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SHEAR STRENGTH OF CONTINUOUS-FILAMENT REINFORCED SAND

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ABSTRACT

The fiber-reinforced soil technique is a method in which discrete fibers or continuous filaments are mixed with soil to improve the shear strength of the composite and to constrain the deformation of reinforced structure. The objective of this study focused on investigating the shear strength of continuous-filament reinforced sand. A series of direct shear tests were performed to examine the shear behavior of reinforced sand. The factors considered in the tests included the content, diameter, and orientation of the fiber reinforcement. The test results show that specimens with reinforcement had higher shear strength than sand alone, in both peak and residual states. It was also found reinforcement could improve the cohesion intercept as well as the friction angle of the composite. However, the increase in friction angle with increasing fiber content was only up to certain content, and thereafter it reduced. Thus, the specimens displayed the best reinforcing effect at an optimum fiber content that varied with the normal stress acting on the specimen. With regard to the diameter of reinforcement, the thinner reinforcement obtained higher resistance than the thicker at the same fiber content. The contribution of the resistance was mainly due to improvement in the apparent cohesion of the specimen. Moreover, fibers orienting perpendicularly to shear plane performed much well than those parallel to the shear plane.

Key words: Continuous filament, reinforcement, sand, direct shear test, shear strength.

1. INTRODUCTION

The fiber-reinforced soil is a technique in which discrete fibers or continuous filaments are mixed with soil to improve the shear strength of the composite and to constrain the deformation of reinforced structure. The technique has been used in various applications ranging from retaining walls and slope protections, reinforcement of embankments, and enhancement of the bearing capacity of footings and pavements. Discrete fibers are generally employed for improving bearing capacity, while the main application of continuous filaments is to prevent slopes from erosion or shallow failure.

The fiber-reinforced soil was developed in early 1980s in France (Leflaive 1982). The characteristics of the composite make it possible to support talus with steep slopes. These very steep works, either on cuts or fills, bring a simple solution to remedial landslides or to stabilize slopes with limited lands (Khay *et al*. 1990; Ishizaki *et al*. 1992). Moreover, the reinforced-soil is malleable to conform to the topography and can alter shape considerably under stress. It can also be applied without destructing existing trees or plant roots. A method using soils reinforced with continuous filaments for vegetation establishment on slopes has been reported (Nakagoshi *et al.* 2006). The primary purpose was to protect and stabilize the surface of bare slopes in a short period of time as well as preserving scenic beauty.

In the study of discrete fibers, a number of researches performed triaxial test, direct shear test, and unconfined compression test to examine the stress-strain characteristics and the strength response of reinforced soils (Gray and Ohashi 1983; Gray and Al-Refeai 1986; Maher and Gray 1990; Al-Refeai 1991; Ranjan *et al.* 1994; Consoli *et al.* 1998; Michalowski and Čermák 2003; Yetimoglu and Salbas 2003; Tang *et al*. 2007). Most of them indicated the failure envelopes of the specimens with discrete fibers were either curved-linear or bilinear, and the improved shear strength was clear. Besides, the shear strength increased with increasing reinforcement content and the aspect ratio (length/diameter) of fiber (Gray and Al-Refeai 1986; Ranjan *et al*. 1994; Michalowski and Čermák 2003). As expected, specimens with long fibers showed higher strength than those with short fibers of the same aspect ratio; nevertheless, there was an optimum length resulting from the difficulty in mixing and controlling the uniformity of specimens as fiber length increased (Gray and Ohashi 1983; Al-Refeai 1991; Ranjan *et al*. 1994). The optimum content of fibers, about 2% of soil weight, was also noted. In other words, the increased strength reached an asymptotic upper limit as the content was about 2%. This might be due to fibers occupying a relatively large volume in the composite (Ranjan *et al*. 1994); thus the quantity of soil matrix available for holding fibers was insufficient to develop an effective bond between the fibers and soil. In summary, inclusion of reinforcement into soil can generally improve the shear strength as well as the ductility of the soil.

Although much research has extensively studied the behav-

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ior of discrete fibers, only a few studied continuous filaments. From a few laboratory studies on soil reinforced with continuous filaments, the results pointed out reinforcement improved the shear strength of sand, clearly on the cohesion intercept but only slightly on the friction angle. Leflaive and Liausu (1986) reported fine sand reinforced with thin filaments had higher shear strength than coarse sand reinforced with thick filaments. It was also found that the fines content in the soil decreased the reinforcing effect. Stauffer and Holtz (1995) reported a reinforced well-graded, sub-angular sand showed greater increases in stress-strain characteristics than a reinforced uniformly-graded, sub-rounded sand. Sand granulometry had no apparent effect on the Mohr-Coulomb parameters of reinforced sands. For different fiber types, continuous filaments could provide more strength increases than discrete fibers.

From aforementioned results, the shear mechanism of reinforced soil was not discussed in details. The aim of this study tries to clarify the effect of orientation of filaments and also to find out the best reinforcing effect of fiber content. Moreover, previous studies commonly prepared specimens by mixing the components of sand and reinforcement by hand until the reinforcement appeared to be randomly distributed throughout the sand. This study used an alternative method to prepare specimens and employed a more accurate image technique to verify the uniformity within the specimens. It is hoped that the results of this study will provide a valuable reference for applying fiber-reinforced soil in the field.

2. TESTING PROGRAM

This study examined the shear behavior of reinforced sand by performing a series of direct shear tests (ASTM D3080-04). The direct shear test is relatively inexpensive, fast, and simple, especially for granular materials. This test can also be used to find the effect of the orientation of filaments with respect to a predetermined shear plane.

The tests were conducted in a shear box of 100 mm × 100 mm in plane and 42 mm in depth. The specimens were subjected to vertical stresses of 50, 100, 200, and 300 kPa. The shearing rate was 0.002 mm/s. Shear stresses were recorded up to a horizontal displacement of 12 mm to observe the post-failure behavior. The main variables considered in the tests are as follows:

1. reinforcement content — 0.3 ~ 2.5% by soil weight.
2. fiber diameter — 0.190, 0.245, and 0.260 mm.
3. orientation — the longitudinal axis of a cylindrical fiber spiral along the x-, y- or z-direction.

To observe the deformation of specimen, some were frozen after the test and the shear patterns of different orientations of reinforcement were compared.

2.1 Material Used for Testing

Soil used in the present investigation was uniform, sub-angular sand. It is classified as poorly-graded sand (*SP*) as per the Unified Soil Classification system, with a coefficient of uniformity $C_u = 1.57$ and a coefficient of curvature $C_c = 0.95$. The physical properties of the sand are as follows: specific gravity $G_s = 2.65$, maximum unit weight $\gamma_{d,\max} = 16.6$ kN/m^3, minimum unit weight $\gamma_{d,\min} = 14.3$ kN/m^3, average diameter $d_{50} = 0.19$ mm, and effective grain size $d_{10} = 0.13$ mm. Besides, the peak and residual friction angles at relative density of 60% of the sand are $\phi_p = 39.2°$ and $\phi_r = 35.5°$, respectively. The average water content of the sand was 0.05%; therefore the sand was regarded as dry.

The high density polyethylene fiber (HDPE) has a density $\rho_f = 0.94$ Mg/m^3, mean tensile strength $\sigma_f = 5.84 \times 10^5$ kPa, elastic modulus $E = 4.55 \times 10^6$ kPa, and elongation at rupture $\varepsilon_f = 25.1\%$. The continuous filament had three kinds of diameter, *i.e.*, 0.190, 0.245, and 0.260 mm. The deniers of each fiber are 420 (0.190 mm), 540 (0.245 mm) and 570 (0.260 mm). Reinforcement content was controlled by the weight of sand.

2.2 Testing Program

The testing variables were the content, diameter, and orientation of reinforcement. Table 1 gives the details of different mixtures and the notation used for the tests. The test numbers are denoted as: *S* for unreinforced sand, *C* for continuous-filament reinforced sands, respectively. In which *C*1 and *C*8 were tested at fiber content equal to 1.0%; *C*2 to *C*7 had contents ranging from 0.3 ~ 2.5%; *Cx*, *Cy* and *Cz* were carried out to examine the effect of fiber orientation.

2.3 Preparation of Specimen

For reinforced and unreinforced specimens, the sand was pluviated into the direct shear box; the pluviating distance was kept at 100 mm to obtain the same relative density of soil, $D_r = 60\%$, excluding the volume of reinforcement.

In the preparation of specimens with randomly distributed continuous filaments, *C*1 to *C*8, the weights of the sand and filament were calculated first. Then the filament was curled by winding it around a steel bar, 300 mm long with a diameter of 6.5 mm, using a self-developed automatic device which can curl a filament of more than 25 m long. After that, the filament was made loose and its shape was adjusted to fit uniformly into the shear box. An imaging technique, MATLAB (Mathworks 2004), was employed to evaluate the deepness of color which represents the amount of filaments in the box; a high color level represents more filaments. The distribution of color levels of grids were used to verify the uniformity of filament distribution in the specimen. As shown in Fig. 1, the gray level was an index of the surface color of filaments in the box. The value in each grid should not differ from the mean value by more than 5%. When the uniformity was attained, the sand was then divided into five portions to pluviate through a funnel into the shear box.

Table 1 Arrangement of direct shear test

Test number	Fiber diameter d_f (mm)	Fiber content ρ (%)	Unit weight γ_d (kN/m^3)	Cohesion intercept c (kPa)	Friction angle ϕ (°)
S	–	–	15.7	0	39.2
*C*1	0.190	1.0	16.2	13.7	43.9
*C*2	0.245	0.3	15.9	2.4	40.9
*C*3	0.245	0.5	16.0	4.2	41.4
*C*4	0.245	1.0	16.2	8.9	43.7
*C*5	0.245	1.5	16.3	13.0	46.7
*C*6	0.245	2.0	16.5	18.9	45.5
*C*7	0.245	2.5	16.7	19.5	44.3
*C*8	0.260	1.0	16.2	7.8	43.6
Cx	0.245	0.3	15.9	2.9	42.1
Cy	0.245	0.3	15.9	3.7	40.2
Cz	0.245	0.3	15.9	2.7	38.4

Note: *S* = sand alone, *C* = sand with continuous filament

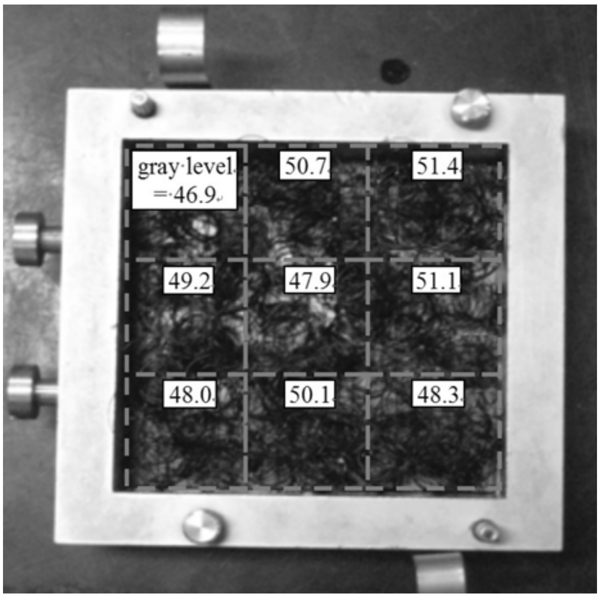
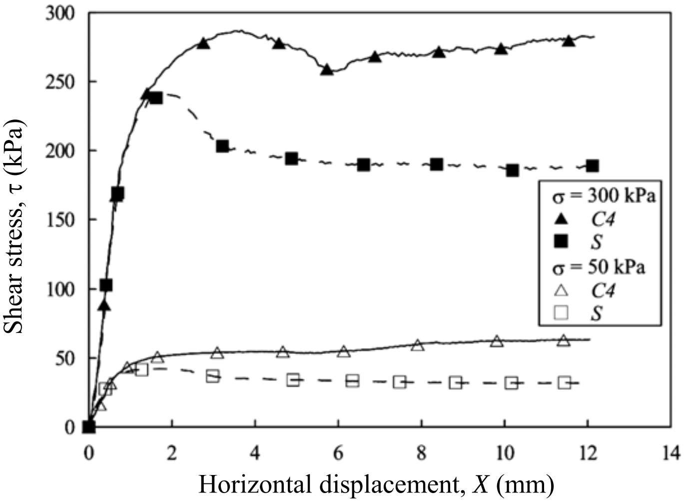


Fig. 1 Preparation of specimen for uniformity analysis on filament distribution

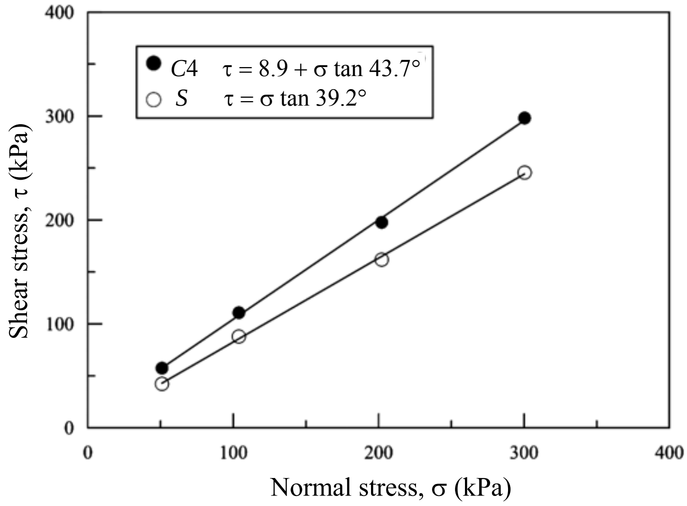
3. TEST RESULTS

To examine the effect of filament inclusion on the shear behavior of specimen, the shear stress versus horizontal displacement curves for unreinforced sand, *S*, and reinforced sands, *C*4 are compared in Fig. 2(a). It can be seen the initial slopes of the curves under the same normal stress remained practically the same for both the reinforced and unreinforced specimens. At this stage, the strength seemed to be mainly provided by the friction of sand only. However, the curves of reinforced specimens displayed better strength both at the peak and residual stages than the unreinforced sand.

Furthermore, the reinforcement changed the brittle behavior of the sand to be more ductile (Fig. 2(a)). For example, under high normal stress of 300 kPa, the strains at rupture in specimens *S* and *C*4 were 2 mm and 4 mm, respectively. The post-peak shear stress in the reinforced sand dropped, but subsequently it tended to rise. This phenomenon was clear for reinforced sand under high normal stresses, due to a developed tensile strength in the reinforcement.



(a) Stress-displacement curves



(b) Failure envelopes

Fig. 2 Comparison of test results on unreinforced and reinforced sand specimens

The Mohr-Coulomb failure envelopes are plotted in Fig. 2(b). It is seen the reinforcement can not only improve the cohesion intercept but also improve the friction angle. The improvement in cohesion intercept resulted from the developed anchorage forces of reinforcements randomly distributed in the voids of soil. As small deformations took place in reinforced soil, reinforcements were placed under tension. This tension mobilized shear stress along the soil-reinforcement interface to a large distance outside the shearing plane. On the other hand, the improvement in friction angle was affected by the contact between soil particles and the interface of soil-reinforcement. Under increasing normal stress, soil particles tended to become denser and closer to fibers; they might even penetrate the fibers resulting in greater shear resistance. Fiber resistance strongly depended on fiber roughness (Frost and Han 1999). As fibers were mixed or samples were compacted, the hard particles of the mixtures impacted and abraded the fiber surface, causing plastic deformation and even removal of part of the surface layer (Tang *et al*. 2007). The above behavior is explained in Fig. 3. The continuous filament provided resistances from the friction on the surface of filament, *f*, the tensile force delivered in the filament, T_2, as well as extra confining stresses, *q*, brought by the filament exerting on adjacent particles. Due to these forces, continuous filaments thus contributed great improvement to the cohesion intercept.

The above findings are the phenomena showing the effect of fiber reinforcement. In the following, specific discussion on the effects of fiber content, fiber diameter, and fiber orientation are presented.

3.1 Effect of Reinforcement Content

For observation of the effect of reinforcement content, fibers of 0.245 mm with content from 0.3% to 2.5% were adopted (serial number *C*2 to *C*7, see Table 1). The shear stress versus horizontal displacement curves are shown in Fig. 4. In general, the peak and residual strengths increased with the increase in fiber content, regardless of normal stress at 50 kPa or 300 kPa. One exception is for specimen with ρ = 2.5% and σ = 300 kPa (Fig. 4(b)), displaying lower peak strength than with ρ = 1.5%. This

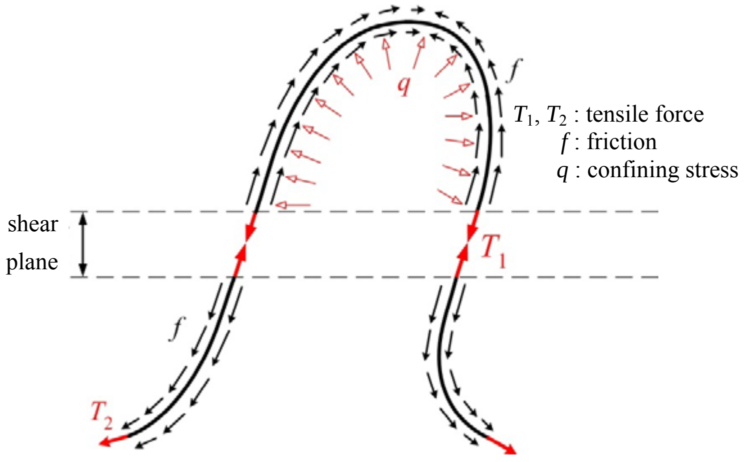
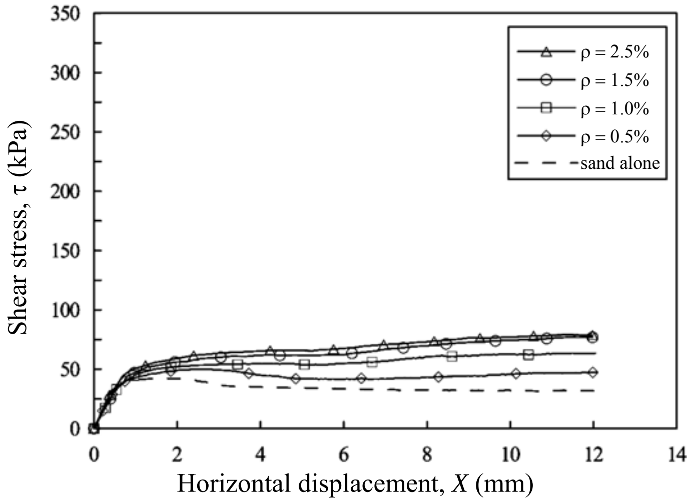
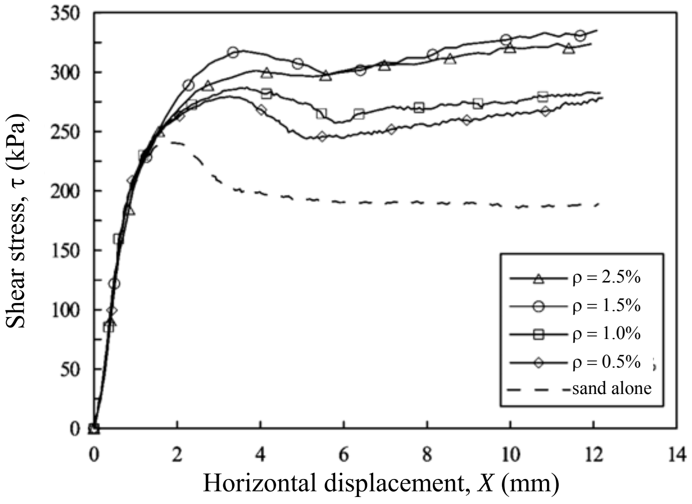


Fig. 3 Free body diagram of a fiber embedded in soil



(a) σ = 50 kPa



(b) σ = 300 kPa

Fig. 4 Stress-displacement curves at different reinforcement contents

suggests an optimum fiber-content, OFC, was present in terms of the shear strength of reinforced sand. In other words, the best reinforcing behavior occurred at the OFC. For this reason, the relationship between the increase in peak strength, Δτ (reinforced sand subtracted from unreinforced sand), and the fiber content are plotted in Fig. 5. Clearly, there is an optimum point for each curve. By connecting the optimum points, a line of OFC can be drawn and the OFC decreases with increasing normal stress.

In an alternating way, the peak strength parameters, c and ϕ, are presented in Fig. 6 for various fiber contents. It is found the cohesion intercept kept increasing as the fiber content increased; nevertheless, the friction angle decreased when $\rho > 1.5\%$. As a result, for the combination of a reduction in ϕ with a high normal stress, the peak strength of reinforced sand decreased even though the cohesion intercept was increasing. This explains the existence of OFC shown in Fig. 5.

The preceding paragraph mentions the improvement in the cohesion intercept partly originated from the confinement of the soil particles. Thus, raising fiber content would enhance the cohesion intercept as well. However, the high fiber content also resulted in less contact between soil particles and might simultaneously reduce the friction angle. When the normal stress was low, the cohesion intercept dominated and contributed more to the shear strength than the friction angle did. Therefore, in Fig. 5, the highest point on the curve of low normal stress, $\sigma = 50$ kPa, is at the highest content, $\rho = 2.5\%$. As the normal stress increased, the contribution of friction angle became more and more important than the cohesion intercept. This explains the reason, at high normal stress of $\sigma = 300$ kPa, the corresponding OFC was low, *i.e.*, $\rho = 1.5\%$ instead of 2.5%.

According to the aforementioned aspect, reinforced sand showed the best reinforcing effect at optimum fiber-contents ranging between 1.5 ~ 2.5%, depending on the normal stress. Theoretically, this implies the fiber content may be adjusted according to the designed overburden pressure. In other words, less fiber content may be used when the overburdened pressure the soil subjected to is high, and vice versa.

3.2 Effect of Fiber Diameter

To study the effect of fiber diameter, three diameters of 0.190, 0.245, and 0.260 mm were adopted and tested under the same content, $\rho = 1.0\%$. Table 2 shows thinner filament displays higher shear strength under different normal stresses. This agrees with previous works that an increase in aspect ratio (length/diameter) resulted in better stress-strain characteristics (Maher 1988; Gray and Maher 1989).

Table 2 also indicates the cohesion intercept decreases with larger fiber diameter, but the difference in the friction angle is practically insignificant. Under the same content, the thinner filament, due to the smaller cross-sectional area and longer, provided higher resistance than the thicker. Besides, the thin filament is more flexible than the thick; thus it was easier to fit in the voids of soil and wrapped around sand particles leading to a better pullout resistance as well as shear strength. The effect is reflected in the appreciable improvement in the cohesion intercept. Since the improvement in the friction angle was mainly provided by the frictional resistance between sand particles, the variation in ϕ among filaments of different diameters was not obvious due to filaments being a small proportion compared to sand.

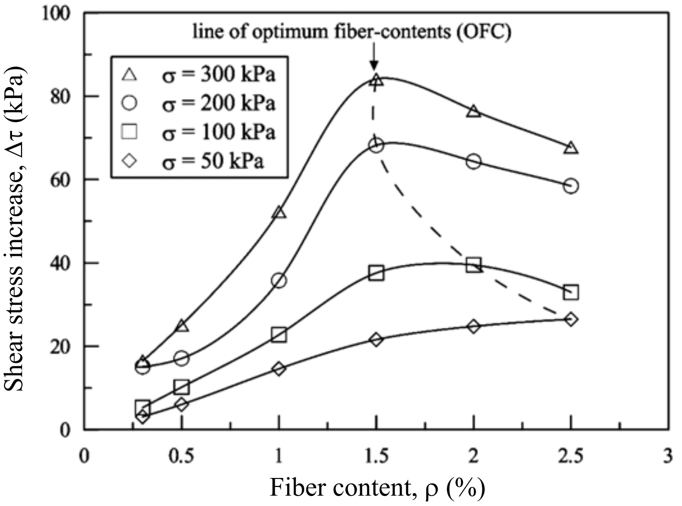


Fig. 5 Optimum fiber contents

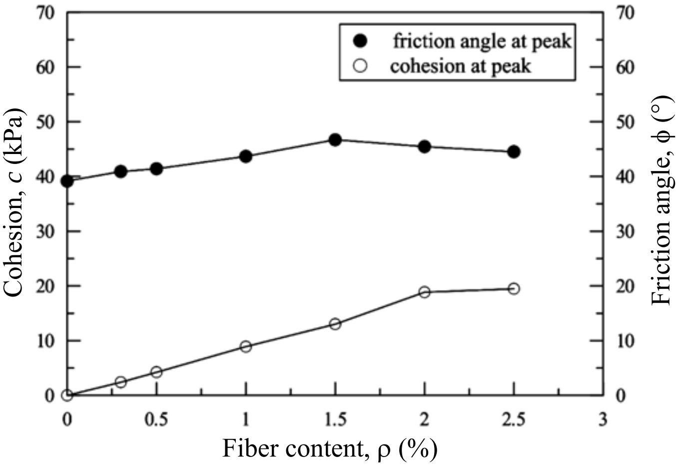


Fig. 6 Relationship between shear strength parameters and fiber contents

Table 2 Shear strengths of sand with fibers of different diameters

Test number	Fiber diameter d_f (mm)	Shear strength at peak τ (kPa)				Cohesion intercept c (kPa)	Friction angle ϕ (°)
		Normal stress σ (kPa)					
		50	100	200	300		
*C*1	0.190	60.3	117.9	204.9	303.2	13.7	43.9
*C*4	0.245	57.3	110.7	197.7	298.0	8.9	43.7
*C*8	0.260	58.2	107.4	193.2	297.4	7.8	43.6

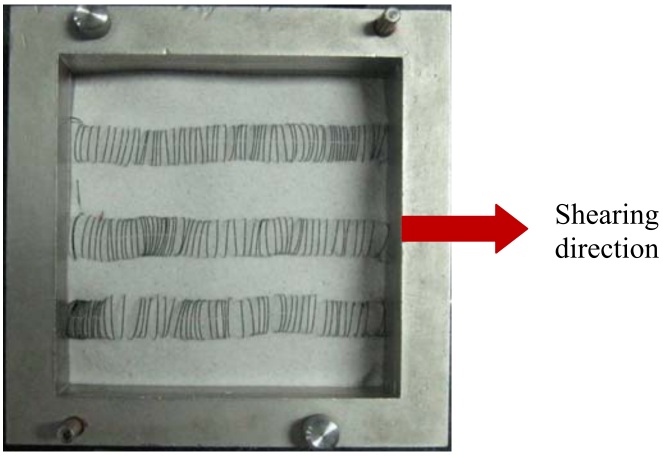
3.3 Effect of Fiber Orientation

In regard to the effect of orientation of discrete fibers, Gray and Ohashi (1983) indicated that the shear strength increases of reinforced soil were greatest for initial fiber orientations of 60° with respect to the shear surface. This orientation coincides with the direction of maximum principal tensile strain in a direct shear test. Michalowski and Čermák (2003) and Diambra *et al*. (2010) also developed significant models to assess the states of discrete-fiber orientations. However, it is still interesting to know to what extent the orientation of continuous filament would affect the shear strength of a composite as well as the reinforcing mechanism. In this respect, a series of tests were conducted on the reinforced sand with filaments of equal diameter and content, d_f = 0.245 mm and ρ = 0.3%, but with different orientations, as shown in Fig. 7. The longitudinal axis of the filament spiral in each specimen was set to orient in the x-, y-, and z-directions. For example, in the test *Cx* the long axis of the filament spiral was in the *x*-direction (Fig. 7(a)), and vice versa. Further, for understanding the deformation process during shearing, the specimen after testing was immediately inundated with water and then frozen to preserve the deformed shape.

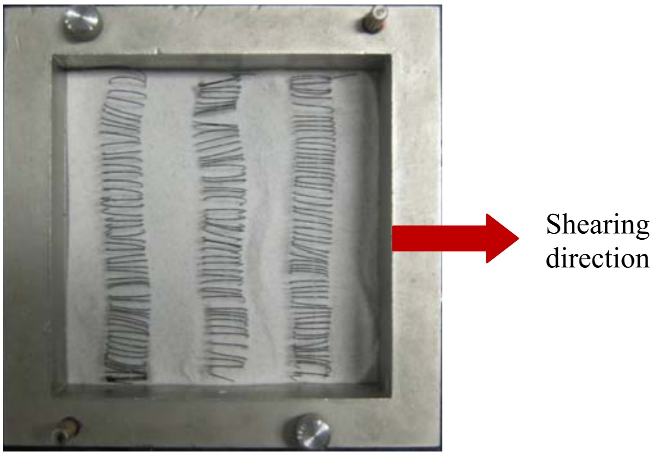
According to the shear strength increases presented in Table 3, specimen *Cx* had the highest shear strength among three tests; specimen *Cz* displayed the lowest strength and nearly no improvement compared with the unreinforced sand. The difference can be explained by examining the deformed shape of each specimen shown in Fig. 8. In fact, specimens of *Cx* and *Cy* had the same number of filaments intersecting with the shear plane (Figs. 8(a) and 8(b)). However, the cross-section of the filament spiral in the *Cy* specimen were sheared and stretched with the two ends of spiral also loosened. Consequently, the pullout resistance was reduced. On the contrary, the spiral in *Cx* specimen was lengthened but its anchoring capacity maintained. In addition, the improvement in the shear strength in *Cx* was mainly from the friction between displaced particles and the sand-fiber interface (Fig. 8(a)). It can be seen the contribution in shear strength was chiefly from the friction angle, 42.1° (Table 3). For the *Cy* specimen, the filament was stretched and exerted confining stresses on the surrounding particles (Fig. 8(b)), therefore resulting in the highest cohesion intercept of 3.7 kPa.

Finally, the specimen of *Cz* displayed the lowest strength. Seemingly, it was because there were only a few filaments near the shear plane, and few of them intersecting with the plane (Fig. 8(c)). Those outside the shear plane were practically not deformed. Even so, the filaments across the shear plane were able to produce some confinement to soil particles as well as anchorage forces when they were stretched, thereby inducing the increase in cohesion intercept (Table 3). However, the resulting friction angle, 38.4°, was not improved and even less than that of the sand, 39.2°.

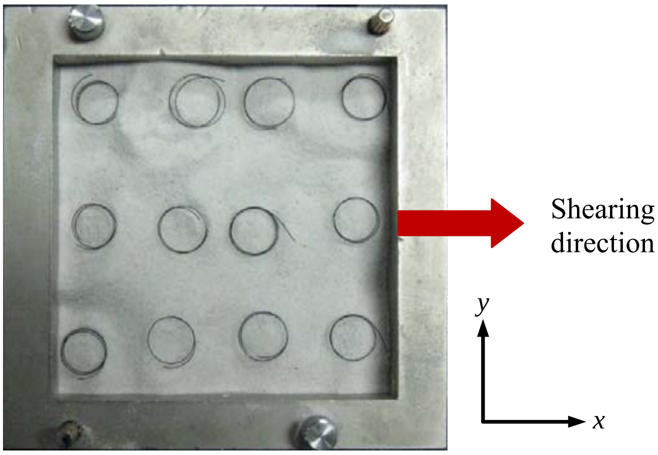
Table 3 also shows the comparison of the average shear strength increase of *Cx* ~ *Cz* specimens with those of *C*2. These tests had the same test conditions except that the filaments in *C*2 were randomly placed. Note, the average values are not very different from those of *C*2. This might be the evidence that the amount of filaments oriented in every direction in a randomly distributed specimen were about the same. Moreover, the average strength increase of *Cx* and *Cy* was greater than that of *C*2.



(a) *Cx*: along *x*-direction



(b) *Cy*: along *y*-direction



(c) *Cz*: along *z*-direction

Fig. 7 Specimens with continuous filaments oriented along different directions

Table 3 Test results of specimens with different fiber orientations

Test number	Shear strength increase $\Delta\tau$ (kPa)						Cohesion intercept c (kPa)	Friction angle ϕ (°)
	Normal stress σ (kPa)							
	50		100		300			
Cx	7.4	(18.3)	7.6	(8.6)	29.1	(11.9)	2.9	42.1
Cy	2.2	(5.6)	5.9	(6.3)	11.0	(4.3)	3.7	40.2
Cz	0.2	(0)	−1.8	(−2.0)	−4.9	(−2.0)	2.7	38.4
Average of *Cx*, *Cy*, *Cz*	3.3	(7.9)	3.9	(4.3)	11.7	(4.7)	3.1	40.2
*C*2	3.1	(8.1)	5.3	(6.0)	16.5	(6.7)	2.4	40.9

Note: The numbers in the parentheses are the strength increase in percent.

It is now clear that the shear resistance was mainly provided from the filaments oriented near perpendicularly to the shear plane, such as the filaments in *Cx* and *Cy*. In practice, when applying this technique to slope protections, filaments are usually injected with sand simultaneously onto the slope face. If the sprayer was manipulated by an up-and-down sequence to make the filaments orientate more perpendicularly to the shear plane, theoretically, it would be more beneficial.

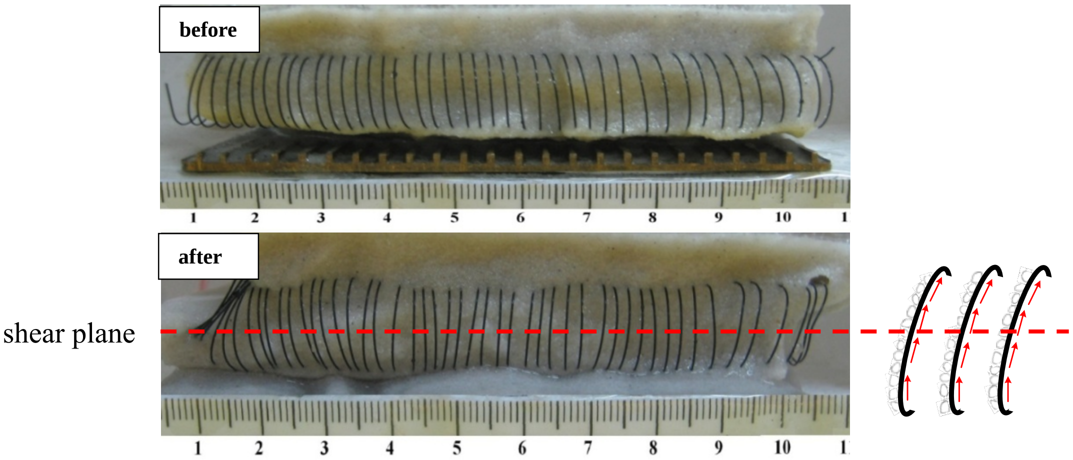
4. DISCUSSION

This study showed that c and ϕ were both increased by adding filaments in sand, whether the specimen was at peak or residual strength states. Comparison for the values of these two parameters with limit data from relevant studies is presented in Fig. 9. In the figure, the results of filaments are denoted as solid symbols, and hollow symbols denote those of the discrete fibers. In general, the variations may be expectedly due to several factors such as test method, reinforcement type, aspect ratio, soil, *etc*. Nevertheless, the trend that high cohesion intercept corresponding to high fiber content is consistent (Fig. 9(a)). Above all, the difference in the range of increased cohesion is most likely attributed to the aspect ratio of reinforcement, *i.e.*, thin and long filaments usually have better confinement on soil particles than thick and short filaments.

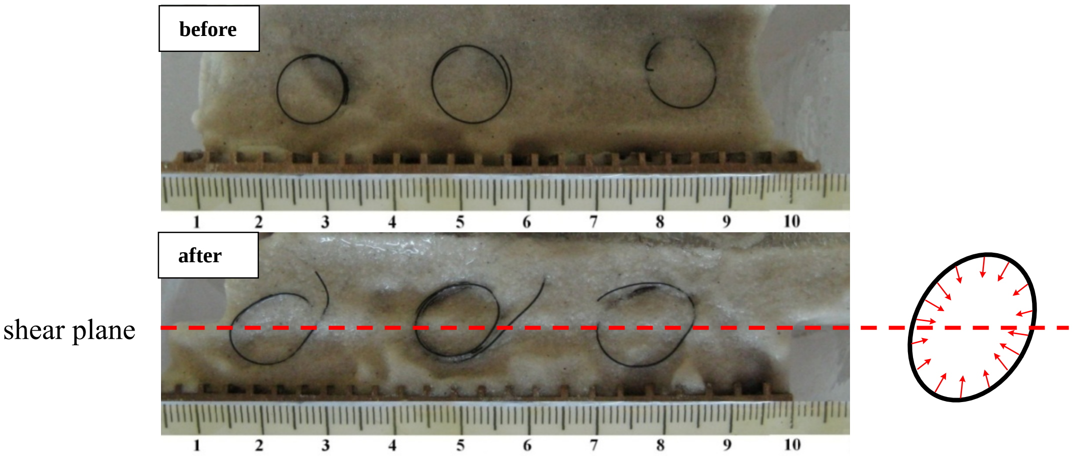
On the other hand, the relationship between friction angle and fiber content is not obvious (Fig. 9(b)). Some results showed that the friction angle increased with increasing fiber content (Stauffer and Holtz 1995; Tang *et al*. 2007). Other results showed reinforcement had no effect on the friction angle (Gray and Ohashi 1983; di Prisco and Nova 1993) or even an adverse effect (Yetimoglu and Salbas 2003). Therefore, the factors influencing the friction angle of a composite are complex and they are the type, extensibility, orientation or surface characteristic of reinforcement, and vice versa.

5. CONCLUSIONS

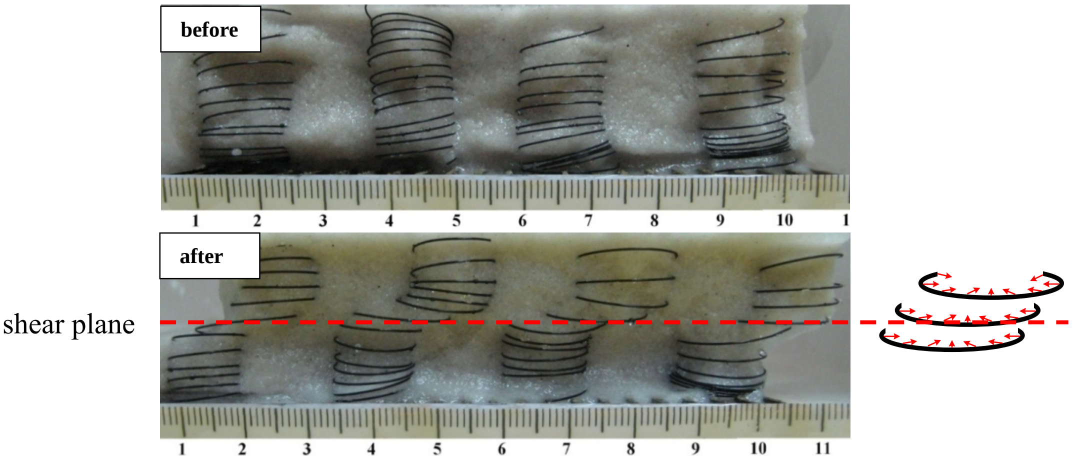
This study focuses on the shear behavior of continuous-filament reinforced sand. With regard to the shear behavior of the



(a) *Cx*

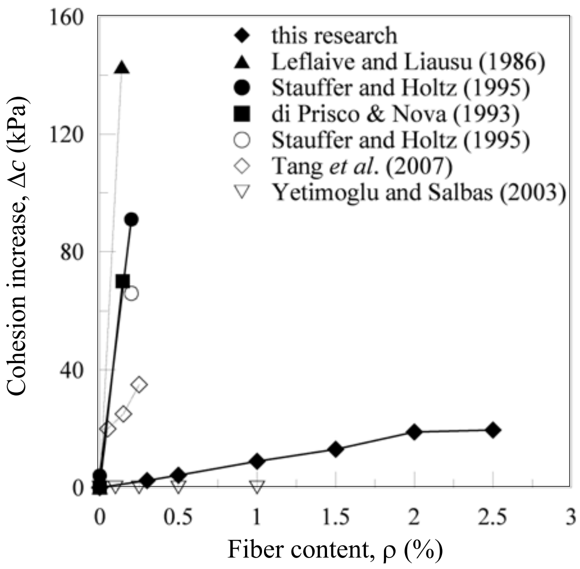


(b) *Cy*

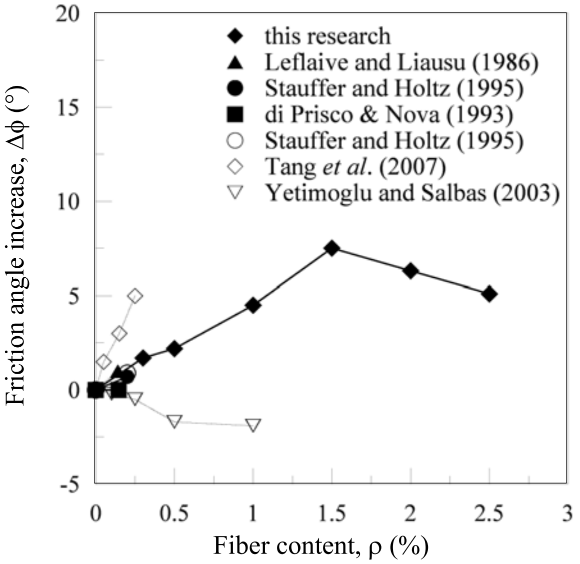


(c) *Cz*

Fig. 8 Cross-sections of filament-spirals in different orientations



(a) Cohesion increase



(b) Friction angle increase

Fig. 9 Comparison of relevant studies on the increase in shear strength parameters

composite, the effects of reinforcement content, fiber diameter and orientation were examined; particularly from separate viewpoints of cohesive and frictional parts on the contribution to the shear strength of reinforced sand. The findings are summarized as follows and the suggestions are furnished as well:

1. Compared to unreinforced sand, the sand reinforced with continuous filaments showed increase in peak strength, strain at failure, and post-peak strength loss.
2. The inclusion of randomly distributed filament improved both the cohesion intercept and the friction angle of reinforced sand. The increase in cohesion intercept with respect to fiber content is more obvious.
3. In regard to the peak strength increase, there was optimum fiber-contents (OFC), ranging between 1.5 ~ 2.5% and varying with the normal stress on the specimen.
4. Thin filament performed higher resistance than the thick. At low normal stress, the contribution to strength is chiefly from the cohesion, therefore fiber diameter plays a very significant role in this respect.
5. Filaments oriented near perpendicularly to a potential shear plane can provide better resistance when under shearing. It would be beneficial to make filaments align in the favorable orientation with respect to the shear plane.

NOMENCLATURES

Basic SI units are given in parentheses

c	cohesion intercept (kPa)
D_r	relative density (%)
d_f	fiber diameter (mm)
d_{10}	effective grain size (mm)
d_{50}	median grain size (mm)
E	elastic modulus of fiber (kPa)
G_s	specific gravity of soil
ε_f	elongation at rupture of fiber (%)
ϕ	friction angle (°)
ϕ_p	peak friction angle (°)
ϕ_r	residual friction angle (°)
γ_d	dry unit weigh (kN/m^3)
$\gamma_{d,\max}$	dry unit weight in the densest state (kN/m^3)
$\gamma_{d,\min}$	dry unit weight in the loosest state (kN/m^3)
ρ	fiber content by weight (%)
ρ_f	density of fiber (Mg/m^3)
σ	normal stress (kPa)
σ_f	tensile strength at failure of fiber (kPa)
τ	shear stress (kPa)
Δc	cohesion increase (kPa)
$\Delta\phi$	friction-angle increase (°)
$\Delta\tau$	stress increase (kPa)

USCS symbols

C_c	coefficient of curvature
C_u	coefficient of uniformity
SP	poorly graded sands

Abbreviations

HDPE	high-density polyethylene
OFC	optimum fiber-content

REFERENCES

Al-Refeai, T. O. (1991). "Behavior of granular soils reinforced with discrete randomly oriented inclusions." *Geotextiles and Geomembranes*, **10**(4), 319–333.

ASTM D 3080-04. (2004). "Standard test method for direct shear test of soils under unconsolidated drained conditions." *ASTM International*, West Conshohocken, PA, U.S.A.

Consoli, N. C., Prietto, P. D. M., and Ulbrich, L. A. (1998). "Influence of fiber and cement addition on behavior of sandy soil." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **124**(12), 1211–1214.

di Prisco, C. and Nova, R. (1993). "A constitutive model for soil reinforced by continuous threads." *Geotextiles and Geomembranes*, **12**(2), 161–178.

Diambra, A., Ibraim, E., Wood, D. M., and Russell, A. R. (2010).

"Fibre reinforced sands: Experiments and modelling." *Geotextiles and Geomembranes*, **28**(3), 238–250.

Frost, J. D. and Han, J. (1999). "Behavior of interfaces between fiber-reinforced polymers and sands." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **125**(8), 633–640.

Gray, D. H. and Al-Refeai, T. O. (1986). "Behavior of fabric- versus fiber-reinforced sand." *Journal of Geotechnical Engineering*, ASCE, **112**(8), 804–820.

Gray, D. H. and Maher, M. H. (1989). "Admixture stabilization of sands with discrete, randomly distributed fibers." *Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering*, Rio de Janeiro, Brazil, **2**, 1363–1366.

Gray, D. H. and Ohashi, H. (1983). "Mechanics of fiber reinforcement in sand." *Journal of Geotechnical Engineering*, ASCE, **109**(3), 335–353.

Hoare, D. J. (1979). "Laboratory study of granular soils reinforced with randomly oriented discrete fibers." *Proceedings of the International Conference on Soil Reinforcement*, Paris, France, **1**, 47–52.

Ishizaki, H., Tanabe, D., and Segawa, S. (1992). "Application of the continuous-fibre soil reinforcement method to the construction of a permanent retaining wall." *Recent Case Histories of Permanent Geosynthetic-Reinforced Soil Retaining Walls- Proceedings of Seiken Symposium.*, Tokyo, Japan, 223–226.

Khay, M., Gigan, J. P., and Ledelliou, M. (1990). "Reinforcement with continuous thread: Technical developments and design methods." *Proceedings of the 4th International Conference on Geotextiles, Geomembranes and Related Products*, The Hague, Netherlands, **1**, 21–26.

Leflaive, E. (1982). "The reinforcement of granular materials with continuous fibers." *Proceedings of the 2nd International Conference on Geotextiles*, Las Vegas, U.S.A., 721–726.

Leflaive, E. and Liausu, Ph. (1986). "The reinforcement of soils by continuous threads." *Proceedings of the 3rd International Conference on Geotextiles*, Vienna, Austria, **4**, 1159–1162.

Maher, M. H. (1988). "Static and dynamic response of sands reinforced with discrete randomly distributed fibers." *PhD thesis submitted to the University of Michigan*, Michigan, U.S.A.

Maher, M. H. and Gray, D. H. (1990). "Static response of sands reinforced with randomly distributed fibers." *Journal of Geotechnical Engineering*, ASCE, **116**(11), 1661–1677.

Mathworks (2004). "Matlab user guide." *The Mathworks Inc.*, Massachusetts, U.S.A.

Michalowski, R. L. and Čermák, J. (2003). "Triaxial compression of sand reinforced with fibers." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **129**(2), 125–136.

Nakagoshi, N., Yamada, N., Horie, N., and Tanaka, J. (2006). "Road construction considering environmental protection." *Proceedings of 2006 International Symposium on Ecological Engineering*, Taipei, Taiwan, 97–124.

Ranjan, G., Vasan, R. M., and Charan, H. D. (1994). "Behavior of plastic-fiber-reinforced sand." *Geotextiles and Geomembranes*, **13**(8), 555–565.

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

Stauffer, S. D. and Holtz, R. D. (1995). "Stress-strain and strength behavior of staple fiber and continuous filament-reinforced sand." *Transportation Research Record*, 1474, Transportation Research Board, Washington, D.C., U.S.A., 82–95.

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

Yetimoglu, T. and Salbas, O. (2003). "A study on shear strength of sands reinforced with randomly distributed discrete fibers." *Geotextiles and Geomembranes*, **21**(2), 103–110.