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Strain-induced toughness and shearing characteristics of short-fiber reinforced soils

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ABSTRACT: In order to study the quantitative effects of short-fiber reinforced soils on shear behaviors, a series of box shear test and unconfined compression test on non-cohesive and cohesive soils were carried out. Reinforcement materials used in the tests were consisted of synthetic fibers with different sizes and surface friction properties. It was found from the experimental works that length, diameter and surface roughness of fibers had marked effects on mechanical properties of the reinforced soils and the recommended optimum mixing rate of the short fibers was presented. Furthermore test results showed the prominent increase in peak shear resistance of fiber-reinforced soils and their high residual strength within the wide range of large deformation. Its strain-induced toughness can be recognized as effective and well-directed for earthquake-proof geotechnical structures.

1 INTRODUCTION

A short-fiber reinforced-earth construction method is recently developed in attempting to use for unstable embankment slopes and poor ground foundations, and in particular for the backfill soils of wall-type reinforced-earth with the aim of strengthening the shear resistance. However theoretical and experimental reinforcement mechanism and fundamental mechanical properties of fiber-soil mixture are not made fully clear at present. Interface friction among soil particles and fibers and their interlocking or intertwine action are considered as fundamental factors of improvement of fiber-reinforced soil which is called as an internal confining reinforcement in this paper.

The fiber-reinforced techniques has some advantageous engineering properties of soft grounds and filling materials. For example, the fiber-reinforced soil construction method can be applied for purposes of supplying an apparent cohesion component for non-cohesive granular sandy soils. Furthermore it can be used for controlling the engineering properties of problematic soils for stabilizing geotechnical structures and for vegetation, erosion control of earth slopes, weak disposal soil materials and so on.

There are two major types of earth-reinforcement techniques using synthetic fibers. One is a widely used conventional method in which continuous filament yarns are employed for non-cohesive granular soils, for example, *Texsol* product (Public Works Research Center, 1992) developed firstly in French. In this type the filaments are mixed with fine sand at the specified moisture content by the jet-mixing equipment and the fiber-sand mixture is built up in the field. Another type is a recently developing method using short length fibers (Research Institute of Public Works, 1997). As the results of improvement, the fiber-reinforced soils acquires extremely high ductility and toughness against the deformation of geotechnical structures and contributes to reduce the lateral earth pressure within embankments and back-fill soils.

Some interaction effects among soils types, shape, size and surface roughness of reinforcement materials are commented in other reports (Research Institute of Public Works, 1997 and Nakahara,H., 1998). In this experimental works mechanical properties of fiber-reinforced fine sand and sand-clay mixture were investigated using both a laboratory shear box test and an unconfined compression test.

2 MATERIAL CHARACTERIZATION

2.1 *Soils*

Two types of soils; *Toyoura* fine sand (abbreviation: S) and *Kaolin* clay (abbreviation: K) were used for this experimental works. Physical characteristics of the fine sand were; particles density $\rho_s = 2.64$ g/cm.^{3} 60 % passing gain diameter $d_{60} = 0.2$ mm, uniformity coefficient $Uc = 2.0$, coefficient of curvature $Uc' = 1.45$, maximum and minimum void ratios $e_{max} = 0.97$, $e_{min} = 0.59$, respectively. Physical properties of the clay (CH: high plasticity clay) were; particles density $\rho_s = 2.56$ g/cm^3, liquid limit $w_L = 85.1$ %, plasticity index $Ip = 54.6$.

The fine sand (S) as a non-cohesive material was used in the air dry condition in a direct shear box test. The soil employed as a cohesive material in an unconfined compression test was a mixture (S+K) of the sand and the clay with the mixing rate of 10 % in dry mass. This mixing rate was determined based on the results by pre-compaction test.

2.2 *Reinforcement materials*

Reinforcement short fiber materials used in the tests were nylon fibers for Test I and II and polypropylene fibers for Test III. Table 1 and 2 show the sizes of nylon fibers tested in a direct shear box test (Test I) and in an unconfined compression test (Test II), respectively.

One group is $L = 1.0$ cm in length with diameters of $d = 0.175$, 0.33 and 0.66 mm, and another group is $d = 0.33$ mm in diameter with $L = 0.5$ to 16 cm in length.

A polypropylene fiber used in Test III is $L = 1.0$ cm in length and two types of the fiber's surfaces are prepared. One has a non-treated smooth surface and another one is a rough surface fiber to which the fine sand particles are adhered with a chemical bond (silicone-sealant 8060).

The mixing ratio of these fibers with the soils was maintained at the constant rate of $M = 1.0$ % of fibers in dry mass in order to investigate the fiber's size and surface friction effects in these types of soils.

Table 1. Reinforcement materials for shear box test.

Soil	Length L (cm)	Diameter d (mm)	Mixing rate M (%)
Sand: S	1.0	0.175	1.0
		0.33	
		0.66	
	0.5	0.33	
	1.0		
	2.0		

Table 2. Reinforcement materials for unconfined compression test.

Soil	Length L (cm)	Diameter d (mm)	Mixing rate M (%)
Mixture: S+K	1.0	0.175	1.0
		0.33	
		0.66	
	0.5	0.33	
	1.0		
	2.0		
	4.0		
	8.0		
	16.0		

3 PROCEDURE

3.1 *Specimen preparation*

In Test I, the air-dried fine sand mixed with the short fibers at the mixing rate 1.0 % were used for a shear box test of 6 cm in diameter and 2 cm in height. The sand specimens mixed with the fibers were compacted under the condition of dry density of 1.43 to 1.45 g/cm^3, *viz.* density index *ID* (or relative density, *Dr*) between 45 and 55 %.

In Test II, firstly fine sand and clay were mixed and then the specified amount of reinforcement fibers were blended uniformly with the mixture. The unconfined compression test specimens of 6 cm in diameter and 14 cm in height and the specimen's dry density of 1.74 g/cm^3 were compacted using a steel mould subjected to the static compression force of 14.7 kN in the condition of the optimum moisture content of 18 %.

The specimens used in Test III were prepared in the same condition and the similar way to Test.

3.2 *Direct shear test*

Direct shearing resistance illustrated in the shear stress-deformation-strength relationships of fiber-reinforced sand (S) were investigated using a standard type shear box device. The shear tests were conducted at the deformation rate of 0.25 mm/min and up to 6 mm in the displacement.

3.3 *Unconfined compression test*

Stress-strain relationships and peak and residual strength properties of fiber-reinforced soils (S+K) were investigated using an uni-axial compression apparatus. The compressive tests were conducted at the compressive strain rate of 1.0 %/min and up to about 7 to 10 % in axial strain.

4 MECHANICAL CHARACTERISTICS OF SHORT-FIBER REINFORCED SOILS

4.1 *Fiber-reinforced sands*

4.1.1 *Effects of fiber's length*

Figure 1 shows the effects of fiber's length on shear resistance of the fiber reinforced fine sand, under conditions of the normal stress $\sigma = 200$ kPa, the fiber's diameter of 0.33 mm and the fiber's mixing rate of 1.0 %, in a direct shear testing. It is found from these shear stress-displacement curves that longer the length of fiber, higher the shear resistance such as peak strength (increase of about 10 to 15 %), residual strength (increase of about 0 to 20%) and modulus of deformation.

It is considered that the reinforcement effects of fibers are caused by interface friction, interlocking and intertwining between the fiber's surfaces and the sand particles. In addition, the high peak and residual strength exhibited in the cases of longer fibers are attributable to the phenomenon of expanding shear zone in proportion to the length of fibers.

Figures 2 shows the internal friction angles affected by the fiber's length obtained from the normal stress and shear stress diagrams. It can be seen from the figure, however, that no cohesion component may be supplemented to granular soil particles by short-length fiber's reinforcement.

Figures 3 illustrates the relationships of the internal friction angles (ϕ) versus the fiber's length (L). It can be seen from Figs. 3 that the internal friction angles of the reinforced sands will increase gradually with the increase in fiber's length. This is probably due to a long continuous friction action of each fiber that will expand effectively the confining zone of sand particles. Therefore, in order to reinforce the fine sands, the optimum size regarding length is supposed to exist at the specified mixing rate and kinds of soil.

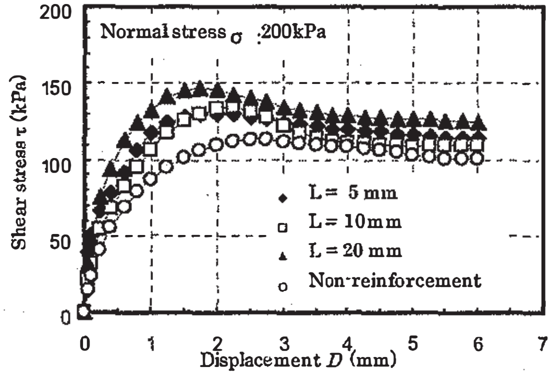

Figure 1. Shear curves in direct shear test (Effects of fiber's length).

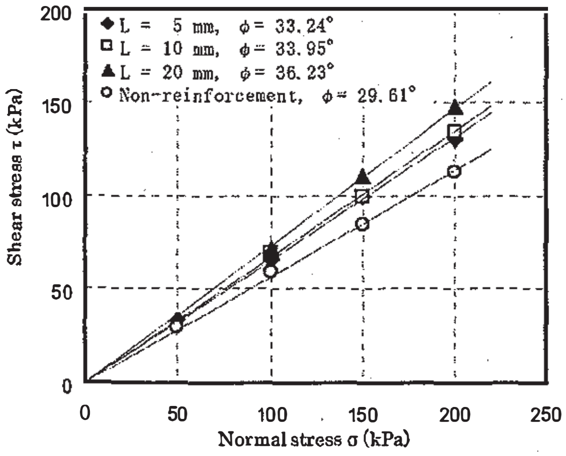

Figure 2. Normal stress vs shear stress curves in direct shear test (Effects of fiber's legth).

4.1.2 *Effects of fiber's diamater*

Figure 4 demonstrates that the effects of fiber's diameter on shear resistance of the reinforced sands using the fiber's length of 1.0 cm, under the same conditions of mixing rate as indicated in Fig.1. It is found from the figure that smaller the diameter, the higher the peak strength and the modulus of deformation. This increasing shear resistance (increase of about 0 to 25 % in the peak strength) is owing to the increased surface area of fibers that are depending to the numbers of fibers in inverse proportion to the diameter of fibers at the constant fiber's mixing rate. However, No difference can be recognized at the residual strength.

Figures 5 shows the internal friction angles affected by the fiber's diameter obtained from the normal stress and shear stress diagrams. It can be seen from the figure that the internal friction angles decrease with the increase in fiber's diameter at the specified mixing rate and will approach finally to almost same value of internal friction angle ϕ= 29.6°of the non-reinforced sand.Therefore, in order

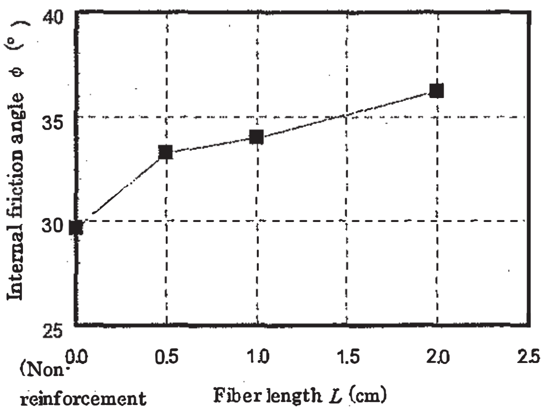

Figure 3. Relation between internal friction angle and fiber's length.

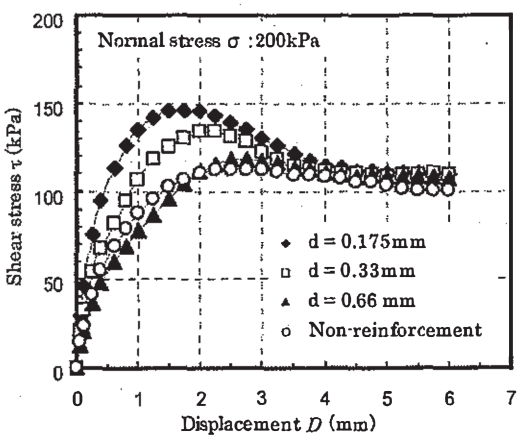

Figure 4. Shear curves in direct shear test (Effects of fiber's diameter).

to reinforce the fine sands, the optimum size regarding length and diameter is supposed to exist at the specified mixing rate and kinds of soil.

4.2 *Fiber-reinforced sand-clay mixtures*

4.2.1 *Effects of fiber's length*

Figures 6 shows the effects of fiber's length on the axial stress-strain relations of the fiber-reinforced sand-clay mixtures under conditions of the fiber's diameter of 0.33 mm and the fiber's mixing rate of 1.0 %, in unconfined compression testing. It is found from these unconfined compressive stress-strain curves that longer the length of fiber, higher the shear resistance. This tendency is similar to the cases in Test I with the same reasons of interface friction, interlocking and intertwining action between the fibers and the soils. However, it can be seen that the marked reinforcing effects are obtained in the case of the soils having cohesion component on both the peak strength (increase of up to about 2.5 times) and residual strength (increase of up to about 5 times).

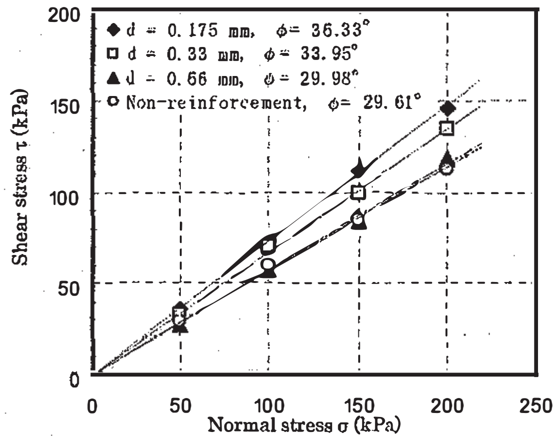

Figure 5. Normal stress vs shear stress curves in direct shear test (Effects of fiber's diameter).

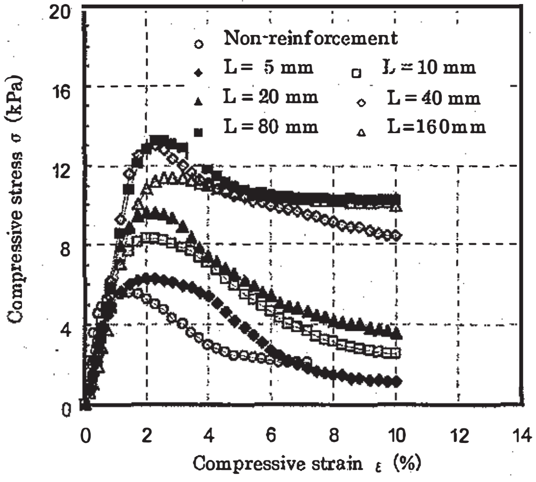

Figure 6. Stress-strain curves(Effects of fiber's length).

Especially the residual strength in the cases of specimens having more than 4.0 cm in the fiber's length are maintained for a very wide range of strain, for example beyond more than 5 %. This means that cohesive soils can be extremely improved by the short fiber reinforcement and they have high ductility and toughness for shearing deformation.

Concerning the induced compressive strength due to its deformation in an unconfined compression test, the relationships between compressive stress and the fiber's length are illustrated in Fig.7. These compressive stresses mean the values mobilized at the arbitrarily specified axial strain, such as the levels of 0.5 to 8.0 %. It is indicated in this figure that the compressive strength mobilized at the strain level of 2 % or more are increased with the increase in fiber's length at the range of 0.5 to 4.0 cm and are maintained constant or decreased at the range of more than 4.0 cm. This tendency is approximately consistent with the empirical value of 10 cm that is supposed to be the optimum length of fibers from the viewpoint of mixing and field construction efficiency.

Figures 8 shows the relationships between the strength reduction rate and the axial strain for dis-

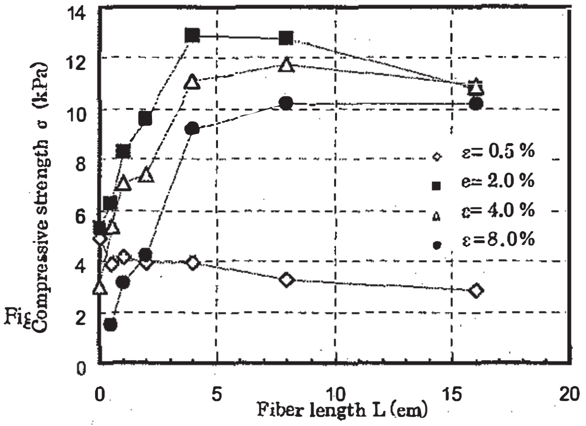

Figure 7. Relation between compressive strength and fiber's length.

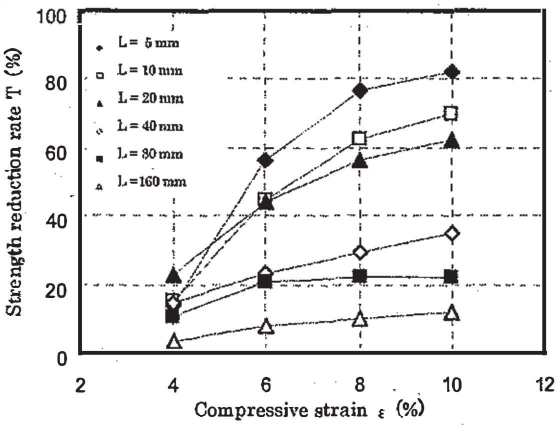

Figure 8. Relation between strength reduction rate and compressive strain (Effects of fiber's length).

playing the effects of fiber's length. The strength reduction rate that indicates the toughness and ductility is defined as the ratio of the difference between the peak and the residual strength to the peak strength. It can be seen from Fig.8 that the strength reduction rate increases with their strain increases and decreases with the increase in the fiber's length. Namely the soils reinforced using longer fabrics retain high strength.

4.2.2 *Effects of fiber's diameter*

Figure 9 demonstrates that the effects of fiber's diameter on the axial stress-strain relations of the fiber-reinforced sand-clay mixtures using the fiber's length of 1.0 cm, under the same conditions of fiber's mixing rate as indicated in Fig.6. It is found from the figure that smaller the diameter, the higher the peak strength (increase of up to about 2 times) and residual strength (increase of up to about 2.5 times at the same strain level).

This increasing shear resistance is owing to the increased circumferential area of fibers that are depending to the numbers of fibers in inverse proportion to the diameter of fibers at the constant fiber's mixing rate. It must be noted that no significant difference of the initial or tangential modulus of deformation can be found among these specimens as shown in Figs.6 and 9.

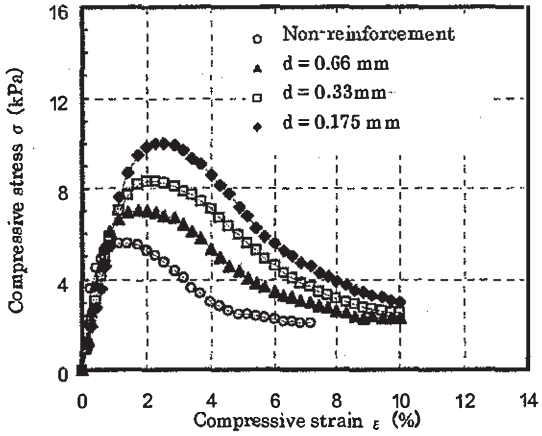

Figure 9. Stress-strain curves (Effects of fiber's diameter).

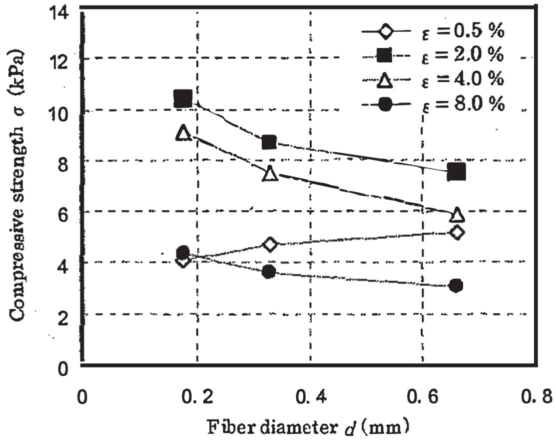

Figure 10. Relation between compressive strength and fiber's diameter.

Figure 10 demonstrates that the mobilized compressive strength increases with the decrease in fiber's diameter at this mixing rate. It is found that fabric-reinforced cohesive soils behave prominently high residual strength in the unconfined compression test. Figures 11 shows the relationships between the strength reduction rate and the axial strain for displaying the effects of fiber's diameter, but no difference can be seen among fiber's diameter in this experimental mixing rate condition.

4.3 *Effects of fiber's surface roughness*

Figure12 shows that the reinforced soil by rough surface fibers demonstrates higher shear resistance than that by the smooth surface fibers. It must be noted that the smooth surface fiber's reinforcement can not maintain its residual strength and is consistence with that of non-reinforced soil at larger strain range. This effect may be caused by a mobilized friction and an interlocking action between fiber and sand.

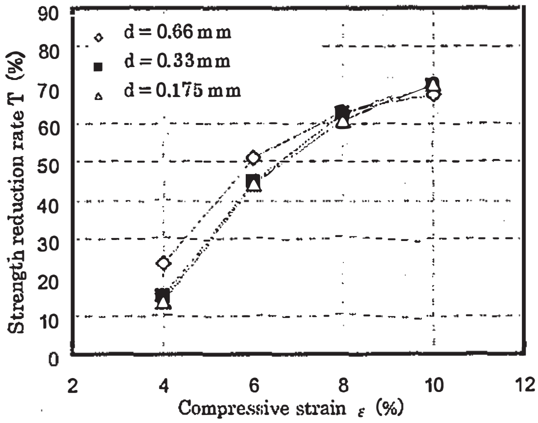

Figure 11. Relation between strength reduction rate and compressive strain (Effects of fiber's diameter).

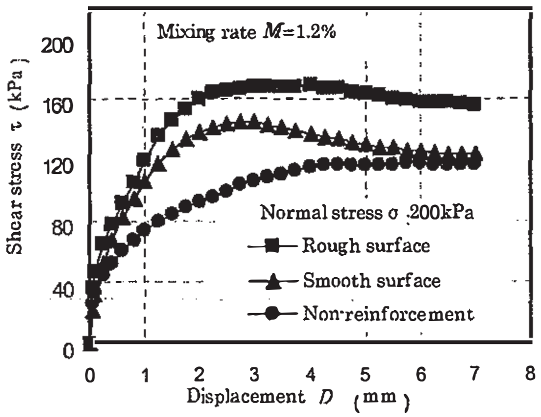

Figure 12. Shear curves in direct shear test (Effects of fiber's surface roughess).

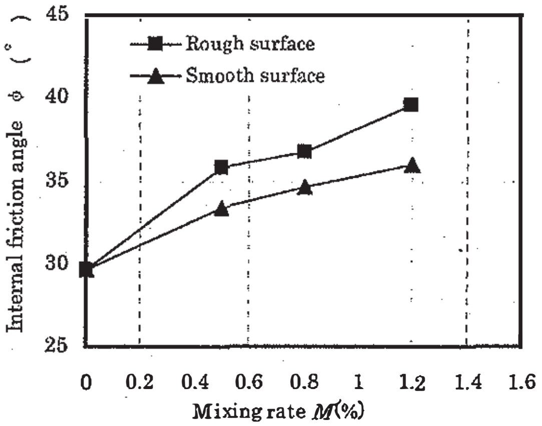

Figure 13. Relation between mixing rate and internal friction angle.

Figure 13 shows that the internal friction angles of both smooth and rough surface fiber's reinforcements increase with the increase in a mixing rate and the angle by rough surface fiber gives a higher value than that by sooth one.

5 CONCLUSIVE REMARKS

Experimental results demonstrated marked effects of the length and diameter of fibers on shear stress-deformational properties of the fiber-reinforced soils. High residual strength in the wide range of large deformation of the reinforced soils was obtained and their toughness and ductility are recognized as beneficial for anti-earthquake geostructures. The principal findings from the results can be summarized as follows;

1) The internal friction angles of the fiber-reinforced non-cohesive sands increase with the increase in fiber's length or with the decrease in fiber's diameter.
2) No cohesion component may be supplemented to granular soil particles by short-length fiber's reinforcement.
3) The marked reinforcing effects are obtained in the case of the soils having cohesion component on both the peak strength and the residual strength.
4) The mobilized compressive strength is increased with the increase in fiber's length at the range of 0.5 to 1.0 cm. This tendency is consistent with the empirical value of about 10 cm that is supposed to be the optimum length of fibers from the viewpoint of mixing and field construction efficiency.
5) The residual strength in the cases of specimens having more than 4.0 cm in the fiber's length are maintained for a very wide range of strain. This means that cohesive soils can be extremely improved by the short fiber reinforcement and they have high ductility and toughness for shearing deformation.
6) The reinforcement effect is influenced by the surface roughness of fibers and the rougher the surface of fiber gives higher the friction angle.

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