Journal of Rock Mechanics and Geotechnical Engineering 6 (2014) 133–137

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Effect of discrete fibre reinforcement on soil tensile strength

Jian Li [a], Chaosheng Tang [a,b,*], Deying Wang [a], Xiangjun Pei [b], Bin Shi [a]

[a] School of Earth Sciences and Engineering, Nanjing University, Nanjing 210093, China
[b] Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China

ARTICLE INFO

Article history:
Received 2 December 2013
Received in revised form
31 December 2013
Accepted 10 January 2014
Available online 31 January 2014

Keywords:
Fibre reinforced soil
Tensile strength
Direct tensile test
Fibre content
Dry density
Water content

ABSTRACT

The tensile behaviour of soil plays a significantly important role in various engineering applications. Compacted soils used in geotechnical constructions such as dams and clayey liners in waste containment facilities can suffer from cracking due to tensile failure. In order to increase soil tensile strength, discrete fibre reinforcement technique was proposed. An innovative tensile apparatus was developed to determine the tensile strength characteristics of fibre reinforced soil. The effects of fibre content, dry density and water content on the tensile strength were studied. The results indicate that the developed test apparatus was applicable in determining tensile strength of soils. Fibre inclusion can significantly increase soil tensile strength and soil tensile failure ductility. The tensile strength basically increases with increasing fibre content. As the fibre content increases from 0% to 0.2%, the tensile strength increases by 65.7%. The tensile strength of fibre reinforced soil increases with increasing dry density and decreases with decreasing water content. For instance, the tensile strength at a dry density of 1.7 Mg/m^3 is 2.8 times higher than that at 1.4 Mg/m^3. It decreases by 30% as the water content increases from 14.5% to 20.5%. Furthermore, it is observed that the tensile strength of fibre reinforced soil is dominated by fibre pull-out resistance, depending on the interfacial mechanical interaction between fibre surface and soil matrix.

1. Introduction

Compared with compressive or shear strength, tensile strength of soil is basically assumed to be zero, or insignificant in geotechnical engineering practice because of its relatively low value. In fact, the tensile strength of soil is difficult to be precisely measured due to the lack of satisfying laboratory techniques. The tensile strength of soil is, however, an important mechanical parameter in the design of geosystems, i.e. slopes, dams, embankments and hydraulic barriers, where tensile cracks are likely to occur (Morris et al., 1992; Miller et al., 1998; Albrecht and Benson, 2001; Tang et al., 2010a, 2011). In recent years, increasing attention has been paid to the investigation of soil tensile characteristics, and to the development of new methods of improving and measuring soil tensile strength (Chen et al., 2009; Hu et al., 2009; Ran et al., 2011; Shindea et al., 2012).

Discrete fibre reinforcement is a newly developed technique to improve soil mechanical behaviour (Yetimoglu and Salbas, 2003; Tang et al., 2007a, 2007b; Ahmad et al., 2010; Consoli et al., 2011). In comparison with conventional geosynthetics (strips, geotextile, geogrid, etc.), the advantages of using discrete fibre are as follows: (1) The discrete fibres are simply added and mixed randomly with soil, like in mixing soil with cement, lime, or other additives. (2) Randomly distributed fibres limit potential planes of weakness that can develop in the direction parallel to the conventionally oriented reinforcement. (3) The inclusion of fibre only changes the physical properties of soil and has no impact on the environment. For these reasons, researchers have shown an increasing interest in mechanical behaviours of fibre reinforced soils. A number of triaxial tests, unconfined compression tests, CBR tests, and direct shear tests have been conducted in recent years for this purpose (Ranjan et al., 1996; Kaniraj and Havanagi, 2001; Yetimoglu et al., 2005; Consoli et al., 2007; Ibraim et al., 2012; Plé and Lê, 2012). The results indicate that the discrete fibre reinforcement can significantly improve the mechanical performances of soil. Tang et al. (2007c) analysed the interfacial mechanical interactions between fibre surface and soil particles using scanning electron microscope. They concluded that the fibre reinforcement benefit on the mechanical properties is governed by the interfacial

* Corresponding author. Tel.: +86 25 83597888.
E-mail addresses: tangchaosheng@nju.edu.cn, tangchaosheng@163.com (C. Tang).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

Production and hosting by Elsevier

1674-7755 © 2014 Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. Production and hosting by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jrmge.2014.01.003

Table 1
Physico-mechanical properties of soil sample.

Specific gravity	Consistency limit			Compaction study		Grain size analysis				I.S. classification
	Liquid limit (%)	Plastic limit (%)	Plasticity index	Optimum moisture content (%)	Maximum dry density (g/cm^3)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	
2.7	36.4	18.6	17.8	16.5	1.7	0.0	1.7	67	31.3	CL

friction and cohesion. In order to determine the interfacial mechanical parameters, Tang et al. (2010b) conducted a series of single fibre pull-out test and measured the interfacial shear strength between fibre and soil matrix. They found that the interfacial shear strength increases with increasing compaction dry density and decreases with increasing compaction water content.

Although the mechanical behaviours (i.e. shear strength, compressive strength and bearing capacity) of fibre reinforced soil have been extensively studied in the past few decades, the effect of fibre reinforcement on soil tensile strength behaviour has not been well understood yet. In this study, discrete fibre reinforcement was proposed to improve soil tensile strength. An innovative tensile apparatus was developed for this purpose. Using this apparatus, a series of direct tensile tests were conducted on fibre reinforced soil in order to determine the tensile strength characteristics. The influences of fibre content, water content and dry density on tensile strength were analysed and associated mechanisms were discussed.

2. Direct tensile tests

2.1. Materials

The used soil was sampled from Nanjing, East China. The physico-mechanical properties are listed in Table 1. Short discrete polypropylene fibre (PP-fibre, 12 mm in length) was used as the reinforcement material. The physico-mechanical parameters of the PP-fibre provided by manufacture are given in Table 2. The PP-fibre shows a very good dispersibility. It is easy to mix with soil and obtain uniform mixture.

2.2. Sample preparation

The collected soil was air-dried ($w = 4.16\%$), crushed and passed through 2 mm sieve. The reinforced soil specimens were prepared by hand by mixing dry soil, distilled water and fibres. During mixing process, the required amount of water was added to the soil prior to adding the fibres. Fibres were mixed manually with the wet soil at small increments. Particular care was taken to achieve satisfactory uniform mixtures. In this experiment, four water contents (w = 14.5%, 16.5%, 18.5% and 20.5%) and five fibre contents (f = 0%, 0.05%, 0.1%, 0.15% and 0.2% by weight of dry soil) were adopted based on a previous study by Tang et al. (2010b). Prior to compaction, the prepared mixtures were conserved in air-proof bags for two days for the purpose of moisture homogenization.

A total of 11 groups of specimens were prepared. In order to investigate the effect of fibre content on soil tensile strength, tests S0–S4 were conducted on the specimens with different fibre contents ($f = 0$–0.2%) while compacted at the same water content ($w = 16.5\%$) and dry density ($\rho_d = 1.7$ Mg/m^3). In order to investigate the effect of water content on soil tensile strength, tests S0, and S5 to S7 were conducted on specimens compacted at different water contents ($w = 14.5\%, 16.5\%, 18.5\%$ and 20.5%) while with the same fibre content ($f = 0.1\%$) and dry density ($\rho_d = 1.7$ Mg/m^3). In order to investigate the effect of dry density on soil tensile strength, tests S2 and S8 to S10 were conducted on specimens compacted at different dry densities ($\rho_d = 1.4$ Mg/m^3, 1.5 Mg/m^3, 1.6 Mg/m^3 and 1.7 Mg/m^3) while with the same fibre content ($f = 0.1\%$) and water content ($w = 16.5\%$).

2.3. Test method and device

There are many methods used to determine soil tensile strength at present, which basically can be divided into two categories: indirect and direct methods. For the former one, the tensile strength is calculated according to some empirical correlations. The common indirect tensile test methods include Brazilian tensile test, flexure beam test, hollow cylinder test, double punch test, etc. (Ghosh and Subbarao, 2006; Viswanadham et al., 2010; Kim et al., 2012). Since the determination of tensile strength by indirect method is based on a series of theoretical assumptions, the calculated value usually cannot directly reflect the intrinsic mechanisms of soil tensile behaviours. Moreover, the measured tensile strength significantly depends on the employed test methods. Despite these limitations, many researchers still favoured it for its great testing convenience.

The direct test method is generally considered as the most reliable approach to measure tensile strength. An increasing tensile load is directly applied to the two ends of the specimens until tensile failure occurs. The monitored maximum tensile load is used to determine the tensile strength. Generally, the obtained tensile strength from direct tensile test is of high accuracy. However, it has been accepted that direct tensile tests are difficult to perform due to problems related to specimen preparation and test procedures. Thereby, this method needs development of new test setups and methodologies (Tang and Graham, 2000; Kim, 2001; Nahlawi et al., 2004; Tamrakar et al., 2005).

In this context, direct test method was employed. In order to facilitate the test procedures, a special compaction mould was designed to prepare 8-shaped specimens (80 mm long and 10 mm high, see Fig. 1). A neck at the centre of the specimen is formed to reduce the specimen width from 40 mm to 20 mm, allowing the specimen failure to occur at the centre section during tensile test. During compaction, the required quantity of soil mixture was put in the compaction mould and statically compacted to the target height (10 mm) at different dry densities (ρ_d = 1.4 Mg/m^3, 1.5 Mg/m^3, 1.6 Mg/m^3 and 1.7 Mg/m^3). After the specimen was compacted, it was extruded from the compaction mould and placed into the tensile mould (Fig. 1). The tensile mould consists of two halves of the split mould whose inner dimension is equivalent to the specimen's one.

Direct tensile tests were then conducted on the prepared 8-shaped specimens, using a newly developed apparatus as shown in Fig. 2. The tensile mould holding the specimen was hung on the crossbeam. The lower part of the tensile mould was connected to a

Table 2
Physico-mechanical parameters of PP-fibre.

Fibre type	Mass per unit length (g/cm)	Average diameter (mm)	Average length (mm)	Breaking tensile strength (MPa)	Modulus of elasticity (MPa)	Fusion point (°C)	Burning point (°C)	Acid and alkali resistance	Dispersibility
Single fibre	0.91	0.034	12	350	3500	165	590	Very good	Very good

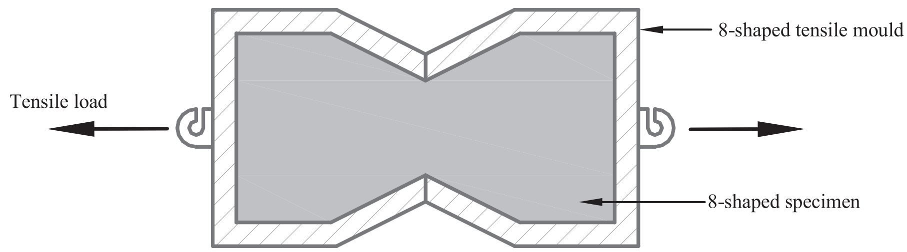

Fig. 1. Schematic drawing of the compacted 8-shaped soil specimen and tensile mould.

weight (2 kg), which was placed on a scale with a capacity of 100 N and a resolution of 0.001 N. During the test, the scale moved downwards with the loading disk at a uniform and low speed of 0.1 mm/min; the weight applied a tensile load to the specimen. This tensile load increased with the increase in displacement of loading disk until tensile failure occurred. The evolutions of tensile load and associated displacement were recorded by the scale and the displacement transducer (with a resolution of 0.01 mm), respectively. All data were then transferred to a computer by a data logger. The tensile strength σ_t was then calculated by dividing the maximum tensile load T_{max}, subtracting the weight W of the lower halves of the tensile mould, by the cross-sectional area A at the specimen's neck (20 mm × 10 mm). The tensile strength σ_t can then be written as

$$\sigma_t = \frac{T_{max} - W}{A} \quad (1)$$

3. Results and discussion

Using the self-developed tensile test apparatus, direct tensile tests were performed on the prepared 11 groups of specimens. The obtained tensile strengths of various tests were presented in Table 3. In the following sections, the tensile characteristics of fibre reinforced soil and the effects of fibre content, water content and dry density on the tensile strength will be discussed.

3.1. Tensile curves

Fig. 3 shows the typical tensile curves (tensile load versus displacement) of the specimens with different fibre contents. It can be seen that the tensile load increases monotonously with increasing displacement before reaching the peak value, where tensile failure occurs. After that, for the specimen without fibre reinforcement (test S0), the tensile load drops to zero abruptly, indicating brittle tensile failure of the specimen. For all the fibre reinforced specimens (tests S1 to S4) similar to the unreinforced specimen, there is a reduction in the applied load once the peak value was attained. However, due to the presence of fibres, a residual tensile load is maintained after failure, suggesting that the fibre inclusion is effective in improving soil failure ductility. This is because, on formation of tension cracks, further overall displacement of the specimen is concentrated on the elastic/plastic extension of the fibres across the opening and the bond slippage of the fibre anchorage in either side of the opening.

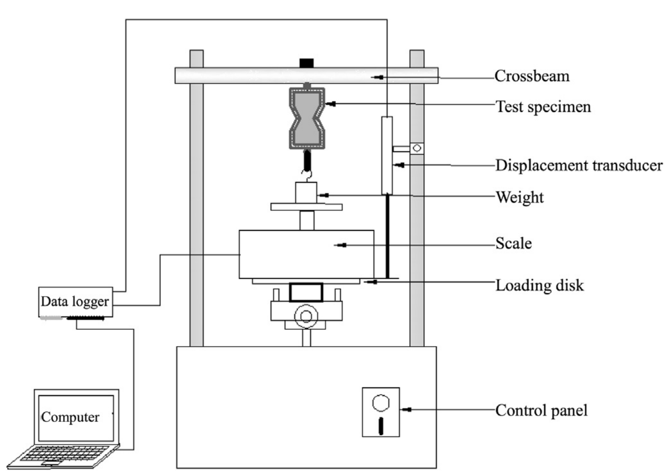

Fig. 2. Schematic drawing of tensile test device.

3.2. Effect of fibre content

Fig. 4 shows changes in tensile strength with different fibre contents. For the specimen without fibre inclusion, the measured tensile strength is 47.15 kPa. Here, the observed tensile strength is thought to be the maximum tensile stress necessary to break the bonds between soil particles along the failure plane. Generally, tensile strength of soil strongly depends on soil cohesion c. For saturated soils, the cohesion is mainly attributed to electrostatic attraction and bonds between particles. For unsaturated soils, the cohesion is also associated with suction. Morris et al. (1992) reported that, because of the different mechanisms involved in tensile failure and shear failure, soil tensile strength was usually far lower than cohesion determined by direct shear tests, the former often being half of the latter. Tang et al. (2007c) measured the cohesion of the same soil samples compacted at the same water content and dry density as described in this investigation, obtained the value of 75.51 kPa. The tensile strength (47.15 kPa) is approximately 0.6 times the cohesion, slightly higher than the empirical value (0.5 times) proposed by Morris et al. (1992).

Fig. 4 also shows that fibre inclusion can improve soil tensile strength, and the tensile strength increases with the increase of fibre content. For instance, the tensile strength increased by 65.7%, from 47.15 kPa to 78.11 kPa, when the fibre content increased from 0% to 0.2%. This is mainly because when the specimen is subjected

Table 3
Tensile results of various tests.

Test No.	Fibre content f (%)	Water content w (%)	Dry density ρ_d (Mg m^{-3})	Tensile strength σ_t (kPa)
S0	0	16.5	1.7	47.15
S1	0.05	16.5	1.7	55.90
S2	0.1	16.5	1.7	62.30
S3	0.15	16.5	1.7	67.23
S4	0.2	16.5	1.7	78.11
S5	0.1	14.5	1.7	71.75
S6	0.1	18.5	1.7	53.45
S7	0.1	20.5	1.7	50.25
S8	0.1	16.5	1.4	14.90
S9	0.1	16.5	1.5	26.31
S10	0.1	16.5	1.6	45.10

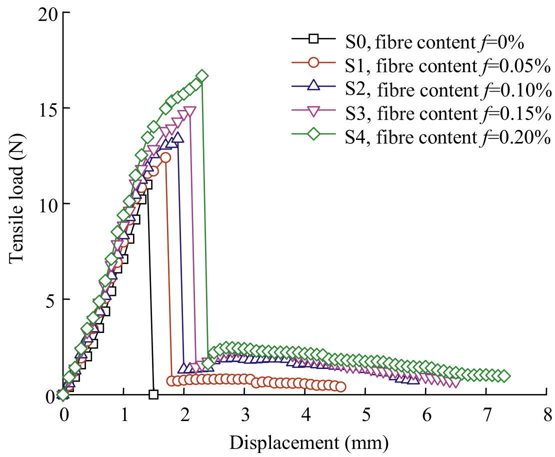

Fig. 3. The typical tensile curves of specimens with different fibre contents.

to tensile load, the slide of fibres in soil matrix is restricted by the interfacial mechanical interactions between fibre surface and soil particles. Consequently, fibres are capable of sharing some tensile load in soil matrix, and therefore increase the tensile strength. With increasing fibre content, the number of fibres per unit volume increased. The acquired reinforcement benefit of fibres to the tensile strength was therefore more pronounced.

3.3. *Effect of dry density*

In Fig. 5, it can be observed that the tensile strength of fibre reinforced soil increases with increasing dry density. When dry density increased from 1.4 Mg/m^3 to 1.7 Mg/m^3, the related tensile strength was increased by 275.2%, from 14.90 kPa to 55.90 kPa. It is believed that the dry density affects the contact conditions of soil particles. A higher dry density leads to more contacts between soil particles. This, in turn, leads to a greater bonding force between particles and hence greater tensile strength. Moreover, the increase of dry density also gives rise to an increase of fibre/soil interfacial contact area, which can improve the interfacial mechanical interactions and increase the interfacial shear strength. As a result, the fibre reinforcement benefit might be enhanced as compared to loose compacted specimen. This has been confirmed by Tang et al. (2010b) who performed single fibre pull-out test. They found that the interfacial shear strength between fibre surface and soil matrix was increased by 220.5% when the compacted dry density increased from 1.4 Mg/m^3 to 1.7 Mg/m^3. The anti-slide capacity and pull-out resistance of fibres in soil could therefore increase with increasing dry density.

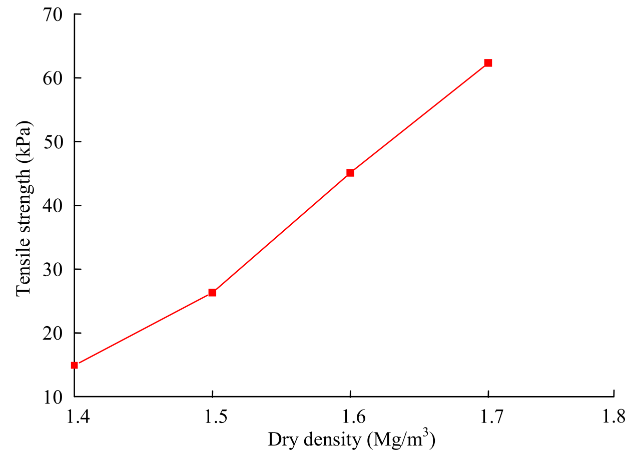

Fig. 5. Changes of soil tensile strength with dry density.

3.4. *Effect of water content*

In order to understand the influence of water content on soil tensile strength, four groups of specimens with different water contents, i.e. 14.5%, 16.5%, 18.5% and 20.5%, were prepared and subjected to direct tensile test. The obtained tensile strengths were presented in Fig. 6. It can be seen that the increase of water content resulted in a decrease of tensile strength. When water content was increased from 14.5% to 20.5%, the tensile strength was decreased by 30%, from 71.75 to 50.25 kPa. This observation can be explained from the following two aspects:

(1) Cohesion and suction decrease with increasing water content, thus the bonds between soil particles are weakened.
(2) The increase of water content may also weaken the interfacial mechanical interactions between fibre and soil matrix, and decrease the capability of fibre to bear the tensile load.

Actually, water plays an important role in lubricating layer on the interface of fibre/soil. Therefore, the increase of water content can induce a decrease of interfacial friction and cohesion. Potyondy (1961) performed a comprehensive investigation on the interface behaviour between construction materials (steel, concrete and wood) and soil, and identified that water content is one of the major factors affecting the interfacial friction. Farrag and Griffin (1993) found that an increase of water content can also result in a

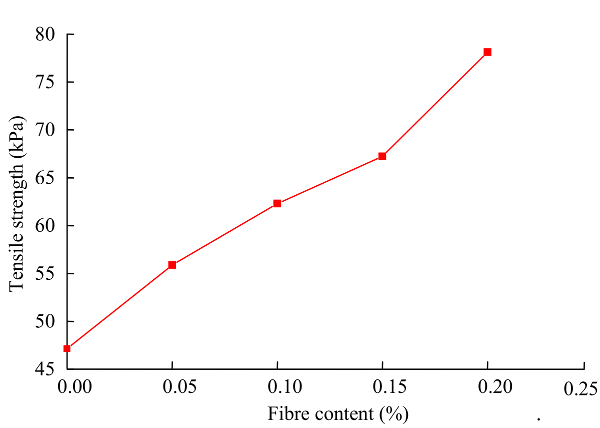

Fig. 4. Changes of soil tensile strength with fibre content.

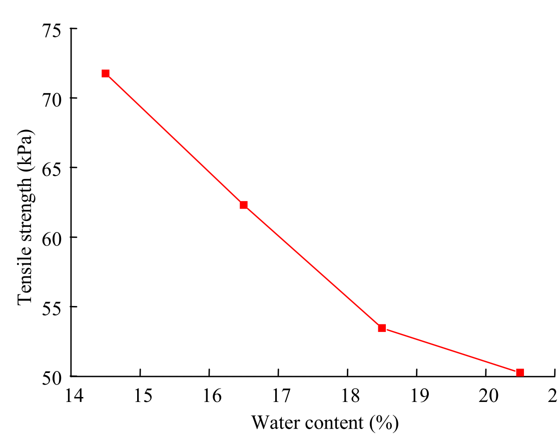

Fig. 6. Changes of soil tensile strength with water content.

decrease of the pull-out resistance of reinforcement. Tang et al. (2010b) quantitatively measured the interfacial shear strength of fibre reinforced soil by performing single fibre pull-out test. The results indicated that the interfacial shear strength was decreased from 177 kPa to 146 kPa.

4. Conclusions

Direct tensile tests were conducted on discrete fibre reinforced soil using the newly developed apparatus. The effects of fibre content, water content, and dry density on soil tensile strength were considered and the obtained results were discussed. The following conclusions can be drawn:

(1) The developed 8-shaped tensile mould constitutes a simple means of fixing soil specimen during tensile test. The proposed method and the developed apparatus provide a convenient way for measuring the tensile strength of geomaterials.
(2) Very small dosage of fibre inclusion can significantly enhance soil tensile strength. The tensile strength basically increases with increasing fibre content. As the fibre content increases from 0% to 0.2%, the tensile strength is increased by 65.7%. Moreover, fibre reinforcement changes soil's brittle tensile failure behaviour to ductile tensile failure behaviour. Due to the presence of fibres, a residual tensile load was maintained after tensile failure. It suggests that the fibre reinforcement is a favourable ground improvement technique, and has the potential to increase soil cracking resistance and the stability of earth structures.
(3) Tensile strength of fibre reinforced soil increases with an increase in dry density. It is mainly because that a higher dry density leads to more contacts between soil particles, and also gives rise to an increase of fibre/soil interfacial contact area. Consequently, the fibre reinforcement benefit on tensile strength is improved.
(4) Tensile strength of fibre reinforced soil decreases with increase in water content. It is because the bonds between soil particles and the interfacial mechanical interactions between fibre surface and soil matrix are weakened by adding water.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgement

This work was gratefully supported by the National Natural Science Foundation of China (Grant Nos. 41072211, 41322019), Natural Science Foundation of Jiangsu Province (Grant No. BK2011339), Opening Fund of State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (Chengdu University of Technology) (SKLGP2013K010).

References

Ahmad F, Bateni F, Azmi M. Performance evaluation of silty sand reinforced with fibers. Geotextiles and Geomembranes 2010;28(1):93–9.
Albrecht BA, Benson CH. Effect of desiccation on compacted natural clay. Journal of Geotechnical and Geoenvironmental Engineering 2001;127(1):67–75.
Chen YL, Wang M, Xu S, Chang LQ, Yin ZZ. Tensile and compressive strength tests on artificial frozen soft clay in Shanghai. Chinese Journal of Geotechnical Engineering 2009;31(7):1046–51 (in Chinese).
Consoli NC, Casagrande MDT, Coop MR. Performance of fibre-reinforced sand at large shear strains. Geotechnique 2007;57(9):751–6.
Consoli NC, da Fonseca AV, Cruz RC, Silva SR. Voids/cement ratio controlling tensile strength of cement-treated soils. Journal of Geotechnical and Geoenvironmental Engineering 2011;137(11):1126–31.
Farrag KA, Griffin P. Pull-out testing of geogrids in cohesive soils. In: Cheng SCJ, editor. Geosynthetic Soil Reinforcement Testing Procedures. Philadelphia: ASTM STP 1190; 1993. pp. 76–89.
Ghosh A, Subbarao C. Tensile strength bearing ratio and slake durability of class F fly ash stabilized with lime and gypsum. Journal of Materials in Civil Engineering 2006;18(1):18–27.
Hu HJ, Jiang MJ, Zhao T, Peng JB, Li H. Effects of specimen-preparing methods on tensile strength of remolded loess. Rock and Soil Mechanics 2009;30(Suppl. 2): 196–9 (in Chinese).
Ibraim E, Diambra A, Russell AR, Muir Wood D. Assessment of laboratory sample preparation for fibre reinforced sands. Geotextiles and Geomembranes 2012;34:69–79.
Kaniraj SR, Havanagi VG. Behaviour of cement-stabilized fiber-reinforced flyash-soil mixtures. Journal of Geotechnical and Geoenvironmental Engineering 2001;127(7):574–84.
Kim TH. Moisture-induced tensile strength and cohesion in sand. Ph.D. Thesis. Boulder Colorado: University of Colorado; 2001.
Kim TH, Kim TH, Kang GC, Ge L. Factors influencing crack-induced tensile strength of compacted soil. Journal of Materials in Civil Engineering 2012;24(3):315–20.
Miller CJ, Mi H, Yesiller N. Experimental analysis of desiccation crack propagation in clay liners. Journal of the American Water Resources Association 1998;34(3): 677–86.
Morris PH, Graham J, Williams DJ. Cracking in drying soils. Canadian Geotechnical Journal 1992;29(2):263–77.
Nahlawi H, Chakrabarti S, Kodikara J. A direct tensile strength testing method for unsaturated geomaterials. Geotechnical Testing Journal 2004;27(4):1–6.
Plé O, Lê TNH. Effect of polypropylene fiber-reinforcement on the mechanical behaviour of silty clay. Geotextiles and Geomembranes 2012;32:111–6.
Potyondy JG. Skin friction between various soils and construction materials. Geotechnique 1961;11(4):339–53.
Ran LZ, Song XD, Tang CS. Laboratorial investigation on tensile strength of expansive soil during drying. Journal of Engineering Geology 2011;19(4):620–5 (in Chinese).
Ranjan G, Vasan RM, Charan HD. Probabilistic analysis of randomly distributed fiber-reinforced soil. Journal of Geotechnical Engineering 1996;122(6):419–26.
Shindea SB, Kalaa VU, Kadalia S, Tirumkudulub MS, Singha DN. A novel methodology for measuring the tensile strength of expansive clays. Geomechanics and Geoengineering: An International Journal 2012;7(1):15–25.
Tamrakar SB, Toytosawa Y, Mitachi T, Itoh K. Tensile strength of compacted and saturated soils using newly developed tensile strength measuring apparatus. Soils and Foundations 2005;45(6):103–10.
Tang CS, Shi B, Gao W, Cai Y, Liu J. Study on effect of sand content on strength of polypropylene fiber reinforced clay soil. Chinese Journal of Rock Mechanics and Engineering 2007a;26(Suppl. 1):2968–73 (in Chinese).
Tang CS, Shi B, Gao W. Influence of polypropylene fiber and cement addition on strength behaviour of clay soil and the mechanisms. Journal of Engineering Geology 2007b;15(1):108–13 (in Chinese).
Tang CS, Shi B, Gao W, Chen FJ, Cai Y. Strength and mechanical behaviour of short polypropylene fiber reinforced and cement stabilized clayey soil. Geotextiles and Geomembranes 2007c;25(3):194–202.
Tang CS, Cui YJ, Tang AM, Shi B. Experiment evidence on the temperature dependence of desiccation cracking behaviour of clayey soils. Engineering Geology 2010a;114(3–4):261–6.
Tang CS, Shi B, Zhao LZ. Interfacial shear strength of fiber reinforced soil. Geotextiles and Geomembranes 2010b;28(1):54–62.
Tang CS, Shi B, Liu C, Suo WB, Gao L. Experimental characterization of shrinkage and desiccation cracking in thin clay layer. Applied Clay Science 2011;52(1–2):69–77.
Tang GX, Graham J. A method for testing tensile strength in unsaturated soils. Geotechnical Testing Journal 2000;23(3):377–81.
Viswanadham BVS, Jha BK, Pawar SN. Experimental study on flexural testing of compacted soil beams. Journal of Materials in Civil Engineering 2010;22(5):460–8.
Yetimoglu T, Salbas O. A study on shear strength of sands reinforced with randomly distributed discrete fibers. Geotextiles and Geomembranes 2003;21(2):103–10.
Yetimoglu T, Inanir M, Inanir OE. A study on bearing capacity of randomly distributed fiber-reinforced sand fills overlying soft clay. Geotextiles and Geomembranes 2005;23(2):174–83.

Dr. Chaosheng Tang is now Associate Professor of Geological Engineering at Nanjing University. His research interests cover soil-atmosphere interactions, geological/geotechnical problems related to climate change, coupled soil science-mechanics-structure behaviour, soil desiccation cracking, fibre reinforced soils, unclear waste disposal, etc.