Pilot study on the mechanical behaviour of soil with inclusion of polypropylene fibre and lime

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Abstract: With the increasing of population and the reduction of available land, more and more construction of buildings and other civil engineering structures have to be carried out on weak or soft soil. Owing to such soil of poor shear strength and high swelling & shrinkage, a great diversity of ground improvement techniques such as soil stabilization and reinforcement are employed to improve mechanical behaviour of soil, thereby enhancing the reliability of construction. As a good stabilizing agent, lime is extensively applied in soil stabilization of foundation or roadbed. However, lime-treated soil is susceptible to high rigidity and hence the characteristic of brittle failure which is the hidden trouble in engineering construction. For the purpose of making up for the deficiencies in ground improvement with lime and further enhancing soil strength, an attempt to randomly admix polypropylene fibre and lime into soil to improve mechanical behaviour of soil was presented in this study. The studied soil samples at six different fibre (%)-lime (%) content, i.e. 00-0%, 0.2-0%, 00-8%, 0.1-8%, 0.1-6% and 0.2-6% by weight of raw soil, were prepared for a series of unconfined compression tests, shear tests, swelling tests without load and shrinkage tests. The outcome of these tests has clearly shown that inclusion of polypropylene fibre and lime in soil can greatly improve compression and shear strength, reduce the capacity of swelling and shrinkage, and transfer the failure characteristic of soil from brittle to ductile failure. It, therefore, can be concluded that admixing of polypropylene fibre and lime into soil can be considered as an effective method of ground improvement.

Résumé: Avec la croissance de la population et la réduction de la terre utilisable, de plus en plus de constructions de bâtiments et d’autres structures du génie civil sont obligées d’avoir lieu sur du sol souple. A cause de ce sol d’une faible résistance au cisaillement et d’un haut potentiel de dilatation et de contraction, un grand nombre de techniques en vue de l’amélioration du terrain comme la stabilisation et le renforcement du sol sont employées pour améliorer les propriétés mécaniques du sol et ainsi pour accroître la sûreté de la construction. Comme un agent stabilisant efficace, la chaux est largement utilisée dans la stabilisation du sol de fondation ou de forme. Cependant, le sol traité à la chaux est susceptible de la haute rigidité et revêt la caractéristique de la déformation fragile, qui est depuis toujours un danger latent dans la construction du génie civil. Pour remédier aux inconvénients de l’amélioration du sol avec chaux et élever la solidité du sol, cette étude a fait une proposition d’améliorer les propriétés mécaniques du sol en mettant, à n’importe quel moment, de la fibre de polypropylène et de la chaux dans le sol. Les six échantillons de sol étudiés avec différents pourcentages de fibre (%) – chaux (%), soit 00-0%, 0.2-0%, 00-8%, 0.1-8%, 0.1-6% and 0.2-6% du poids du sol brut, ont été prêts à essais à la compression non confinés, essais au cisaillement, essais de dilatation sans charge et essais de contraction. Le résultat de ces essais a clairement montré que l’inclusion de fibre de polypropylène et de chaux vive dans le sol pouvait condidérablement améliorer les résistances à la compression et au cisaillement, réduire le potentiel de dilatation et de contraction et transformer la déformation fragile du sol en déformation plastique. Par conséquent, il peut se conclure que l’addition de fibre de polypropylène et de chaux vive dans le sol peut être considérée comme une méthode efficace de l’amélioration du sol.

Keywords: brittleness, cohesion, clay, strength, mechanical properties

INTRODUCTION

Soil stabilization technique is well developed and extensively applied in the improvement engineering of foundation and roadbed. As a stabilizing agent of efficiency and cheapness, lime exerts profound influences on the ground improvement of soft soils and expansive soils. Some investigators found that soil treated with lime experienced notable increases in strength, optimum moisture, California bearing ratio and water stability while undergoing a decrease in maximum dry density which is helpful to compaction of landfill (Bell, 1996; Qian & Feng, 1998; Wang *et al.*, 1999). Rajasekaran & Narasimha Rao (2002) carried out the experiments on the marine clay and found the 30 to 45-day treatment with lime caused a reduction of 1/2 to1/3 in the compressibility. Furthermore, the swelling-shrinkage potential of expansive soil is sharply reduced after the treatment with lime (Cheng *et al.*, 2002; Du, Li & Hayashi, 1999; Al-Rawas, Hago & Al-Sarmi, 2005). Although the use of lime effectively improves many engineering properties of soil, it also leads to the increase in brittleness of soils (Sabry, Abdel-Ghani & El Nahas, 1996), which causes the rapid decline in strength of lime-treated soil and consequently can reduce significantly in certain circumstances the safety and stability after construction.

In the recent years, discrete fibre has been used in geotechnical engineering serving as a new reinforced material. Prabakar & Sridhar (2002) pointed out that admixture of discrete sisal fibre into soils can improve the strength of soils. Soils reinforced with discrete polypropylene fibre have increases in tensile strength and fracture toughness, which can prevent the further development of cracks and enhance the self-seaming ability of soils (Li *et al.*, 1995; Zhang, Zhou & Zhou, 1998). Some investigators observed that the addition of discrete fibre into cement or concrete could improve greatly the tensile strength of cement or concrete and prevent the surface from dehiscing (Ling & Jiang, 1994; He, Liao & Wang, 1998; Mo *et al.*, 1999; Kaufmann, Winnefeld & Hesselbarth, 2004).

As fibres are of resistance to tensile failure, cracking, acid and alkali attack, an attempt to admix the polypropylene fibre into lime soil to improve the engineering properties of lime soil was investigated. The results from this study are presented in this paper. For the purpose of understanding the influence of fibre on the behaviour of lime soils, six groups of soil samples were prepared at the different fibre and lime contents and then were subjected to unconfined compression and shear tests. In addition, the swelling-shrinkage potential and failure characteristics of all soil samples were also investigated. The primary objective of this research was to assess the usefulness of admixture of polypropylene fibre and lime, as a soil treatment material for improving the mechanical behaviour of soils.

MATERIALS AND EXPERIMENTAL PROGRAMME

Materials

The soils used herein are Xiashu soils, a typical clayey soil extensively distributed in Nanjing regions, China. Owing to high field moisture content and bulk mass, the soil was air-dried and then broken into pieces in the laboratory. Engineering properties of these soils are presented in Table 1. Polypropylene fibre was selected as reinforcement materials in this investigation. The behaviour of this fibre is given in Table 2. The total percentage of CaO & MgO content in lime used was 74.9%, ensuring the effectiveness of lime for soil stabilization.

Table 1. Engineering properties of soil used in this study

S. No	Soil properties	Values
1	Specific gravity	2.82
2	Sand content	6.73%
3	Silt content	63.49%
4	Clay content	29.78%
5	Liquid limit	34.2%
6	Plasticity index	17.3
7	Optimum moisture content	15.7%
8	Maximum dry density	1.71 g/cm^3
9	Cohesion	86.03 kPa
10	Angle of internal friction	20.11 degree
11	I.S Classification	CL

Table 2. Behaviour of polypropylene fibre used in this study

S. No	Fibre behaviour	Values
1	Fibre type	Single fibre
2	Unit weight	0.91 g/cm^3
3	Average diameter	0.034 mm
4	Average length	12 mm
5	Breaking tensile strength	350 Mpa
6	Modulus of elasticity	3500 Mpa
7	Fusion point	165 °C
8	Burning point	590 °C
9	Acid and alkali resistance	Very good
10	Dispersibility	Terrific
11	Fibre type	Single fibre

Preparation of samples

In line pertinent studies (e.g. Li *et al.*, 1995; Bell, 1996; Jie, Li & Chen, 1998; Han & Wang, 2001), the maximum percentages of fibre and lime content selected in the research presented in this paper were respectively 0.2% and 8% by weight of raw soil. At first, the different amounts of fibre and lime were admixed with raw soil, and then different volumes of water were added to the corresponding fibre-lime-soil admixture. Finally six groups of soils were formed and used in this study. Most of the samples were prepared with static compaction method (GB/T 50123-1999) at a water content of 15.7% and at a dry density of 1.6 g/cm^3. However, those prepared for shrinkage tests were compacted at a water content of 20%. Considering the influence of curing time on the behaviour of lime soils, the samples with inclusion of lime were wrapped with thin plastic film and stored in the curing box (20°C±, 96±2%RH) for 7 days prior to testing.

Laboratory tests

In order to understand the influence of fibre on properties of lime soils, the six groups of samples investigated were subjected to unconfined compression tests, shear tests and swelling & shrinkage tests. As a prerequisite, the engineering properties of soils used including specific gravity, consistency limit, optimum moisture content, maximum dry density and shear parameters, were all determined in the laboratory according to GB/T 50123-1999, a national criteria for geotechnical tests in China.

The conventional unconfined compressive apparatus was employed in this study and its corresponding remoulding cylinder has the bore diameter of 39.1mm and the bore length of 80mm. The tests were performed at the strain rate of 2.4mm/min until specimens failed. The specimens for unconfined compression tests were duplicated in order to study the water stability of fibre-lime treated soils. One specimen was tested after 7-day curing while the others were tested after one-day immersion in water following 6-day curing.

In shear tests, the quick shear method was adopted in this study. The dimensions of the specimens are 61.8 mm in diameter and 20 mm in length. The shear tests were carried out at the strain rate of 0.8 mm/min under the normal pressures of 50, 100, 200 and 300 kPa.

Owing to low potential of swelling & shrinkage of soils used in this investigation, the unloaded swell method was employed. In order to slow the evaporation rate of water from the specimens, the room temperature was controlled under 25°C during the shrinkage test. The dimensions of specimens for swelling & shrinkage tests resemble those of specimens for shear tests.

RESULTS AND DISCUSSION

The results of tests in the study were shown in Table 3. The influence of fibres on the strength, swelling and shrinkage potential and failure characteristics of lime soils was analysed and the interactions between fibre, lime and soils were explained. Some investigators have reported the mechanisms of soil stabilization with lime (Mathew & Narasimha, 1997; Nalbantoglu & Gucbilmez, 2001; Wang, Zeng & Suo, 2003). Hence, the emphasis was placed on the analysis of mechanism between fibre and the particles of lime treated soils in this paper.

Table 3. Summary of test results

Samples No.	Unconfined compression strength (Mpa)		Cohesion (kPa)	Angle of internal friction (degree)	Unloaded Swell percentage (%)	Shrinkage percentage (%)	Shrinkage coefficient
	Soaking	Non-soaking					
S1	Collapse	0.14	62.73	19.81	22.43	1.24	0.104
S2	Collapse	0.19	78.56	21.50	18.65	1.28	0.118
S3	0.50	0.74	154.17	33.34	0.50	0.83	0.059
S4	0.59	0.91	198.96	37.72	0.25	0.85	0.060
S5	0.54	0.85	176.06	35.01	0.29	0.95	0.071
S6	0.57	0.88	192.05	35.15	0.27	0.97	0.074

Effect of fibre inclusion on strength of lime soils

It was observed that untreated/fibre-reinforced samples collapsed completely after immersion in water while lime/fibre-lime samples kept initial shapes and had the strength up to 0.59 MPa. From the observations, it was shown that fibre-lime soils took on high water stability like lime soils and the improvement in water stability attributed to the addition of lime not that of fibre. The specimen had decreases of 0.2 to 0.3 MPa in compressive strength after 24-hour immersion in water. With an increase in fibre content, the compressive strength of samples increased. In the case of equal fibre or lime content, fibre-lime soils experienced a more notable increase than lime-treated soil or fibre-reinforced soils in the unconfined compression strength. The prominent improvement of fibre-lime soils in compressive strength is due to the combined action of lime and fibre. On one hand, the reactions between lime and clayey particles changed the natures of soils and consequently improved the strength of soils. On the other hand, the development of friction between fibre and soil particles confined the lateral deformation of specimens and hence increased the compressive strength.

It was indicated that cohesion and internal friction angles of samples increased with fibre content. Among all samples for shear tests, the maximum values of cohesion and friction angles, 198.96 kPa and 37.7 degrees, were observed at 0.1% fibre + 8% lime content (sample number of S4), which are approximately triple of the cohesion and double of the friction angle compared with untreated soils. Order by the descending values of cohesion and friction angles, fibre-lime soils were located first, with lime soils placed secondly, fibre soils ranked third followed by untreated soils, inasmuch as besides the effect of lime stabilization on the cohesion and friction angles, the addition of fibre caused the appearance of friction between fibre and clayey particles which enhances the bonding action between particles and hence improves cohesion of soils. In addition, the interlocking effect between fibre and clay particles also contributes to an increase in internal friction angles of soils.

Effect of fibre inclusion on swelling & shrinkage potential of lime soils

Although soils used in this investigation have low potential of swelling & shrinkage, it was observed clearly from the test results that effect of fibre is different from that of lime on swelling-shrinkage potential of soils. By an increase in lime content, both swelling potential and shrinkage potential of soils decrease. This is likely to be due to cementation of calcium carbonate which causes a notable increase in bonding force between clayey particles and hence results in a greater resistant to swelling and shrinkage of soils.

For any particular lime content, an increase in fibre content causes a decrease in swelling potential of soils while an increase in shrinkage potential of soils. When a specimen is immerged into water and dilatancy occurs, discrete fibres in soils are tensed and develop tensile force to give a resistance to swell pressure, which effectively impedes the further dilatancy of specimens. In view of a decrease in swelling potential due to lime stabilization, the fibre-lime treated sample with serial number of S4 has the lowest potential of swelling as 0.25% among all test specimens. From the shrinkage curves shown in Figure 1 is can be seen that the addition of fibre increased the shrinkage potential of soils, which is opposite to effect of lime. When a specimen shrinks owing to loss of water, the fibres in soils start to slacken and so cannot offer a resistance to shrinkage of soils. Furthermore, as bypasses linking inside and outside of specimens, discrete fibres in soils make loss of water content easier, which promotes the further shrinkage of soils. As far as shrinkage potential of soils is concerned, lime, opposite to discrete fibres, has positive improvement effect. Therefore, the lime-treated sample, S3, has the minimum values of shrinkage percentage and shrinkage coefficient as 0.83% and 0.059.

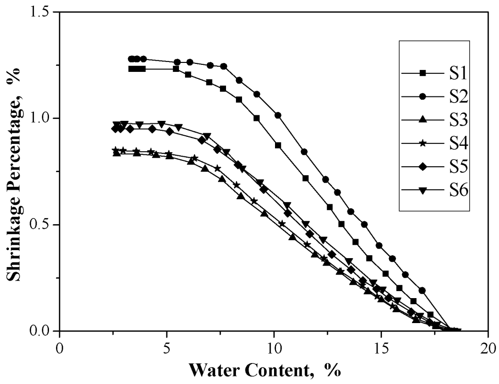

Figure 1. Shrinkage curves of samples tested

Effect of fibre inclusion on failure characteristics of lime soils

The curves of stress-strain relationship of six test samples were illustrated in Figure 2. From those curves, it is shown that each samples in this investigation has own failure characteristic. Lime-treated soils take on brittle failure whereas fibre-reinforced soils take on strain-hardening ductile failure. Between these two failure characteristics, strain-softening ductile failure is taken on by fibre-lime treated soils and untreated soils. Moreover, fibre-lime treated soils have the higher residual strength than fibre-reinforced soils or untreated soils. To lime-treated soils, it has no residual strength after failure. Figure 3 presents the photos of six samples studied after failure. It was observed from Figure 3 that lime-treated sample broke while other samples cracked. In addition, the difference in development of cracks in samples during compression tests is also observed. The addition of fibre promotes the development of small cracks in samples while the use of lime leads to the appearance of big cracks.

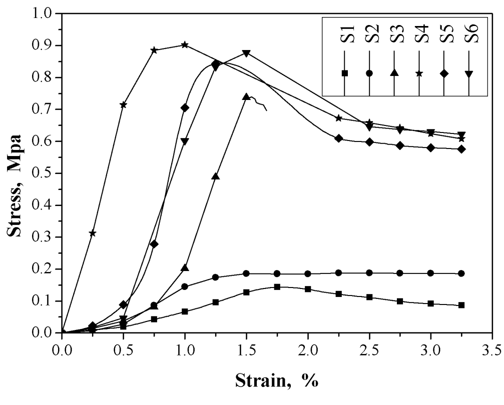

Figure 2. Stress-strain relationship curves of samples tested

Figure 3. Photos of test samples after failure

The above phenomena are due to the difference between two types of mechanism: stabilization and reinforcement. When lime is added into soils in the present of water, the reactions between lime and clayey particles cause an increase in soil rigidity that improves the brittleness of soils. As for the soils with inclusion of discrete fibre, when soils crack owing to concentration of local stress, the discrete fibres near cracks are responsible for the tension in soils, which effectively impedes the further development of cracks and consequently prevents soils from complete brittle failure. Besides these, due to the cementation of calcium carbonate, the friction between fibre and particles of lime soils is greater than that between fibre and clayey particles. Discrete fibres in fibre-lime soils, therefore, can bear great tensile stress after soil failure, which causes a notable increase in residual strength of fibre-lime soils.

CONCLUSIONS

Pilot study on the mechanical behaviour of fibre-lime treated soils was carried out through various tests including unconfined compression tests, shear tests and swelling & shrinkage tests. On the basis of comparison between test data of different samples studied, the influence of fibre on mechanical behaviours of soils, particular in lime-treated soils, is introduced and some conclusions are presented as follows:

(1) When lime is added into soils, the reactions between lime and clayey particles change the properties of soils and hence cause increases in compression strength and shear strength of soils. If an amount of discrete fibres is mixed with lime soils, the compression strength and shear strength of soils will be further improved because friction between fibre and soil particles increases the bonding between particles of soils.

(2) Actions between fibre and clayey particles are not chemical but physical actions. When soils dilate, fibres in soils develop tensile stress to give a resistance to dilatancy of soils, which makes the swelling potential of fibre-lime soils smaller than that of lime soils. However, the addition of discrete fibres in soils may increase the loss of water content in soils easier, which will lead to an increase in shrinkage potential of fibre-lime treated soils. Thus the use of fibre can therefore reduce the swelling potential of soils, but can't decrease the shrinkage potential of soils.

(3) The addition of fibre can improve the plasticity of lime soils and as a result causes the variation of failure modes from brittle failure to ductile failure. Moreover, with an increase in fibre content and a decrease in lime content, the cracks in soils after failure gradually become small. In addition, cementation of calcium carbonate causes an increase in friction between fibre and particles of lime soils. Hence, fibres can still bear the great tensile stress after failure of soils, which makes the residual strength of fibre-lime soils greater than pure fibre soils and untreated soils.

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