., 2002. Effect of random inclusion of sisal fibre on strength behaviour of soil. Construction and Building Materials 16, 123–131.

Rajasekaran, G., Rao, S.N., 1997. Lime stabilization technique for the improvement of marine clay. Soil and Foundations 37 (2), 97–104.

Ramanatha Ayyar, T.S., Joseph, J., Beena, K.S., 1988. Bearing capacity of sand reinforced with coir rope. In: Proceedings of the First Indian Geotextiles Conference on Reinforced Soil. Bombay, India, pp. 11–16.

Ramesh, H.N., Manoj Krishnaa, K.V., Mamatha, H.V., 2010. Compaction and strength behavior of lime-coir fiber treated Black Cotton soil. Geomechanics and Engineering 2 (1), 19–28.

Ranjan, G., Vasan, R.M., Charan, H.D., 1996. Probabilistic analysis of randomly distributed fiber-reinforced soil. Journal of Geotechnical Engineering 122 (6), 419–426.

Sivakumar Babu, G.L., Vasudevan, A.K., 2008. Strength and stiffness response of coir fiber-reinforced tropical soil. Journal of Materials in Civil Engineering 20 (9), 571–577.

Ziegler, Stacy, Leshchinsky, Dov, Ling, Hoe I., Perry, Edward B., 1998. Effect of short polymeric fibers on crack development in clays. Soils and Foundations 38 (1), 247–253.

Szabolcs, I., 1989. Salt-Affected Soils. CRC Press, Boca Raton, Florida.

Wang, Y.M., Sun, G.P., Chen, W.W., Ding, L., 2003. Strength characteristics of sand fixated by SH. Journal of Rock Mechanics and Engineering 22 (Suppl. 2), 2883–2887.

Wang, Y.M., Yang, Z.C., Chen, W.W., Han, W.F., 2005. Strength characteristics and mechanism of loess solidified with new polymer material SH. Chinese Journal of Rock Mechanics and Engineering 24 (14), 2554–2559.

Xie, H.Z., 2004. Construction technique of rammed-earth construction of Fujian Earth Building. Housing Science 7, 39–42.

Yetimoglu, T., Salbas, O., 2003. A study on shear strength of sands reinforced with randomly distributed discrete fibers. Geotextiles and Geomembranes 21, 103–110.

Zhang, H.Y., Zhao, T.Y., Wang, X.D., 2008. Construction methods of Chinese ancient earthwork. Duhuang Research 5, 81–90.