ARTICLE IN PRESS

Geotextiles and Geomembranes xxx (2015) 1–9

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

# Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay

Mu Chen [a], Shui-Long Shen [b,*], Arul Arulrajah [c], Huai-Na Wu [d], Dong-Wei Hou [d], Ye-Shuang Xu [d]

[a] Department of Civil Engineering, Shanghai Jiao Tong University, 800 Dong Chuan Road, Minhang District, Shanghai 200240, China
[b] State Key Laboratory of Ocean Engineering, Department of Civil Engineering, Shanghai Jiao Tong University, 800 Dong Chuan Road, Minhang District, Shanghai 200240, China
[c] Department of Civil Engineering, Swinburne University of Technology, Victoria 3122, Australia
[d] Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

*Article history:*
Received 10 March 2015
Received in revised form
28 April 2015
Accepted 21 May 2015
Available online xxx

*Keywords:*
Waste polymer textile bag
Fiber-reinforced soil
Cement
Polymer fiber
Unconfined compression strength

ABSTRACT

This paper presents a laboratory evaluation on the strength behavior of cement–clay admixture improved by polypropylene fiber. Waste polymer textile bags are harmful to the environment and sustainable means to reuse them are urgently being sought. A novel method to recycle these waste polymer textile bags is applying them in soft soil improvement projects, such as compacted-pavement base/subbases. In order to verify the effectiveness of fiber bundles used in soil mixing, a series of laboratory investigation are conducted on fiber-reinforced cement-improved soft Shanghai clay. In the tests, two types of polymer fibers were employed; the first one is monofilament polypropylene fiber and the other is fiber bundles split from polymer textile bags. The tests were conducted using unconfined compressive strength (UCS) test after the specimen of fiber–soil–cement admixture were cured for some period. The results show that fiber additive can significantly improve the strength and ductility of the cement treated Shanghai clay. The UCS of fiber–soil–cement admixture is related to both content and length of fiber. Both two kinds of fiber-reinforced cement clay reached their peak strength at fiber content of 0.5%. UCS will slowly reverse if the fiber content continues to increase. Even though the polypropylene fiber works better than the fiber bundles, the difference is less than 5%. These results indicate that the fiber bundles split from polymer bags can be used as the reinforcement in soil mixing, thus providing a novel approach to treat waste polymer textile bags.



## 1. Introduction

Polymer bags woven from bundle polypropylene fibers are extensively used in packaging applications as well as for industrial products, due to its low economic cost and practicalities. However, used polymer bags are a waste material destined for landfills. It was estimated that, in China, nearly 3 million tons of polymer textile bags are discarded every year. Ideally, chemical processing is possible to some extent to reprocess discarded polymer textile bags, but significant quantities inevitably end up in landfills. Waste textile bags generated from polyolefinic sources can be recycled and reprocessed into polypropylene pipes, plastic bags and petroleum products, etc. (Zhang et al., 2007; Al-Salem et al., 2009). Even though, the thermos-chemical treatment methods used still require the involvement of new polymer material and crude oil, resulting in significant cost and time. Reutilizing waste bags by physical means would be much more economical and practical (Adanur et al., 1998; Koch and Domina, 1999; Woolridge et al., 2006; Pappu et al., 2007).

Ground improvement technology is essential for the construction of underground structures and infrastructure in deeper ground conditions, e.g. deep mixing columns (Shen et al., 2003a,b, 2008),

* Corresponding author. Tel.: +86 21 3420 4301; fax: +86 21 6419 1030.
*E-mail addresses:* channel_m@163.com (M. Chen), slshen@sjtu.edu.cn (S.-L. Shen), aarulrajah@swin.edu.au (A. Arulrajah), wu-hn@sjtu.edu.cn (H.-N. Wu), dongwei_hou@163.com (D.-W. Hou), xuyeshuang@sjtu.edu.cn (Y.-S. Xu).

http://dx.doi.org/10.1016/j.geotexmem.2015.05.004
0266-1144/

Please cite this article in press as: Chen, M., et al., Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay, Geotextiles and Geomembranes (2015), http://dx.doi.org/10.1016/j.geotexmem.2015.05.004

**List of notations**

| | |
|---|---|
| $e$ | void ratio (dimensionless) |
| $q_u$ | unconfined compressive strength ($ML^{-1} T^{-2}$) |
| $m_v$ | coefficient of volume compressibility ($LT^2 M^{-1}$) |
| $m_0$ | mass of dry soil need to be added (M) |
| $m_w$ | mass of water needed (M) |
| $V$ | volume of one specimen ($L^3$) |
| $w$ | natural water content (%) |
| $w_p$ | plastic limit (dimensionless) |
| $w_L$ | liquid limit (dimensionless) |
| $w_0$ | water content of the soil sample before mixing (%) |
| $w_t$ | natural water content of the undisturbed soil (%) |
| $\rho_t$ | dry density of soil ($ML^{-3}$) |
| $\gamma_t$ | unit weight ($LT^{-2}$) |
| $\sigma_{bc}$ | compressive strength of cement ($ML^{-1} T^{-2}$) |

jet grouting columns (Shen et al., 2013a,b; Wang et al., 2013, 2014) and shallow ground to be used as subgrade of road (Shen et al., 2007). However, some traditional techniques are significantly expensive and impractical. For instance, the use of backfill of high quality sandy soil borrowed far away from construction sites may lead to high haulage costs and long construction period. In recent years, reutilizing excavated clayey soil as backfill or subgrade after treatment is increasingly prevalent (Hufenus et al., 2006; Consoli et al., 2010). Increasingly, researchers have improved the strength of soft soils and aggregates by mixing them with cement and fly ash to improve their compression strength (Kaniraj and Havanagi, 1999; Kolias et al., 2005; Horpibulsuk et al., 2009, 2011; Porcino et al., 2012; Disfani et al., 2014; Mohammadinia et al., 2015). Along the coastal regions of China, thick deposits of soft soils are prevalent. As China continues to develop at a rapid rate, there has been an ever increasing need to construct road infrastructure projects as these soft soil locations. Furthermore, haulage of coarse-grained soil as suitable engineering fill materials for these road infrastructure projects is becoming increasingly expensive and furthermore impacts significantly on the environment. Therefore, the usage of fibers in combination with cement to stabilize soft clayey soils in-situ, as compacted-base/subbase layers, is both economical and sustainable.

It is known that soil resists well against compression and shear forces but behaves poorly in resistance to tension. Poor durability is furthermore a shortcoming of cement–clay stabilized materials. Utilizing tensile elements, such as fibers and fiber bundles to improve the tensile strength and the flexural strength, has the advantage of improving the strength and durability of improved soil and will furthermore be effective because of its strength isotropy, absence of potential failure plane, improvement in peak friction angle and cohesion, environmentally savings and economical cost (Kaniraj and Havanagi, 2001; Sobhan and Mashnad, 2002; Yetimoglu et al., 2005; Kumar et al., 2006; Viswanadham et al., 2009; Park, 2011; Hejazi et al., 2012; Mirzababaei et al., 2012; Onyejekwe and Ghataora, 2014; Jamsawang et al., 2014). Several past studies have proved the effectiveness of polymer fiber reinforcement in treating cemented soft soil and provided experimental evidence on the improvement in its mechanical behavior (Li et al., 1995; Kaniraj and Gayathri, 2003; Tang et al., 2007; Park, 2009; Noorzad and Mirmoradi, 2010; Tang and Gu, 2011). However, most of these earlier investigations have focused on polypropylene fiber as a reinforcement material only and furthermore neglected crucial information such as the effect of cement content, fiber content and fiber length. Limited studies have also been attempted on the effect of curing time (Sukmak et al., 2013). Moreover, no research has been attempted to date on the behavior of soil–cement admixture reinforced by fiber bundles split from waste polymer bags, a sustainable method to easily reuse discarded polymer textile bags.

This study therefore aims *i*) to investigate the mechanical behavior of the fiber-reinforced cement–clay and *ii*) to discuss the potential usage of waste polymer bag as a new reinforcement material in soft soil improvement.

## 2. Materials and methods

### 2.1. Materials

The soft soil sample used in this research was soft silty clay and was obtained from a depth of −9.88 m in an excavation pit at South Hongmei Road Tunnel construction site in Shanghai, China. The soft silty clay was collected in a disturbed state by manual excavation. The soft deposit of Shanghai is composed of six aquifers and five aquitards, one overburdened another (Xu et al., 2009; Shen et al., 2010, 2014). Fig. 1 shows the soil profile and geotechnical properties obtained by borehole at this site based on the method. A dark yellow silty clay layer (SC) exists near the ground surface (from 0 to 2.55 m deep). The underlying layer from a depth of 2.55 m to 17.5 m is gray mucky silty clay (MSC). Below the MSC layer there is a silty clay (SC) layer, whose color is gray (from 17.5 m to 43.8 m deep). As shown in Fig. 1, distribution of liquid limit ($w_L$) and natural water content ($w$) with depth are almost the same. The changes of plastic limit ($w_P$) are very small. Large scatter is noticed in the distribution of unit weight, void ratio, and coefficient of volume compressibility. Fig. 2 depicts the grain size distribution curve of the soil sample used in this test. The soil were air-dried and broken into pieces after its initial water content was determined.

Portland cement was chosen as the cementing agent for the improvement of the soft silty clay. The Portland cement used in this research was procured from Conch Cement in southwest Shanghai. The major composition are $3CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, $3CaO \cdot Al_2O_3$ and $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$, with an overall specific gravity of 3.08. Its compressive strength $\sigma_{bc}$ was about 42.5 MPa after 28 days curing time, using a water–cement ratio of 0.485 (ASTM C109/C109M–02, 2002). Since the cement is applicable for general use, the Portland cement was classified as Type II according to ASTM C150 (2007).

Polypropylene fibers and fiber bundles were the two kinds of polymer fiber investigated for reinforcement of the cemented soil, as shown in Figs. 3 and 4. The polypropylene fibers were 3, 6, 9, 12 mm in length and 0.035 mm in diameter. The fiber bundles were obtained from woven polymer bags. The bags were cut into squares with size of 10, 20, 30, 40 mm, respectively. Then, the woven polymer squares were split into fiber bundles. The resulting fiber bundles were 10, 20, 30, 40 in length, 0.035 mm in thickness and 3.5 mm in width. The fibers and fiber bundles were both made of polypropylene, their specific gravity was 0.91, with tensile strength of 120 MPa, elastic modulus of 3 GPa and linear strain at failure of 80%. The two types of fibers also behaved satisfactorily with regards to acid and alkali resistance, with fusion point of 160 °C.

### 2.2. Sample preparation

The fiber-reinforced cement silty clay is a combination of silty clay, cement, polymer fiber, and water. For the unconfined compression tests, cylindrical specimens, 39.1 mm in diameter and 80 mm in height, were used. The initial water content of the soft clay before mixing with cement and fiber was around 47.6%. Thus, the mass of the dry soil and water needed for one specimens can be determined by Eqs. (1) and (2):

Please cite this article in press as: Chen, M., et al., Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay, Geotextiles and Geomembranes (2015), http://dx.doi.org/10.1016/j.geotexmem.2015.05.004

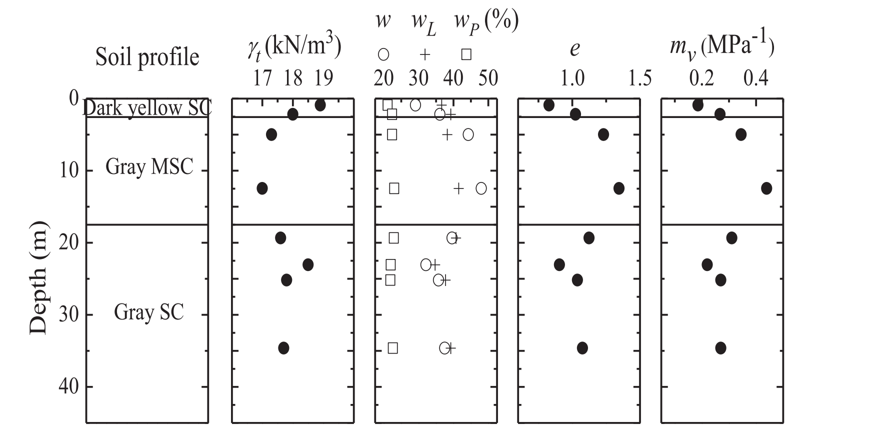


**Fig. 1.** Soil profile and geotechnical properties of borehole samples.

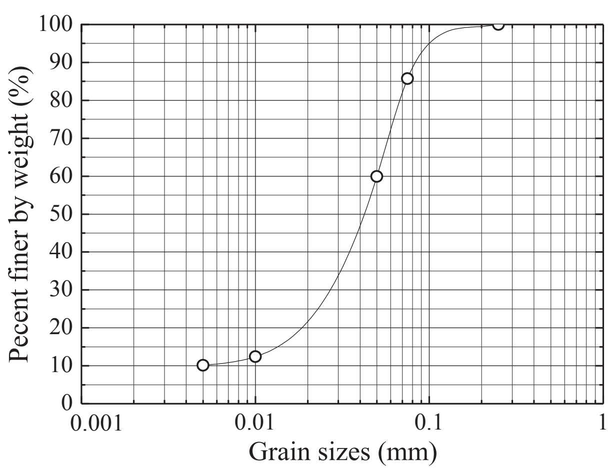


**Fig. 2.** Grain distribution size curve for Shanghai clay used in the tests.

$$m_0 = (1 + 0.01w_0)\rho_t V \quad (1)$$

$$m_w = \frac{m_0}{1 + 0.01w_0} \times 0.01(w_t - w_0) \quad (2)$$

where $m_0$ = the dry soil need to be added; $m_w$ = water needed; $w_0$ = water content of the studied soil (in this program: $w_0 = 0$); $w_t$ = the water content of the intact soil (in this program: $w_t = 47.6\%$); $\rho_t$ = the dry density; $V$ = the volume of one specimen.

For each mixing, the amount of the fibers and cement to be added was calculated according to their target ratios. This was based on the mass of dry soil and water added. In this research, both polypropylene fibers and fiber bundles were added into the cement–clay, respectively. For each kind of fiber-reinforced cement soft clay, the specimens were prepared with cement content varying from 0% to 8%, at an increasing rate of 2% and with fiber contents of 0%, 0.5%, 1.0%, 1.5%, 2.5%. For cement–clay improved by polypropylene fibers, its fiber length varied from 3 mm to 12 mm at an increasing rate of 3 mm. This varied from 10 mm to 40 mm at an

**Fig. 3.** Polypropylene fibers applied in this research.

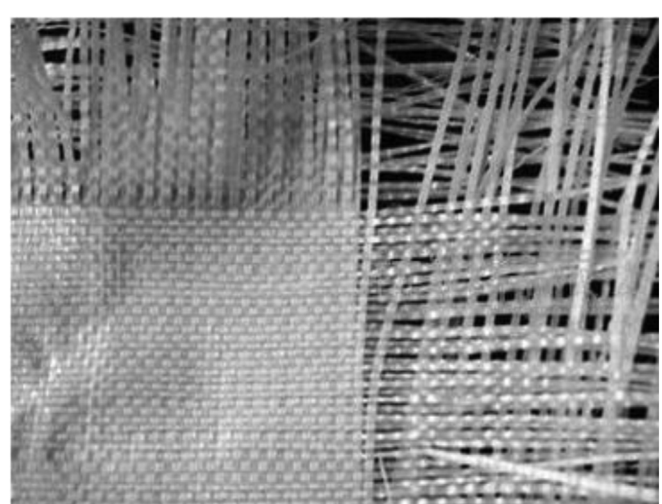

**Fig. 4.** Fiber bundles split from waste polymer textile bags.

Please cite this article in press as: Chen, M., et al., Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay, Geotextiles and Geomembranes (2015), http://dx.doi.org/10.1016/j.geotexmem.2015.05.004

**Table 1**
Parameters of specimens with polypropylene fibers.

| Serial number | Cement content | Fiber content | Fiber length (mm) | Curing time (days) |
|---|---|---|---|---|
| A1 | 2% | 1.5% | 6 | 28 |
| A2 | 4% | 1.5% | 6 | 28 |
| A3 | 6% | 1.5% | 6 | 28 |
| A4 | 8% | 1.5% | 6 | 28 |
| B1 | 8% | 0.5% | 6 | 28 |
| B2 | 8% | 1.0% | 6 | 28 |
| B3 | 8% | 1.5% | 6 | 28 |
| B4 | 8% | 2.5% | 6 | 28 |
| C1 | 8% | 0.5% | 3 | 28 |
| C2 | 8% | 0.5% | 6 | 28 |
| C3 | 8% | 0.5% | 9 | 28 |
| C4 | 8% | 0.5% | 12 | 28 |

increasing rate of 10 mm for the cement–clay improved by fiber bundles.

To reduce some unnecessary tests, a series of preliminary tests were conducted to evaluate the possible optimal mixing ratios as well as to eliminate some ratios that have little influence on the strength of improved clay. Thus, the specimens with optimal ratios were prepared to investigate their strength. Table 1 shows parameters of specimens of polypropylene fibers used in the test. Table 2 shows the parameters of specimens of fiber bundles. In addition, to investigate the influence of curing time on the development of the unconfined compression strength, tests were conducted with polypropylene fiber-reinforced cement soft clay as well as the cement clay without fibers, as shown in Table 3. To ensure the precision of the test results, three identical specimens for each ratio was tested and the average value reported.

The fiber-reinforced and cement stabilized clay admixture was prepared and mixed with a cement mixer. Both polypropylene fibers and fiber bundles were supposed to be randomly distributed in the clay admixture. Initially, dry soil and required cement were mixed for 2 min. To prevent the fibers from floating, water was added into the cement–soil admixture prior to the addition of fibers. After 3 min of mixing, fibers were gradually added and the soil admixture was stirred throughout the mixing process for additional 3 min. For specimens remolding, the unreinforced and fiber-reinforced compacted soft clay specimens were filled in a lubricated three axial saturation appliance and statically compacted several times. The entire procedure was in accordance with the ASTM D2166-06 (2006). The specimens were extracted out of the mold after 24-h molding and curing, as shown in Fig. 5. The specimens were then immediately wrapped in plastic bags and cured in a controlled environment at 23–28 °C with humidity of 90% for 28 days.

**Table 2**
Parameters of specimens added with fiber bundles.

| Serial number | Cement content | Fiber content | Fiber length (mm) | Curing time (days) |
|---|---|---|---|---|
| D1 | 2% | 1.5% | 40 | 28 |
| D2 | 4% | 1.5% | 40 | 28 |
| D3 | 6% | 1.5% | 40 | 28 |
| D4 | 8% | 1.5% | 40 | 28 |
| E1 | 8% | 0.5% | 40 | 28 |
| E2 | 8% | 1.0% | 40 | 28 |
| E3 | 8% | 1.5% | 40 | 28 |
| E4 | 8% | 2.5% | 40 | 28 |
| F1 | 8% | 0.5% | 10 | 28 |
| F2 | 8% | 0.5% | 20 | 28 |
| F3 | 8% | 0.5% | 30 | 28 |
| F4 | 8% | 0.5% | 40 | 28 |

**Table 3**
Parameters of specimens with different curing time.

| Serial number | Cement content | Fiber content | Fiber length (mm) | Curing time (days) |
|---|---|---|---|---|
| G1 | 2% | – | – | 7, 14, 28 |
| G2 | 4% | – | – | 7, 14, 28 |
| G3 | 6% | – | – | 7, 14, 28 |
| G4 | 8% | – | – | 7, 14, 28 |
| H1 | 8% | 0.5% | 6 | 7, 14, 28 |
| H2 | 8% | 1.5% | 6 | 7, 14, 28 |
| H3 | 8% | 2.5% | 6 | 7, 14, 28 |

### 2.3. Methods

In this research, the unconfined compression strength was chosen as the main indicator to study the effectiveness of the stabilization of soft silty clay with cement and fibers. The various factors that influenced on the mechanical behavior of the improved soil were furthermore studied. An automatic strain-controlled unconfined compression apparatus, with maximum capacity of 5 kN, was used for the unconfined compression tests, with an applied shearing rate of 2.4 mm/min.

After 28 days of curing, the specimens were taken out and soaked in a water tank for 24 h for saturation prior to loading. Loading was continued until the load values reached the maximum and subsequently decreased with increasing strain, or until 15% strain was reached. In the whole loading procedure, all the tests were carried out according to the ASTM D2166-06 (2006). For the acceptance criteria, the unconfined compression strength of the three specimens at the same ratio should not deviate by more than 15% of the mean value.

## 3. Results and discussion

### 3.1. Effect of fiber additive

Figs. 6–8 depict the stress–strain curves for the cement–clay improved by fibers and fiber bundles with the variation of cement content, fiber content and length. As shown in Fig. 6, specimens with cement content of 2% performed much more ductile when others reached their peak strength at the strain 1.5%. It is suggested that both types of fiber additives assisted with ductility of improved clay with low cement content, which can be attributed to the bonds between soil particles provided by fiber reinforcement. However, the cementation effect was an influencing factor on the ductility of the improved clay when the cement content increased. Figs. 7 and 8 give the stress–strain curves for the specimens with the optimal cement content 8%. All these specimens reached their maximum axial stress at the strain of around 1.5%, regardless of the fiber type, fiber content and fiber length.

Fig. 9 gives a comparison of stress–strain curves of Group G3 and Group F4. Both G3 and F4 have cement content of 8%, but G3 has no fiber and F4 has a fiber content of 0.5%. Evidently, the specimens with fiber bundles gained significant improvement in its strength. Interestingly, the improved clay behaved better in ductility than those without any fiber. The peak stress of specimens without fiber is at 0.8% when the others reached their peak stress at nearly 1.6%. The addition of fiber bundles was found to improve ductility of cement clay as well as its bearing capability.

### 3.2. Effect of cement content

Groups A and D were tested and the strength compared for both types of specimens of fibers and fiber bundle with cement content

Please cite this article in press as: Chen, M., et al., Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay, Geotextiles and Geomembranes (2015), http://dx.doi.org/10.1016/j.geotexmem.2015.05.004

**Fig. 5.** Fiber-reinforced cement–clay specimens.

of 2%, 4%, 6%, and 8%, respectively. Fig. 10 presents the relationship between UCS of the improved clay versus cement contents. According to the figures, the strength of the two types of specimens increased drastically with the increase of the cement content. The addition of cement was found to have a significant effect on the improvement in strength of soft clay. In fact, the cementation effect binds the fiber bonds and soil grains together resulting in an increase in the overall strength (Horpibulsuk et al., 2012). In addition, the hydration reaction between cement and water reduced the water content of the improved soil, which subsequently improved the mechanical behavior of the improved soil. In the cement content range investigated, the relationship of strength versus cement content is approximately linear. However practically, if the cement content of the specimens increases, the strength will subsequently reduce.

### 3.3. Effect of fiber content

Fig. 11 plots UCS of the two types of fiber-reinforced cement–clay with fiber content of 0, 0.5%, 1.0%, 1.5%, 2.5%. As evident, both types of improved soil had relatively higher unconfined compression strength. For specimens improved with polypropylene fibers and fiber bundles, its strength increased when the fiber content increased from 0 to 0.5% but decreased if the fiber content is further increased. The fiber inclusion could be easily distributed in the specimens and bear the pulling stress inside when the fiber content is relatively low. But it would be hard to blend the fiber or strips discretely if the fiber contents were excessive. Thus, excessive fiber inclusion might tangle together in some parts of the specimens so that the cementation and fiber bonds there were obstructed. It can be concluded that both two types of improved soil reached their peak strength at the fiber content of 0.5% and that, considering the fiber content of 0.5% as a threshold, the strength had an overall trend to decrease with the increase of fiber content beyond the threshold.

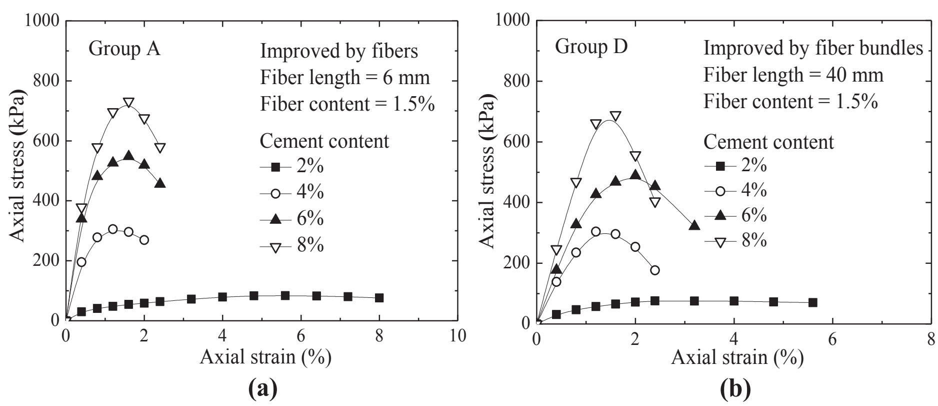


**Fig. 6.** Stress–strain curves for specimens improved with different cement content under fiber content 1.5%: a) fibers and b) fiber bundles.

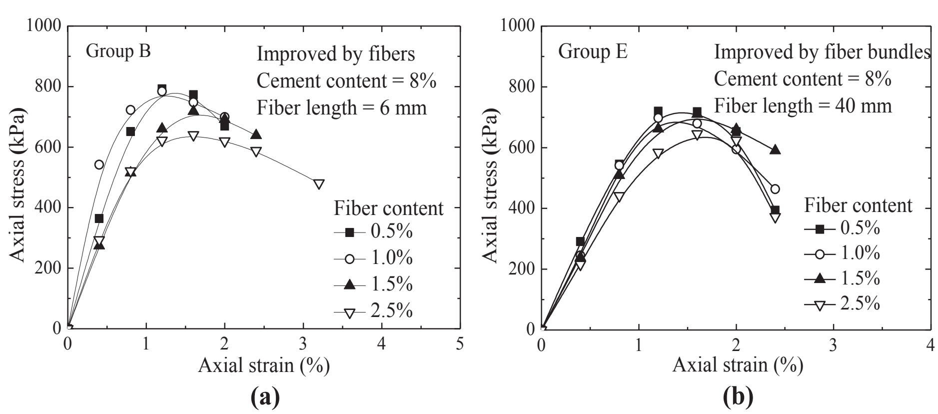


**Fig. 7.** Stress–strain curves for specimens improved with different fiber content under cement content 8%: a) fibers and b) fiber bundles.

Please cite this article in press as: Chen, M., et al., Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay, Geotextiles and Geomembranes (2015), http://dx.doi.org/10.1016/j.geotexmem.2015.05.004

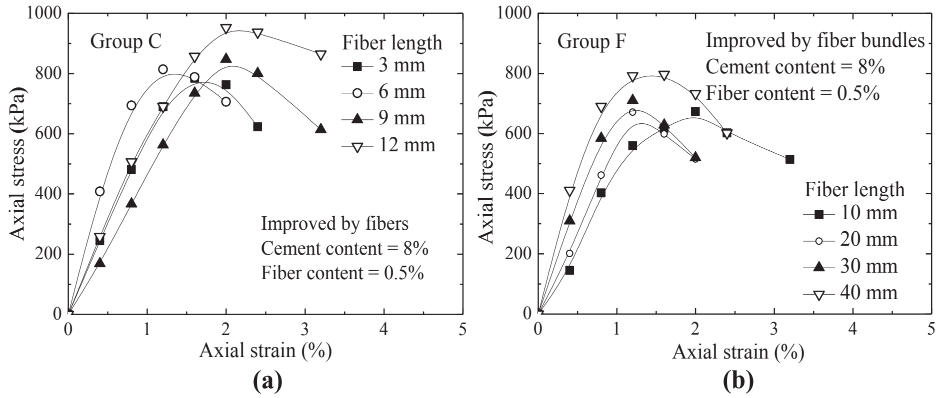


**Fig. 8.** Stress–strain curves for specimens improved with different fiber lengths under cement content 8% and fiber content 0.5%: a) fibers and b) fiber bundles.

To verify whether the threshold was similar for all cement contents, more test data on samples were plotted in Fig. 12. Specimen with different cement contents, mixing with fiber bundles of 40 mm or with polypropylene fibers of 6 mm, were cured for 28 days and tested to show the relationship between their strength versus fiber contents. When the fiber content was 2%, the relationship between strength versus fiber contents is approximately linear. The fiber bonds and tensile strength provided by fibers were the main source of improvement for specimens with low cement contents. However, for the specimens with cement content of 4% and 6%, it appears that the cementation effect became the dominant source of improvement and that excessive fibers do not further assist in increasing the strength of improved clay. The strength of both types of specimens reached a maximum point in the fiber content range tested. For the improved clay with a cement content of 4%, the threshold is around the fiber content of 1.5%. The threshold is found to be between fiber content 0.5% and 1% at a cement content of 6%.

Therefore, based on Fig. 12, it can be concluded that the more cement added, the lower the optimal content of the fibers. Since the cement content for improved clay is usually higher than 8% in practice, fiber contents lower than 0.5% would be considered optimal for engineering practice.

### 3.4. Effect of fiber length

Fig. 13 shows the unconfined compression strength of the two types of improved soil with varying fiber lengths. Stabilized with the same optimal cement content of 8% and the fiber content of 1.5%, the strength of the cement–clay improved by fiber bundles were relatively lower than the specimens added with polypropylene fibers, but the difference is less than 5%. When fiber length increased, the strength of polypropylene fiber-reinforced cement soil also grew, with the growth rate accelerating. The same results came again as for cement–clay improved by fiber bundles. It indicates that long fibers were more helpful rather than short fibers in the length range we studied.

For optimal length of fiber additive, both types of fiber-reinforced cement soft clay reached their maximum strength when mixed with fibers of the longest lengths, with an accelerating growth rate. Therefore, it can be estimated that the optimal fiber lengths are probably higher than what the authors have tested. When the improved clay were mixed with the same content of fibers or fiber bundles, the inclusion of longer length fibers means that fewer single fibers will be mixed. Less single fibers will result in an even distribution of fibers. Longer fibers are hard to be pulled out and can bond more soil particles together. Therefore, considering the magnitude of the ground as well as what the authors have analyzed above, the optimal lengths of the two fiber additives should be much longer in practice.

### 3.5. Effect of curing time

Group G and H tested the strength of the specimens at different curing time points. The test results are presented in Fig. 14. In the tests of Group G1–G4, stress–strain curves of cement clay with

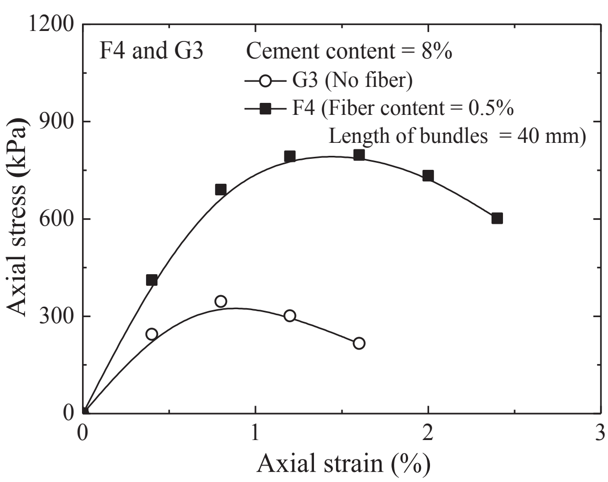


**Fig. 9.** Stress–strain curves for specimens without & with fiber bundles.

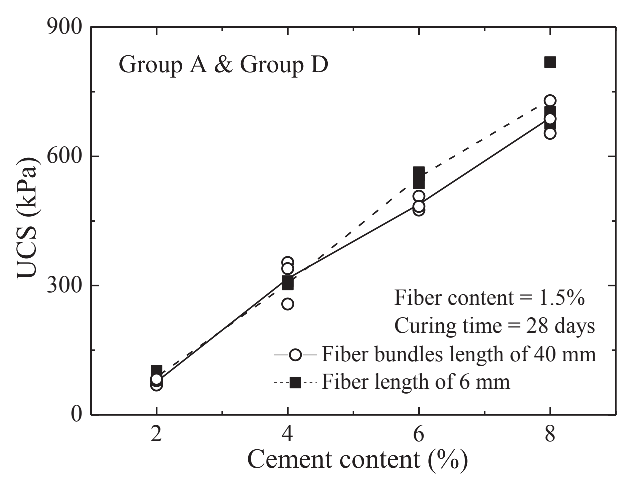


**Fig. 10.** UCS of the improved clay versus cement contents.

Please cite this article in press as: Chen, M., et al., Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay, Geotextiles and Geomembranes (2015), http://dx.doi.org/10.1016/j.geotexmem.2015.05.004

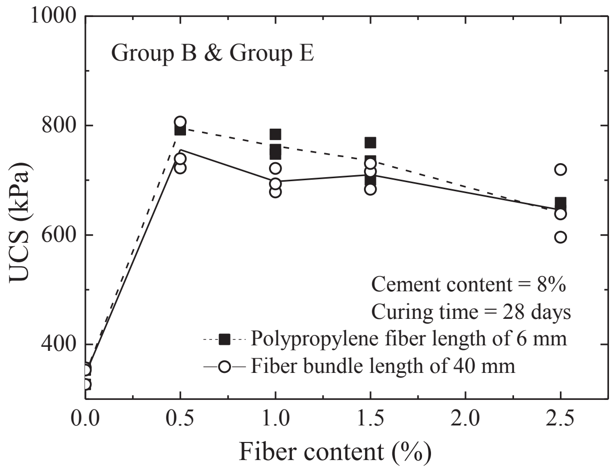


**Fig. 11.** UCS of the improved clay versus fiber contents.

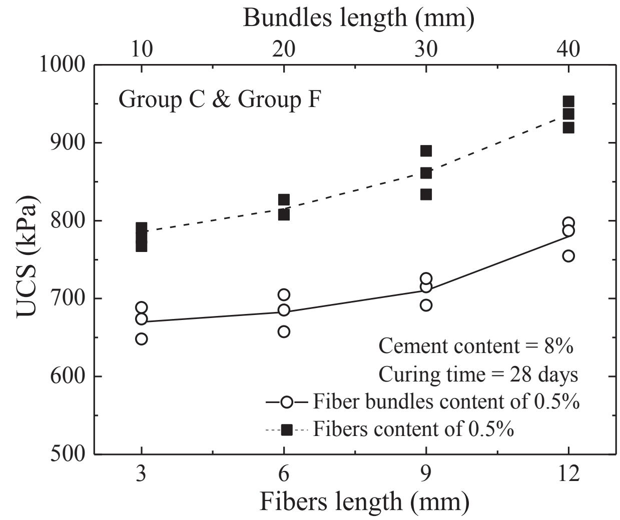


**Fig. 13.** UCS of the improved clay versus fiber lengths.

different cement content shared a similar shape, with different peak strengths. Take the stress–strain curves of G4 as an example, hollow symbols in Fig. 14 depict the stress–strain curves of the 8% cement content specimens at different curing times. Its peak strength grew higher with the increase of the curing time while the specimens seemed to be less ductile and more brittle.

Fig. 14 also presents the stress–strain curves for specimens improved with a cement content of 8%, polypropylene fiber content of 2.5% and fiber length of 6 mm at different curing times, as plotted by the solid symbols. Unlike specimens without fibers, for specimens added with polypropylene fibers, it is evident that the more fiber added, the less the ductility would change with increasing curing times. As an illustration, Fig. 14 shows that the specimens with a fiber content of 2.5%, reaching their peak stress nearly at the same strain, behaved almost similarly in ductility regardless of the curing time. Fiber addition indeed improves the ductility behavior of cement clay.

Fig. 15 plots the strength of the cement–clay without fibers. Compared with those whose cement content was 2%, the other specimens with relatively high contents of cement obtained a remarkable increase in their strength. The increase of the strength mainly occurred in the first 14 days. Specimens with higher cement contents seemed to take a longer time to reach their final strength than others.

Fig. 16 illustrates strength growth curves of fiber-reinforced cement clay. As apparent, the average strength of improved cement–clay was nearly twice as much as the strength of those without fibers for each of the curing periods. The fiber-reinforced cement clay appeared to behave better in its early strength stage and have a higher strength growth rate in the first 7 days. Since the hydration reaction and cementation were not fully accomplished in the early curing periods, the early strength of the improved soil was mainly provided by the fiber bonds. Therefore, if early strength is required, fiber reinforcement will be a serviceable method to improve the strength of cement–clay in practice.

The specimens with high fiber content performed better in the early curing time periods but strength development grew only slowly afterwards. It was the specimens with less fiber of 0.5% that appeared to develop strength rapidly and reach the highest strength. Improved clay with high fiber content took a shorter time to reach its final strength, which can be attributed to unevenly distribution of excessive fiber additive in soil–cement clay admixture.

### 3.6. Comparison with previous investigations

In stress–strain relation of this study, when mixed with high cement contents, specimens all reached their maximum axial stress

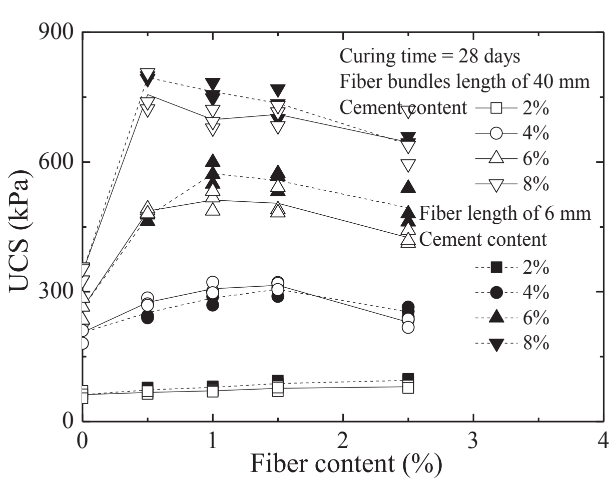


**Fig. 12.** UCS of the improved clay with different cement contents versus fiber contents.

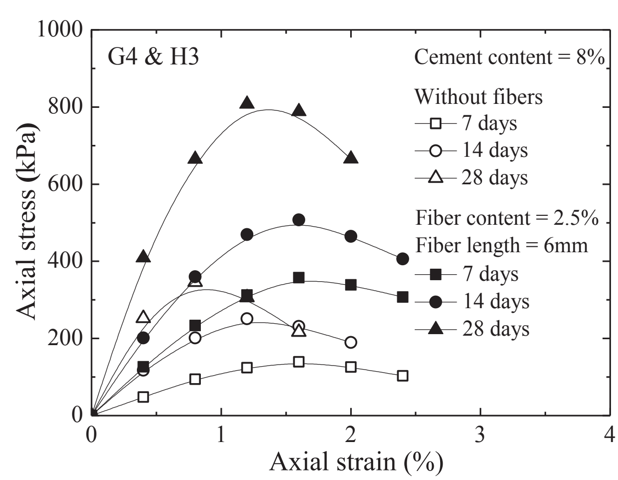


**Fig. 14.** Stress–strain curves for without-fiber specimens and polypropylene fiber-reinforced specimens with different curing time.

Please cite this article in press as: Chen, M., et al., Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay, Geotextiles and Geomembranes (2015), http://dx.doi.org/10.1016/j.geotexmem.2015.05.004

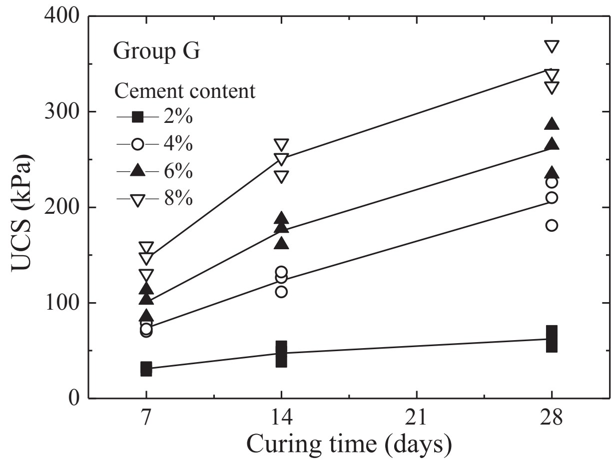


**Fig. 15.** Effect of curing time for specimens without fiber.

at the strain of approximately 1.5%, irregardless of fiber type, fiber content, and fiber length. This is quite different from the trend previously reported by Park (2011) that the peak strain is proportional to the fiber ratios for cemented sand. Fiber bonds and cementation do help the improved clay become more ductile, but its behavior in ductility is not proportional to the fiber content. This is due to difference in properties between cemented sand and cemented clay.

In the strength properties, cement caused an increase in strength of improved clay in linear relationship to the cement content, which has been reported by several researchers (e.g., Kolias et al., 2005; Consoli et al., 2010; Park, 2011).

Figs. 11 and 12 show the effect of fiber content on the strength of improved clay. It is evident that there is a threshold strength in their relationship versus fiber contents, irregardless of the cement contents. Furthermore, the optimal content of fiber diminished with the increase of cement. Tang et al. (2007) reported that there was no threshold in their results and the increase of fiber content improve the strength without decline. The fiber contents in their tests ranged only from 0 to 0.25%, which made it impossible for the threshold and the trend of optimal contents to be obtained. The authors also found, when compared with the results of Park (2011), that the optimal content of fiber for cemented sand are higher than those for cemented silty clay when mixed with the same cement contents.

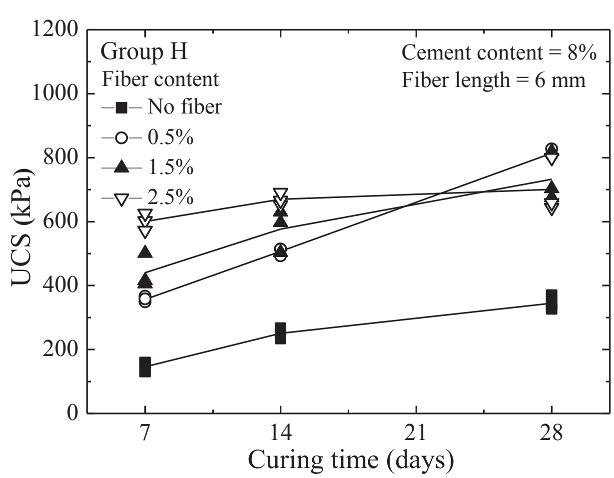


**Fig. 16.** Effect of curing time for specimens with different polypropylene contents.

In the study on the aspect of fiber lengths, when mixed with cement of content 8%, long fibers were found to be more effective rather than short fibers in the lengths range tested. Based on a similar trend reported by Tang and Gu (2011) with cement content of 15%, the authors conclude that, for fibers of lengths under 12 mm, longer fibers behave better as reinforcement.

Kaniraj and Havanagi (2001) have studied the effect of curing time on strength. However, the difference in the strength growing curves of different mixing ratios and different fiber contents were not reported.

For improved clay mixed with fiber bundles, since the fiber bundles is a reinforcement material with no previous study, the difference between behaviors of the two types of improved clay are compared. From the strain–stress curves as shown in Figs. 6–8, their behaviors in ductility are nearly similar, reaching their peak stress at the strain 1.5%. In test results shown in Figs. 10–13, it is evident that the two types of improved clay behaved almost identically in their strength versus the influencing factors. Polypropylene fiber works better than the fiber bundles. However, the difference is less than 5%, which can be attributed to more uniform distribution of fibers than fiber bundles in the soil. Instead of the high cost for using polypropylene fibers, reusing fiber bundles split from waste polymer bags is environmentally friendly and furthermore is readily available at no cost. Therefore, the fiber bundles can be used as the reinforcement in soil mixing and provide a novel approach to treat the waste polymer textile bags.

## 4. Conclusions

Based on the results of unconfined compression tests on the fiber-reinforced cement–clay and fiber bundles reinforced Shanghai clay, as well as analysis and discussion all above, the following conclusions can be drawn:

(1) Polypropylene fiber can effectively improve the strength of cement treated Shanghai clay. The strength of improved clay will change with the addition of the fiber and cement. The fiber type, fiber content, fiber length, and cement content are factors that affect the strength and ductility of the improved clay. Cement content is the most influential factor for the improvement of silty clay. The addition of cement could significantly improve the strength of soft clay.
(2) Both polypropylene fiber and fiber bundles assist with the strength and ductility of the improved clay. In terms of the effect of reinforcement and stabilization, the polypropylene fiber worked a little better than the fiber bundles. This is due to the uniform distribution of fibers in the soil.
(3) The strength of the improved clay will also change along with the change of fiber length. Overall, the strength of both two types of fiber-reinforced cement clay grew with the fiber length. Also, the optimal contents of fiber reduced with the increase of cement content.
(4) Improved clay with higher cement content took a longer time to reach its final strength. The fiber-reinforced cement clay behaved better in its early strength stage and had a higher growth rate in the first 7 days than the no-fiber cement clay. But the increase of strength could be restrained in its middle and later curing time if too much fiber is added.
(5) The fiber bundles split from polymer bags can be used as the reinforcement in soil mixing, which provides a new way to treat the waste polymer textile bags.

## Acknowledgments

The research work described herein was funded by the National Nature Science Foundation of China (NSFC) (Grant No. 41372283) and National Basic Research Program of China (973 Program: 2015CB057806). These financial supports are gratefully acknowledged.

## References

Adanur, S., Hou, Z., Broughton, R.M., 1998. Recovery and reuse of waste PVC coated fabrics. Part 1: experimental procedures and separation of fabric components. J. Ind. Text. 28 (1), 37–55.

Al-Salem, S.M., Lettieri, P., Baeyens, J., 2009. Recycling and recovery routes of plastic solid waste (PSW): a review. Waste Manag. 29 (10), 2625–2643.

ASTM C109, 2002. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens).

ASTM D2166-06, 2006. Standard Test Method of Unconfined Compressive Strength of Cohesive Soil. Astm Int'L.

ASTM C150, 2007. Standard Specification for Portland Cement, Annual Book of ASTM Standards. ASTM, Philadelphia, PA.

Consoli, N.C., Bassani, M.A.A., Festugato, L., 2010. Effect of fiber-reinforcement on the strength of cemented soils. Geotext. Geomembr. 28 (4), 344–351.

Disfani, M.M., Arulrajah, A., Haghighi, H., Mohammadinia, A., Horpibulsuk, S., 2014. Flexural beam fatigue strength evaluation of crushed brick as a supplementary material in cement stabilized recycled concrete aggregates. Constr. Build. Mater. 68, 667–676.

Hejazi, S.M., Sheikhzadeh, M., Abtahi, S.M., Zadhoush, A., 2012. A simple review of soil reinforcement by using natural and synthetic fibers. Constr. Build. Mater. 30, 100–116.

Horpibulsuk, S., Rachan, R., Raksachon, Y., 2009. Role of fly ash on strength and microstructure development in blended cement stabilized silty clay. Soils Found. 49 (1), 85–98.

Horpibulsuk, S., Rachan, R., Suddeepong, A., Chinkulkijniwat, A., 2011. Strength development in cement admixed Bangkok clay: laboratory and field investigations. Soils Found. 51 (2), 239–251.

Horpibulsuk, S., Suddeepong, A., Chinkulkijniwat, A., Liu, M.D., 2012. Strength and compressibility of lightweight cemented clays. Appl. Clay Sci. 69, 11–21.

Hufenus, R., Rueegger, R., Banjac, R., Mayor, P., Springman, S.M., Brönnimann, R., 2006. Full-scale field tests on geosynthetic reinforced unpaved roads on soft subgrade. Geotext. Geomembr. 24 (1), 21–37.

Jamsawang, P., Voottipruex, P., Horpibulsuk, S., 2014. Flexural strength characteristics of compacted cement-polypropylene fiber sand. J. Mater. Civ. Eng. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001205, 04014243.

Kaniraj, S.R., Havanagi, V.G., 1999. Compressive strength of cement stabilized fly ash–soil mixtures. Cem. Concr. Res. 29 (5), 673–677.

Kaniraj, S.R., Havanagi, V.G., 2001. Behavior of cement-stabilized fiber-reinforced fly ash-soil mixtures. J. Geotech. Geoenviron. Eng. 127 (7), 574–584.

Kaniraj, S.R., Gayathri, V., 2003. Geotechnical behavior of fly ash mixed with randomly oriented fiber inclusions. Geotext. Geomembr. 21 (3), 123–149.

Koch, K., Domina, T., 1999. Consumer textile recycling as a means of solid waste reduction. Fam. Consumer Sci. Res. J. 28 (1), 3–17.

Kolias, S., Kasselouri-Rigopoulou, V., Karahalios, A., 2005. Stabilisation of clayey soils with high calcium fly ash and cement. Cem. Concr. Compos. 27 (2), 301–313.

Kumar, A., Walia, B.S., Mohan, J., 2006. Compressive strength of fiber reinforced highly compressible clay. Constr. Build. Mater. 20 (10), 1063–1068.

Li, G.X., Chen, L., Zheng, J.Q., Jie, Y.X., 1995. Experimental study on fiber-reinforced cohesive soil (in Chinese). J. Hydraul. Eng. 6 (6), 31–36.

Mirzababaei, M., Miraftab, M., Mohamed, M., McMahon, P., 2012. Unconfined compression strength of reinforced clays with carpet waste fibers. J. Geotech. Geoenviron. Eng. 139 (3), 483–493.

Mohammadinia, A., Arulrajah, A., Sanjayan, J., Disfani, M., Bo, M., Darmawan, S., 2015. Laboratory evaluation of the use of cement-treated construction and demolition materials in pavement base and subbase applications. J. Mater. Civ. Eng. 27 (6), 04014186.

Noorzad, R., Mirmoradi, S.H., 2010. Laboratory evaluation of the behavior of a geotextile reinforced clay. Geotext. Geomembr. 28 (4), 386–392.

Onyejekwe, S., Ghataora, G.S., 2014. Effect of fiber inclusions on flexural strength of soils treated with nontraditional additives. J. Mater. Civ. Eng. 26 (8).

Pappu, A., Saxena, M., Asolekar, S.R., 2007. Solid wastes generation in India and their recycling potential in building materials. Build. Environ. 42 (6), 2311–2320.

Park, S.S., 2009. Effect of fiber reinforcement and distribution on unconfined compressive strength of fiber-reinforced cemented sand. Geotext. Geomembr. 27 (2), 162–166.

Park, S.S., 2011. Unconfined compressive strength and ductility of fiber-reinforced cemented sand. Constr. Build. Mater. 25 (2), 1134–1138.

Porcino, D., Marcianò, V., Granata, R., 2012. Static and dynamic properties of a lightly cemented silicate-grouted sand. Can. Geotech. J. 49 (10), 1117–1133.

Shen, S.L., Han, J., Huang, X.C., Du, S.J., 2003a. Laboratory studies on property changes in surrounding clays due to installation of deep mixing columns. Mar. Georesour. Geotechnol. 21 (1), 15–35.

Shen, S.L., Miura, N., Koga, H., 2003b. Interaction mechanism between deep mixing column and surrounding clay during installation. Can. Geotech. J. 40 (2), 293–307.

Shen, S.L., Hong, Z.S., Xu, Y.S., 2007. Reducing differential settlements of approach embankments. Proc. ICE-Geotech. Eng. 160 (4), 215–226.

Shen, S.L., Han, J., Du, Y.J., 2008. Deep mixing induced property changes in surrounding sensitive marine clays. J. Geotech. Geoenviron. Eng. ASCE 134 (6), 845–854.

Shen, S.L., Du, Y.J., Luo, C.Y., 2010. Evaluation of the effect of double-o-tunnel rolling-correction via apply one-side block loading. Can. Geotech. J. 47 (10), 1060–1070.

Shen, S.L., Wang, Z.F., Horpibulsuk, S., Kim, Y.H., 2013a. Jet-grouting with a newly developed technology: the twin-jet method. Eng. Geol. 152 (1), 87–95.

Shen, S.L., Wang, Z.F., Yang, J., Ho, E.C., 2013b. Generalized approach for prediction of jet grout column diameter. J. Geotech. Geoenviron. Eng. 139 (12), 2060–2069.

Shen, S.L., Wu, H.N., Cui, Y.J., Yin, Z.Y., 2014. Long-term settlement behavior of the metro tunnel in Shanghai. Tunn. Undergr. Space Technol. 40 (2014), 309–323.

Sobhan, K., Mashnad, M., 2002. Tensile strength and toughness of soil-cement-fly-ash composite reinforced with recycled high-density polyethylene strips. J. Mater. Civ. Eng. 14 (2), 177–184.

Sukmak, P., Horpibulsuk, S., Shen, S.L., Chindaprasirt, P., Suksiripattanapong, C., 2013. Factors influencing strength development in clay–fly ash geopolymer. Constr. Build. Mater. 47, 1125–1136.

Tang, C.S., Shi, B., Gao, W., Chen, F., Cai, Y., 2007. Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. Geotext. Geomembr. 25 (3), 194–202.

Tang, C.S., Gu, K., 2011. Strength behaviour of polypropylene fiber reinforced cement stabilized soft soil (in Chinese). China Civ. Eng. J. 44, 5–8.

Viswanadham, B.V.S., Phanikumar, B.R., Mukherjee, R.V., 2009. Swelling behaviour of a geofiber-reinforced expansive soil. Geotext. Geomembr. 27 (1), 73–76.

Wang, Z.F., Shen, S.L., Ho, E.C., Kim, Y.H., 2013. Investigation of field installation effects of horizontal twin-jet grouting in Shanghai soft soil deposits. Can. Geotech. J. 50 (3), 288–297. http://dx.doi.org/10.1139/cgj-2012-0199.

Wang, Z.F., Shen, S.L., Ho, C.E., Xu, Y.S., 2014. Jet grouting for mitigation of installation disturbance. Geotech. Eng. ICE Proc. 167 (GE6), 526–536.

Woolridge, A.C., Ward, G.D., Phillips, P.S., Collins, M., Gandy, S., 2006. Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: an UK energy saving perspective. Resour. Conserv. Recycl. 46 (1), 94–103.

Xu, Y.S., Shen, S.L., Du, Y.J., 2009. Geological and hydrogeological environment in Shanghai with geohazards to construction and maintenance of infrastructures. Eng. Geol. 109 (3–4), 241–254.

Yetimoglu, T., Inanir, M., Inanir, O.E., 2005. A study on bearing capacity of randomly distributed fiber-reinforced sand fills overlying soft clay. Geotext. Geomembr. 23 (2), 174–183.

Zhang, G.H., Zhu, J.F., Okuwaki, A., 2007. Prospect and current status of recycling waste plastics and technology for converting them into oil in China. Resour. Conserv. Recycl. 50 (3), 231–239.

Please cite this article in press as: Chen, M., et al., Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay, Geotextiles and Geomembranes (2015), http://dx.doi.org/10.1016/j.geotexmem.2015.05.004