

# Stress-Strain and Strength Behavior of Staple Fiber and Continuous Filament-Reinforced Sand

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Laboratory triaxial compression tests were performed to examine the stress-strain behavior and strength characteristics of sands reinforced with randomly distributed staple fibers and continuous filaments. A medium uniform sand and a medium moderately well-graded sand, both with the same  $D_{50}$ , were tested in consolidated-drained triaxial compression with volume changes measured. The reinforcement consisted of randomly distributed 100-mm-long staple fibers and continuous filaments of an untwisted, multifilament 100 percent polyester yarn of the same type used in Texsol construction. Reinforcement concentration was 0.2 percent by weight of sand, the same commonly used in the field. Results indicate that randomly distributed staple fibers and continuous filaments increase the compressive strength, axial and volumetric strain at failure, and postpeak strength loss of the composite compared with unreinforced sand behavior. Filament reinforcement was found to contribute significantly more to the increase in stress-strain behavior than staple fiber reinforcement. Finally, a reinforced well-graded subangular sand had a greater increase in the stress-strain characteristics than a reinforced uniformly graded subrounded sand.

Reinforced soil is a composite material in which the strength of the soil is enhanced by the addition of tensile reinforcement. The most notable example is of course reinforced earth, developed by Henri Vidal in France; steel strips are horizontally embedded in engineering fill to provide the reinforcement. Since the introduction of reinforced earth in 1966, alternative reinforcing materials—such as grids, sheets, and fibers made out of materials ranging from steel and other metals, plastics, and various synthetic polymers—have been developed and used extensively (1).

Another type of composite material developed in France, Texsol, is a mixture of randomly distributed continuous polyester filaments deposited simultaneously with sand using special equipment (2). The Texsol yarn provides tensile resistance to the sand, thereby greatly improving its strength and stability.

Composite materials consisting of randomly distributed staple fibers in granular soils have also been found to improve the strength properties of sand. The main advantages of randomly distributed staple fibers and continuous filaments when compared with horizontally oriented reinforcement are the absence of potential planes of weakness and some construction simplicity.

Previous studies have focused on the behavior of either staple fibers or continuous filaments, instead of comparing both. Wargo-Levine (3) looked at both staple fiber-reinforced and continuous filament-reinforced sand, specifically the influence of fiber and filament characteristics on the composite properties.

This paper describes an experimental program to determine the stress-strain behavior and strength characteristics of randomly distributed staple fiber (SF)-reinforced sand composites and randomly distributed continuous filament (CF)-reinforced sand composites. In addition, the influence of sand granulometry (i.e., gradation, particles size, and shape) on continuous filament composites was also investigated.

## REVIEW OF PAST WORK

### Composites With Staple Fibers

Triaxial tests were used to investigate the influence of various percentages of randomly oriented staple fibers on the properties of a granular soil (4). Although the presence of fibers decreased the density of the composite, the fibers increased the shear strength and failure strain of the sand tested (4).

Triaxial tests were also performed to examine the stress-strain and strength response of SF-reinforced sands (5). It was observed that (a) staple fibers increased the ultimate strength and stiffness of the composites, (b) shear strength increased linearly with increased fiber content until it reached an asymptotic upper limit of 2 percent by weight, and (c) the strength increase was more dependent on the surface friction of the fiber than the modulus (5).

A comprehensive experimental program was conducted to investigate the constitutive behavior of SF composites (6,7). It was found that the addition of randomly distributed staple fibers increased the shearing strength and stiffness, compared with unreinforced sand. An increase in the fiber aspect ratio,  $C_u$  and sand angularity, or a decrease in mean grain size increased the shear strength or both. Finally, a planar failure surface oriented at  $45^\circ + \phi/2$  was observed in the composite (6,7).

### CONTINUOUS-FILAMENT COMPOSITES

Soil reinforced with continuous filaments (Texsol) was developed in France in the early 1980s. Some preliminary test results (8) showed great increases in the shear strength of sands with only 0.2 percent by weight of continuous filaments. Later a comprehensive series of triaxial tests to study the mechanical behavior of randomly distributed CF-reinforced sands was performed (9). It was found that (a) CF composites showed an increase in shear strength and strain at failure when compared with unreinforced soil, (b) the internal friction angle of the composite was always greater than that of

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unreinforced soil, and (c) an increase in weight percentage of filament resulted in a greater value of pseudo or apparent cohesion.

The mechanical behavior of Texsol was studied (10) by performing triaxial compression tests, uniaxial compression tests, and direct shear tests. The results showed that the compressive strength of the CF composites increased in direct proportion to the weight percentage of the filament and decreased with filament linear density.

The stress-strain behavior of CF-reinforced sands using triaxial compression tests was examined (11). It was concluded that the continuous filaments increased the compressive strength, postpeak strength loss, strain at failure, and angle of internal friction of the sand.

**Staple Fiber- and Continuous Filament-Reinforced Sand**

In the only previous study of both staple fiber- and continuous filament-reinforced sand, the stress-strain behavior and strength characteristics of these composites under both static and dynamic loading conditions were investigated (3). It was found, among other things, that (a) CF reinforcement makes a greater contribution to the strength of the composite than does SF reinforcement; (b) the addition of either staple fibers or continuous filaments to the sand increased the compressive strength, strain at failure, and postpeak strength loss of the composite compared with unreinforced sand; (c) the failure surface of all randomly distributed fiber-reinforced sands was planar and had an orientation of  $45 + \phi/2$ ; and (d) fail-

ure in both types of reinforcement appeared to be due to simultaneous slipping, stretching, and rupture of the fibers and filaments.

Volume changes were not measured and tests were performed with only one sand (3). Thus, it was appropriate to determine the effect of sand granulometry (i.e., gradation, mean grain size, and shape) on the stress-strain and strength characteristics of continuous filament-reinforced sands.

**EXPERIMENTAL PROGRAM**

Consolidated-drained triaxial compression tests were performed to determine the stress-strain and strength behavior of SF and CF sand composites under static loads. Specimens of two different sands at the same relative density were tested unreinforced, or reinforced with 0.2 percent by weight of either 100-mm staple fibers or continuous filaments.

**Sands and Reinforcement**

Two sands, both with the same mean grain size, were selected for this study. One was a well-graded subangular sand (Mortar sand) and the other was a uniformly graded, subrounded sand (Lonestar #3 sand). The grain size distribution curves of the sands are presented in Figure 1; other selected properties are in Table 1.

A 100 percent polyester multifilament yarn, provided by Societ  d'Application du Texsol, Paris, France, was used in the testing pro-

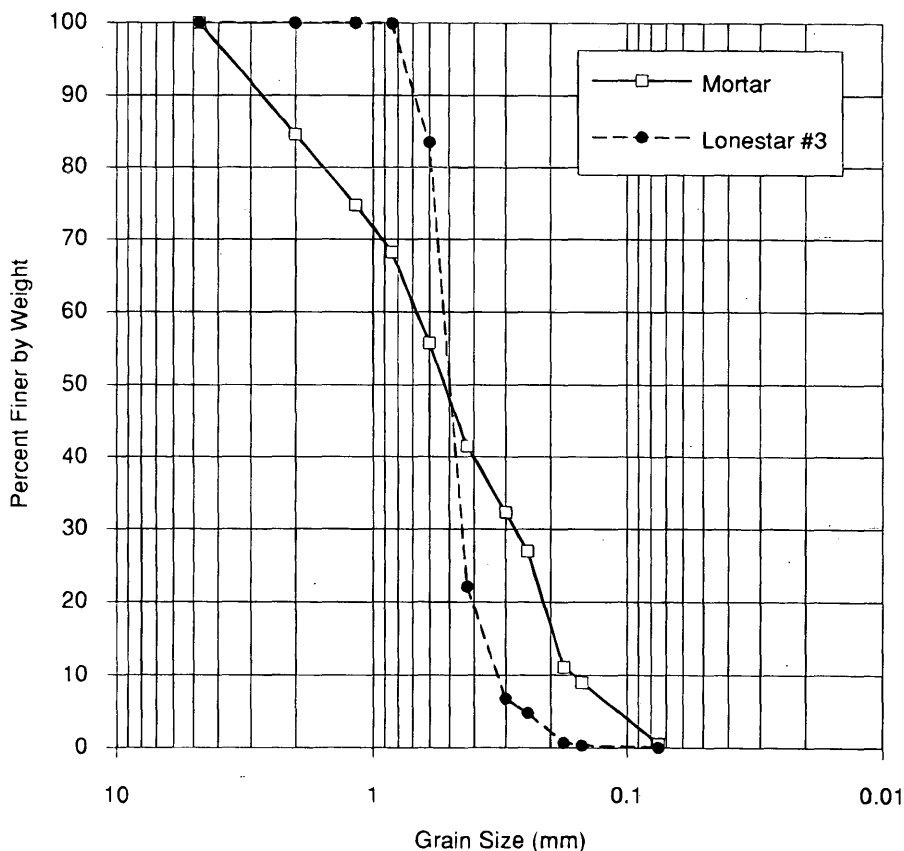


FIGURE 1 Grain size distribution curves for Mortar and Lonestar #3 sands.

TABLE 1 Properties of Sands Used in Experimental Program

Sand	$D_{50}$ (mm)	$C_u$	$G_s$	$e_{min}$	$e_{max}$	$D_r$ (%)	$e$	$\rho_d$ (MN/m <sup>3</sup> )	Water Content (%)
Mortar	0.52	4.22	2.67	0.41	0.66	80	0.46	1.83	0.30
Lonestar #3	0.51	1.65	2.65	0.59	0.88	80	0.65	1.61	0.10

gram. The yarn consisted of 30 untwisted filaments with a linear density of 167 dtex and an elongation at rupture of 28 percent. A single piece of yarn over 100 m long was used for the CF composites. To make the staple fibers, the Texsol yarn was cut into staple fibers 100 mm long and in sufficient quantities to provide 0.2 percent by weight of the test specimen. This 0.2 percent value was selected because it is a common percentage used in the field (2).

### Specimen Preparation and Testing

The sand and 0.2 percent reinforcement proportions were determined by considering the fibers and filaments as a solid in the voids-solid matrix. To avoid segregation of sand and reinforcement, a small initial water content (Table 1) was used. The components were mixed by hand until the reinforcement appeared to be randomly distributed throughout the sand. Individual test specimens were prepared inside a triaxial membrane supported by a split mold under vacuum. The moist tamping method (12) was used to achieve a uniform relative density of 80 percent throughout the specimen (71 mm in diameter and 152 mm in height). Test specimens were then saturated by flowing de-aired water through them and by applying a back pressure of 200 kPa. Consolidated-drained triaxial

compression tests under several different effective confining pressures were conducted with volume changes measured. The vertical load was applied by a material test system at a constant strain rate of 0.5 percent. Additional details of the experimental program can be found elsewhere (13).

### TEST RESULTS

This section presents the results of the experimental testing program and compares these results with those of previous investigations on SF- and CF-reinforced sands.

Specific sand and reinforcement parameters were considered in terms of their influence on the (a) compressive strength, (b) axial strain at failure, (c) volumetric strain at failure, (d) stiffness, and (e) postpeak strength loss. In addition, the influence of the test variables on the Mohr-Coulomb strength parameters is also discussed.

### Stress-Strain Behavior

Typical stress-strain curves for SF and CF composites and unreinforced sand are shown in Figures 2 through 4, for confining pressure of 50, 100, and 150 kPa, respectively. Figures 5 and 6 show the

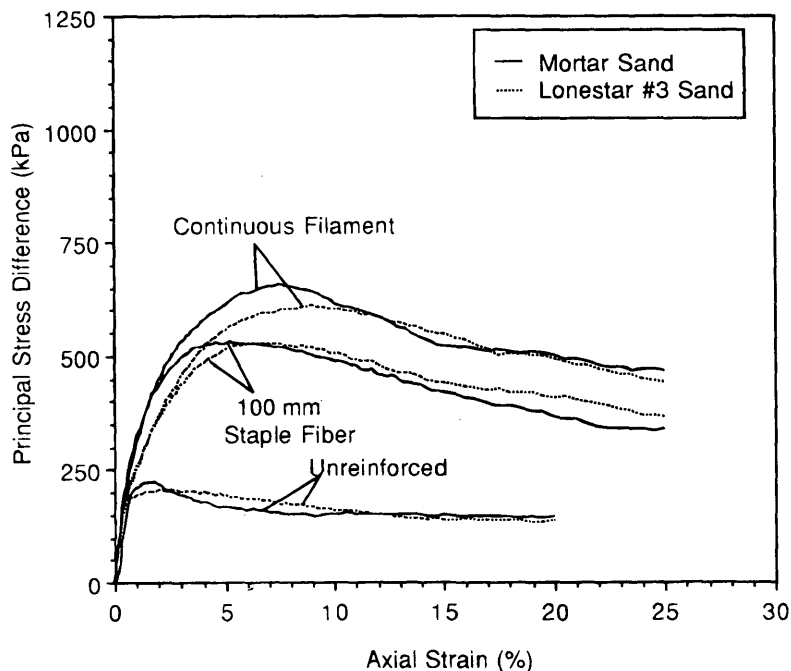


FIGURE 2 Representative stress-strain curves at 50 kPa confining pressure.

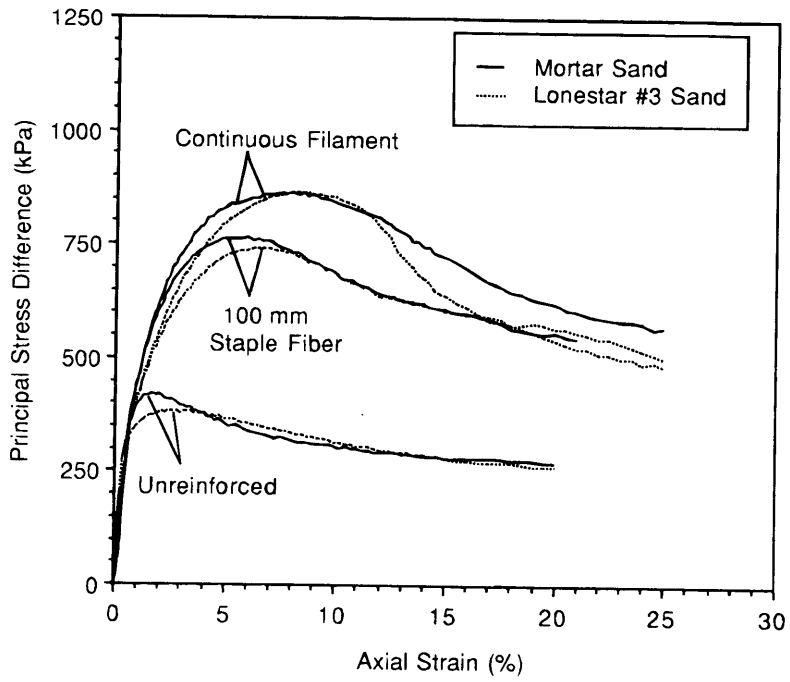


FIGURE 3 Representative stress-strain curves at 100 kPa confining pressure.

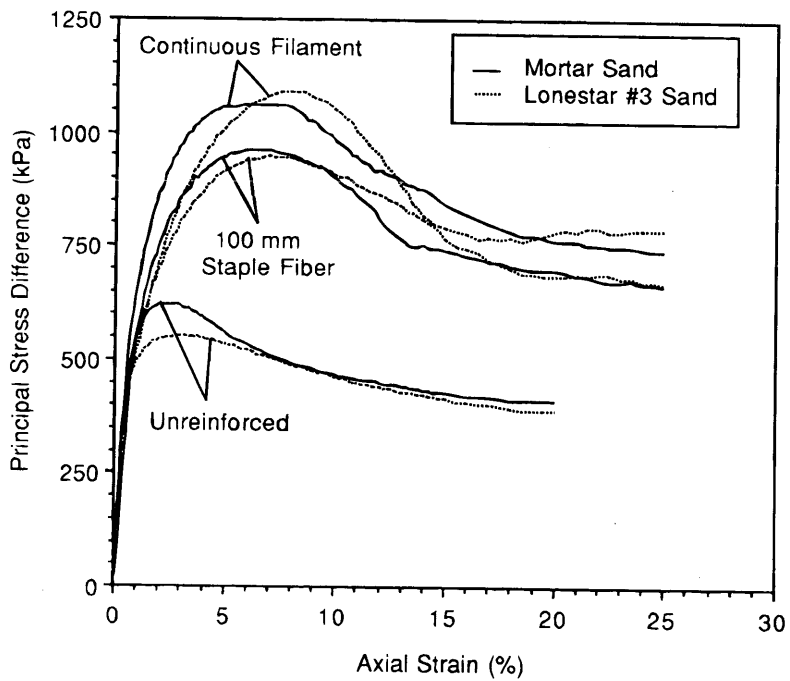
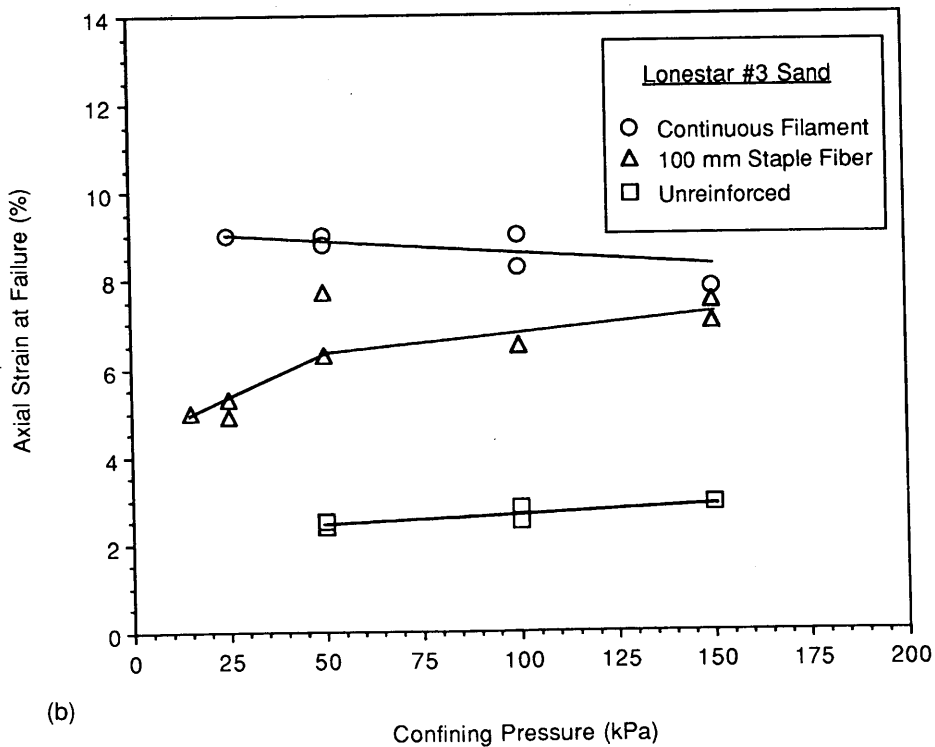
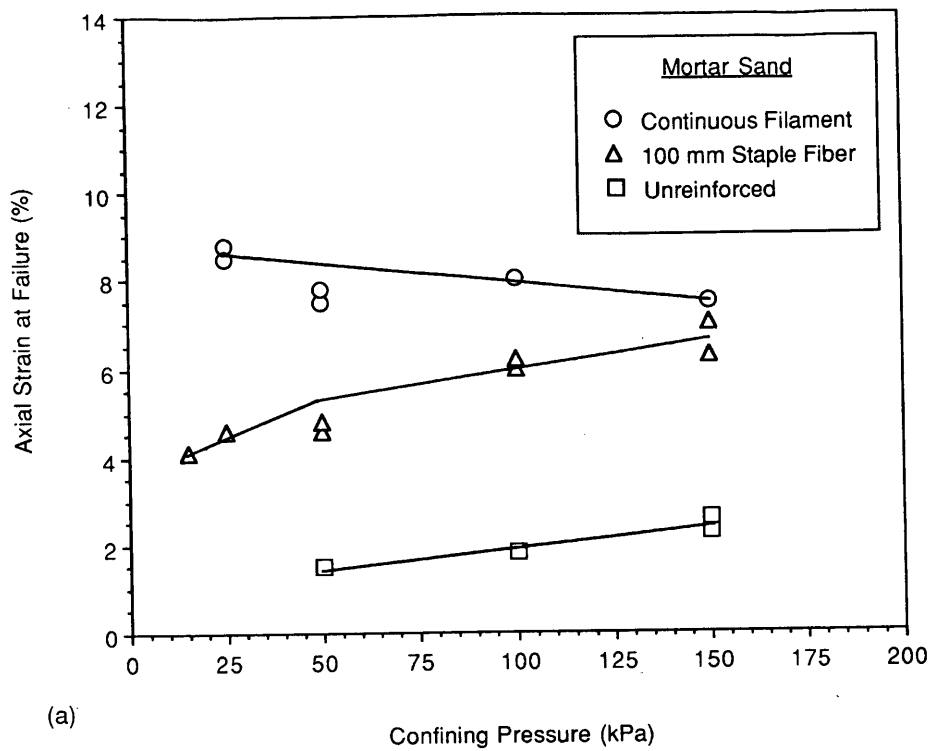
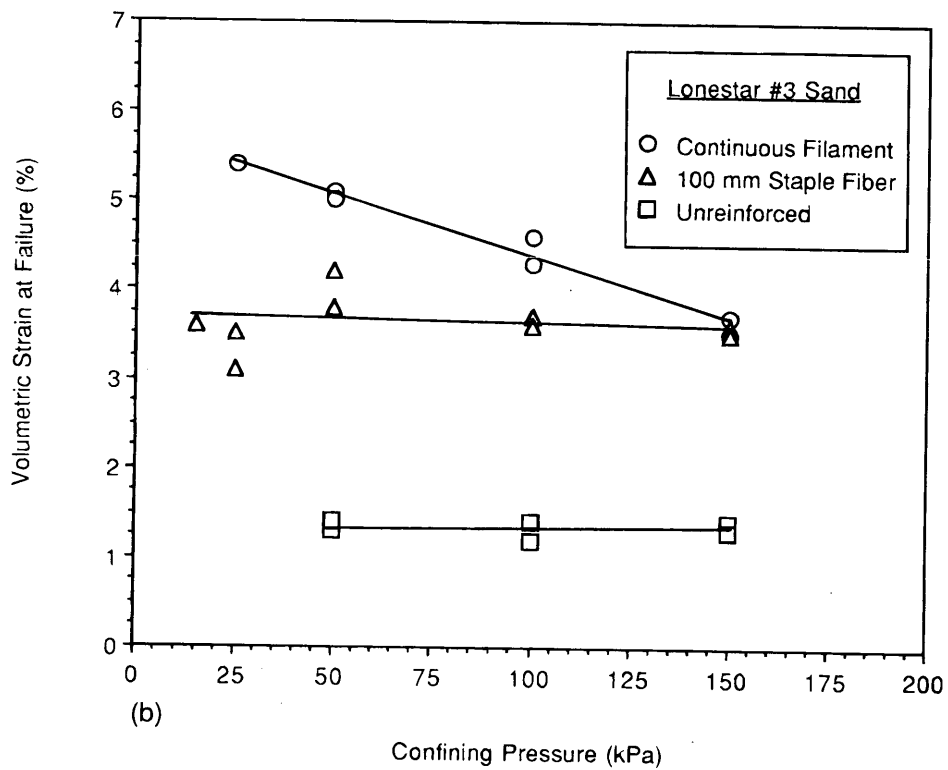
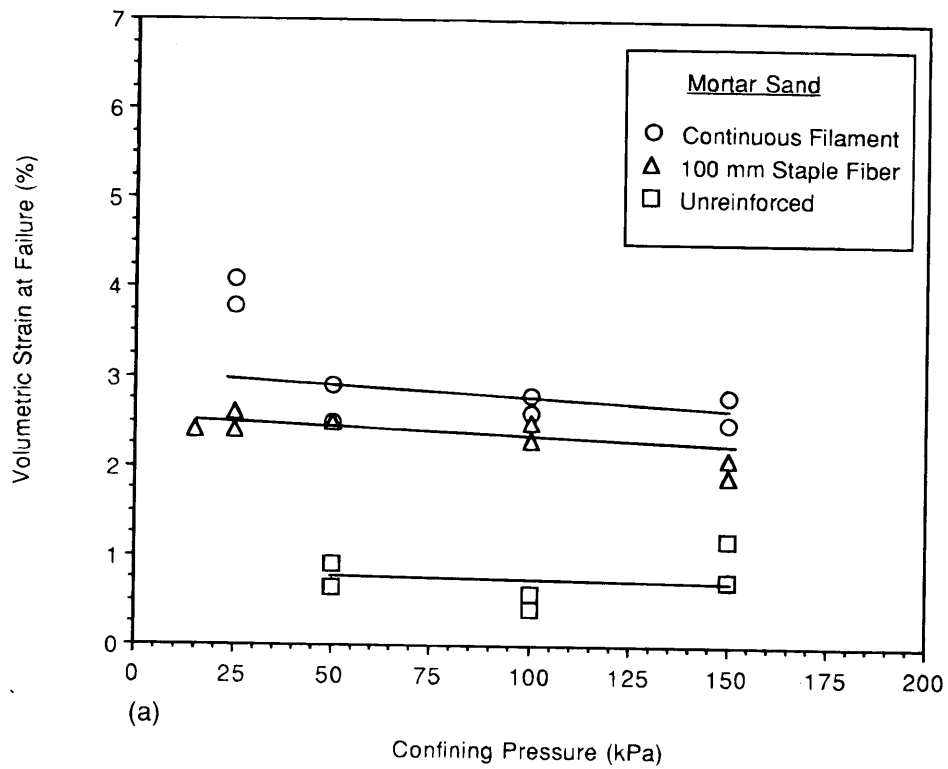


FIGURE 4 Representative stress-strain curves at 150 kPa confining pressure.



**FIGURE 5** Axial strain at failure versus confining pressure for (a) Mortar sand and (b) Lonestar #3 sand.



**FIGURE 6** Volumetric strain at failure versus confining pressure for (a) Mortar sand and (b) Lonestar #3 sand.

axial and volumetric strains at failure for the two sands, and Figure 7 shows the secant modulus at 2 percent strain. Figure 8 gives the postpeak strength loss (residual stress subtracted from the maximum principal stress) versus confining pressure.

For both sands, the randomly distributed staple fibers increased the principal stress difference, axial and volumetric strain at failure, stiffness of the test specimens, and postpeak strength loss. These results agree with previous investigations.

Similar results were observed for CF composites. The continuous filaments increased the principal stress difference, axial and volumetric strain at failure, stiffness, and postpeak strength loss compared with unreinforced sand. Again, these results are in general agreement with the limited previous work on CF sands.

A comparison of the stress-strain behavior of SF- and CF-reinforced sands shows that continuous filaments contribute significantly more to the compressive strength, axial strain at failure, and postpeak strength loss than do 100-mm staple fibers. This is in agreement with works by Maher and Gray (6) and Gray and Maher (7) that reported that an increase in the length to diameter ratio resulted in improved stress-strain characteristics. It was found that fibers were placed in tension as small deformations took place in reinforced soil (14). This tension mobilized shearing stresses along the soil-reinforcement interface to large distances outside of the shearing plane. The likelihood of the reinforcement being outside of the shearing plane is greater in CF composites than in SF composites. Therefore, continuous filaments should be expected to contribute more to the stress-strain characteristics than 100-mm staple fibers.

Although the residual strength of the SF and CF composites was always greater than the unreinforced sand, it gradually approaches to a certain extent the residual strength of unreinforced sand. This appears to be caused by gradual rupturing of the reinforcement as the axial strains increase. Additional analysis of the results can be found elsewhere (13).

### Strength Parameters

The results of triaxial tests on unreinforced and reinforced specimens are given in Figures 9 through 11. Figure 12 shows all failure envelopes. Friction angles and cohesion intercepts determined using Mohr-Coulomb failure criterion are summarized in Table 2.

Both reinforced sands revealed a minor cohesion intercept, probably the result of the straight line approximation of the slightly curved failure envelopes.

Both SF and CF specimens have greater cohesion intercepts and larger friction angles than their unreinforced counterparts. As shown in Figures 10 and 12, the sand-staple fiber composites exhibit bilinear Mohr-Coulomb failure envelopes. Below the "break" in the envelope, the reinforced friction angles are slightly larger than for sand alone. Above the "break," both the intercepts and the reinforced friction angles are greater than for the unreinforced sands.

### Influence of Sand Granulometry

An increase in soil gradation (higher  $C_u$ ) resulted in an overall higher compressive strength for both the SF and CF composites (Figures 2-4). This is in general agreement with previous work (6).

SF- and CF-reinforced composites have a higher axial and volumetric strain at failure than unreinforced sands (Figures 5 and 6). The percentage increase in axial strain is slightly greater for the better graded Mortar sand than for Lonestar #3 for both reinforcements. The opposite is true for the volumetric strain at failure.

The secant modulus is slightly greater for the well-graded (Mortar) sand than for the uniformly graded (Lonestar #3) sand at the same relative density (Figure 7). The percentage increases for both staple fibers and continuous filaments are also greater for a well-graded sand at all strains, probably the result of better reinforcement-particle interaction.

The postpeak strength loss for unreinforced well-graded (Mortar) sand is greater than unreinforced uniformly graded (Lonestar #3) sand. When both SF and CF reinforcement is added, the postpeak strength losses are similar (Figure 8). This result was unexpected, considering the greater interaction for well-graded sand. The better interaction, along with a high angularity, should have caused more reinforcement breakage and resulted in greater postpeak strength losses. See the work by Stauffer (13) for a detailed discussion of these points.

With respect to sand granulometry, the well-graded (Mortar) sand has a higher cohesion intercept but a smaller friction angle than a uniformly graded (Lonestar #3) sand (Table 2). This result was unexpected.

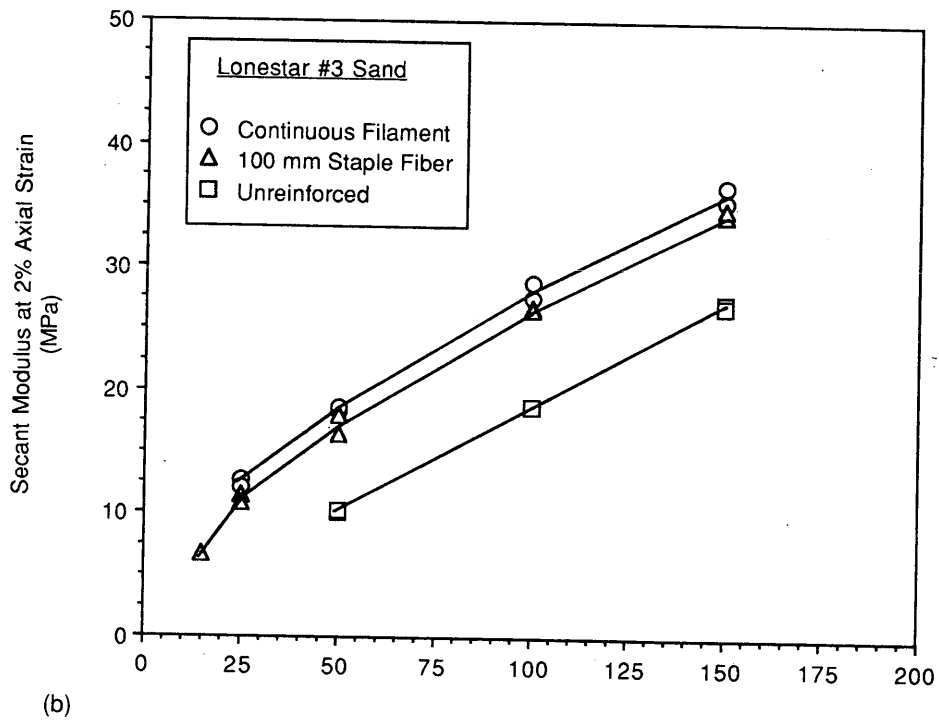
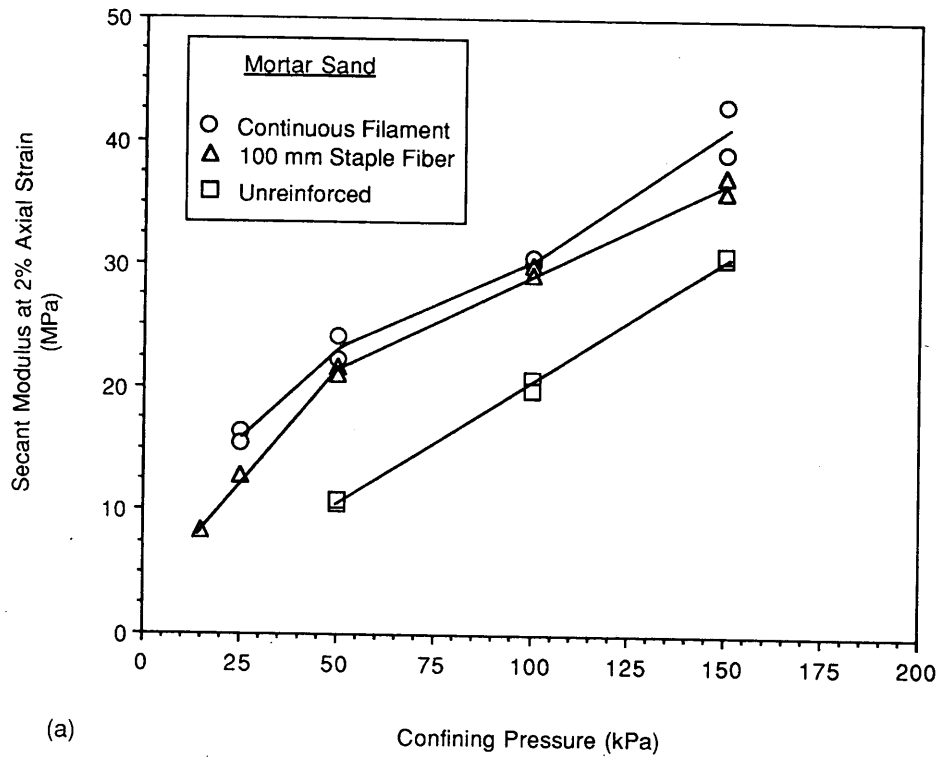
The Mortar sand staple fiber composites have a greater cohesion intercept and reinforced friction angle than Lonestar #3 composites above the break in the envelope. Below the break, Lonestar #3 shows a larger cohesion intercept value but a smaller reinforced friction angle. The existence of a larger cohesion intercept in the uniformly graded sand suggests that its strength envelope has a slightly greater curvature than does the well-graded sand.

## CONCLUSIONS

1. The addition of randomly distributed staple fibers or continuous filaments to sand results in increased compressive strength, stiffness, axial and volumetric strain at failure, and postpeak strength loss compared with unreinforced sand.
2. Continuous filaments contribute significantly more to the strength of a composite than do staple fibers.
3. The triaxial compression failure envelopes for staple fiber composites are bilinear. Bilinear envelopes are not evident in continuous filament composites.
4. Reinforced sand friction angles are greater than for unreinforced sands for both types of reinforcement.
5. A reinforced well-graded subangular sand shows greater increases in stress-strain characteristics than a reinforced uniformly graded subrounded sand. Sand granulometry has no apparent effect on the Mohr-Coulomb parameters of reinforced sands.

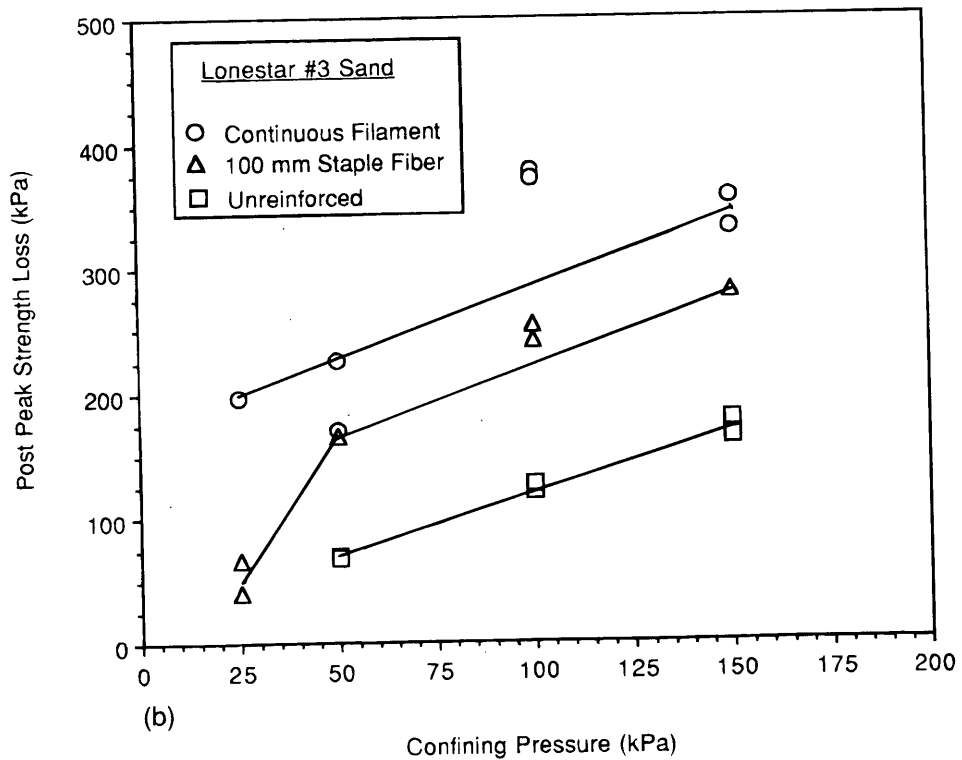
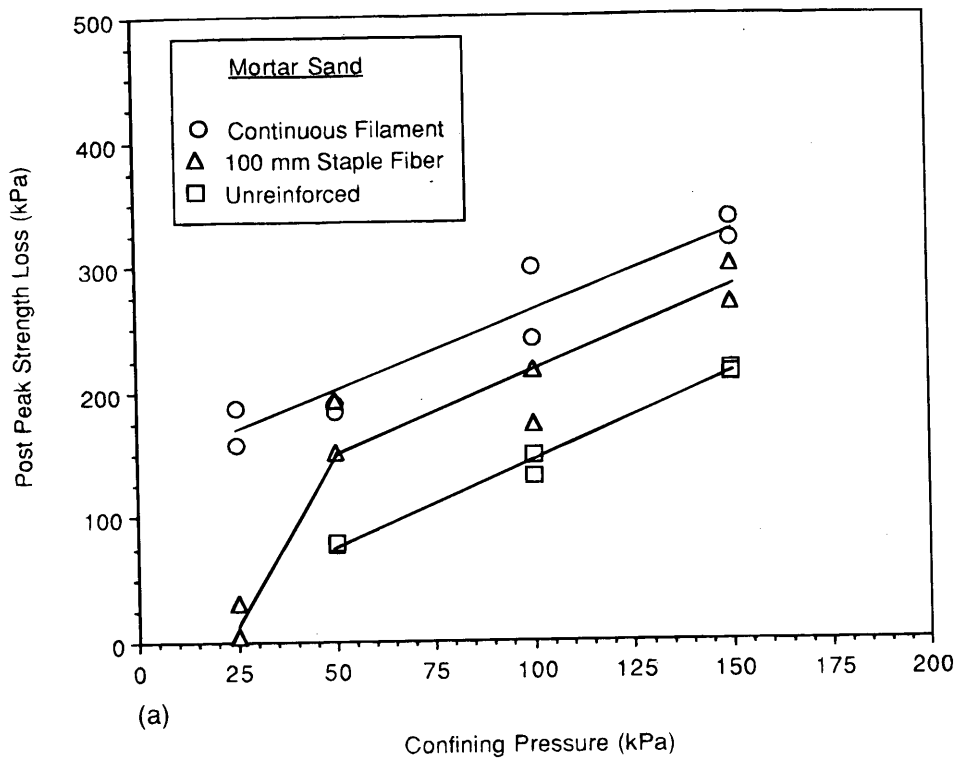
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**FIGURE 7** Initial tangent modulus versus confining pressure for (a) Mortar sand and (b) Lonestar #3 sand.





**FIGURE 8** Postpeak strength loss versus confining pressure for (a) Mortar sand and (b) Lonestar #3 sand.

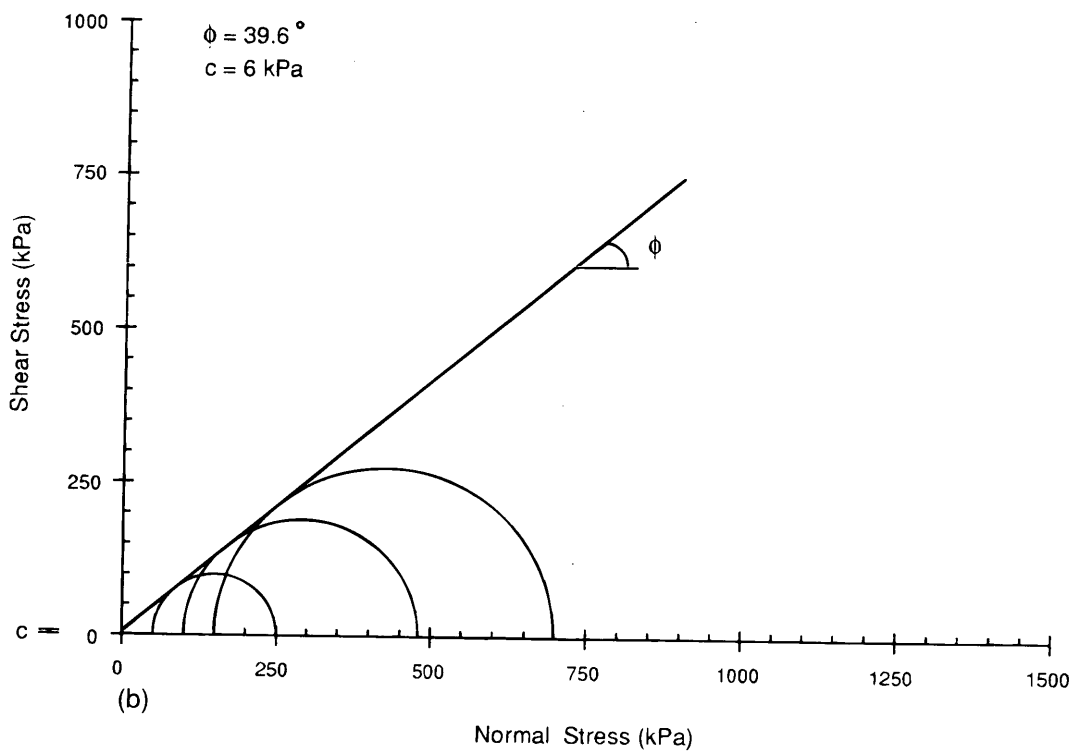
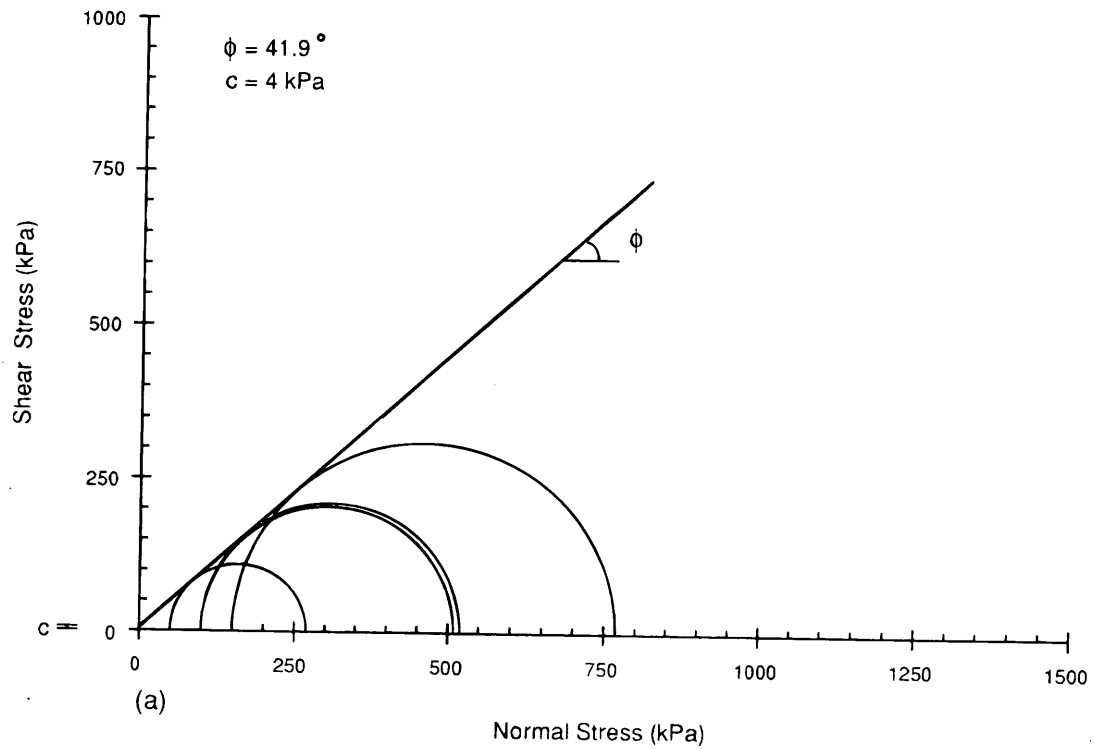
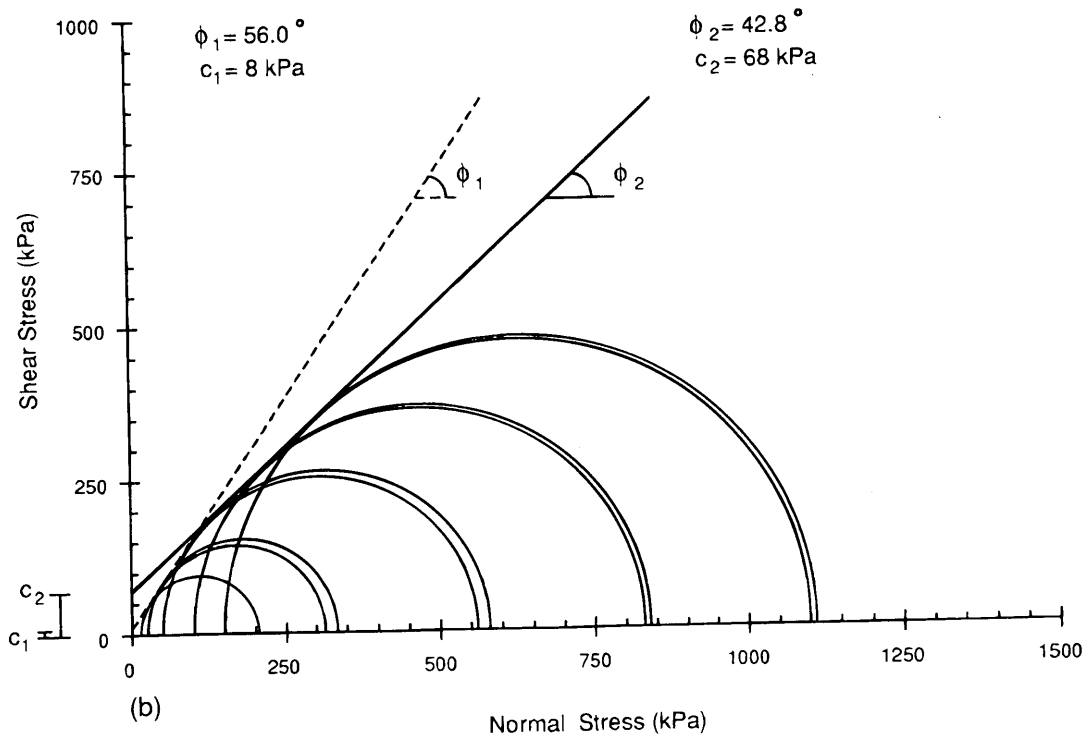
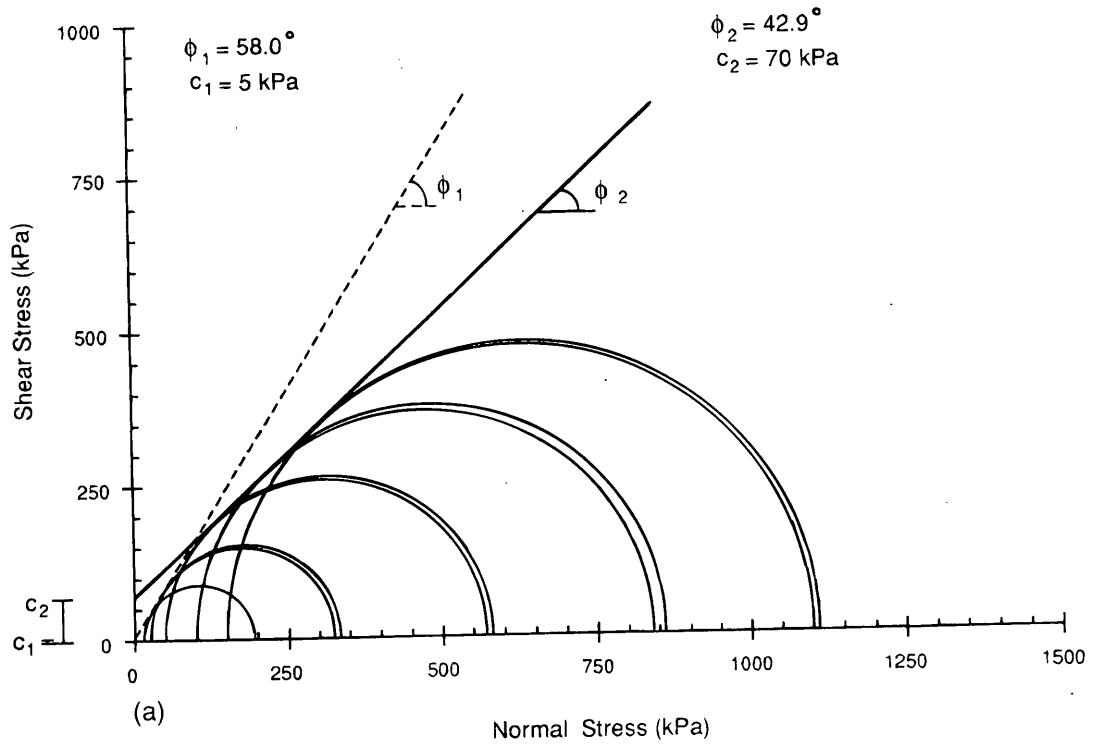


FIGURE 9 Mohr-Coulomb failure envelopes for unreinforced (a) Mortar sands and (b) Lonestar #3 sands.



**FIGURE 10** Mohr-Coulomb failure envelopes for (a) Mortar sands and (b) Lonestar #3 sands reinforced with 100-mm staple fibers.

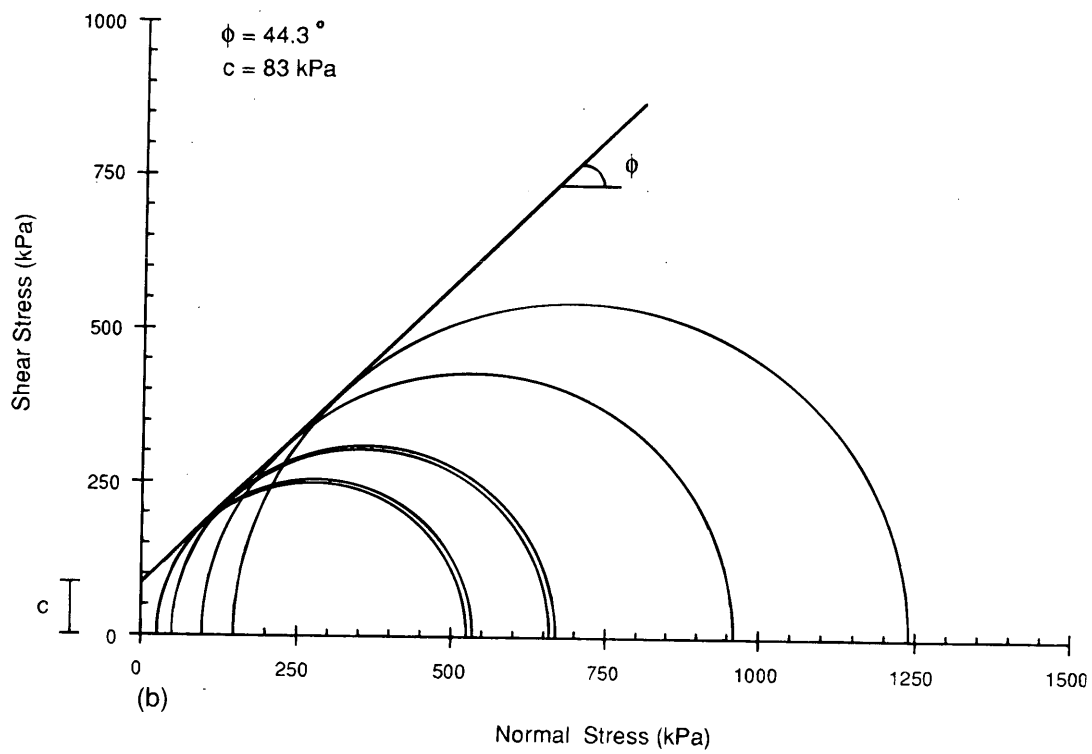
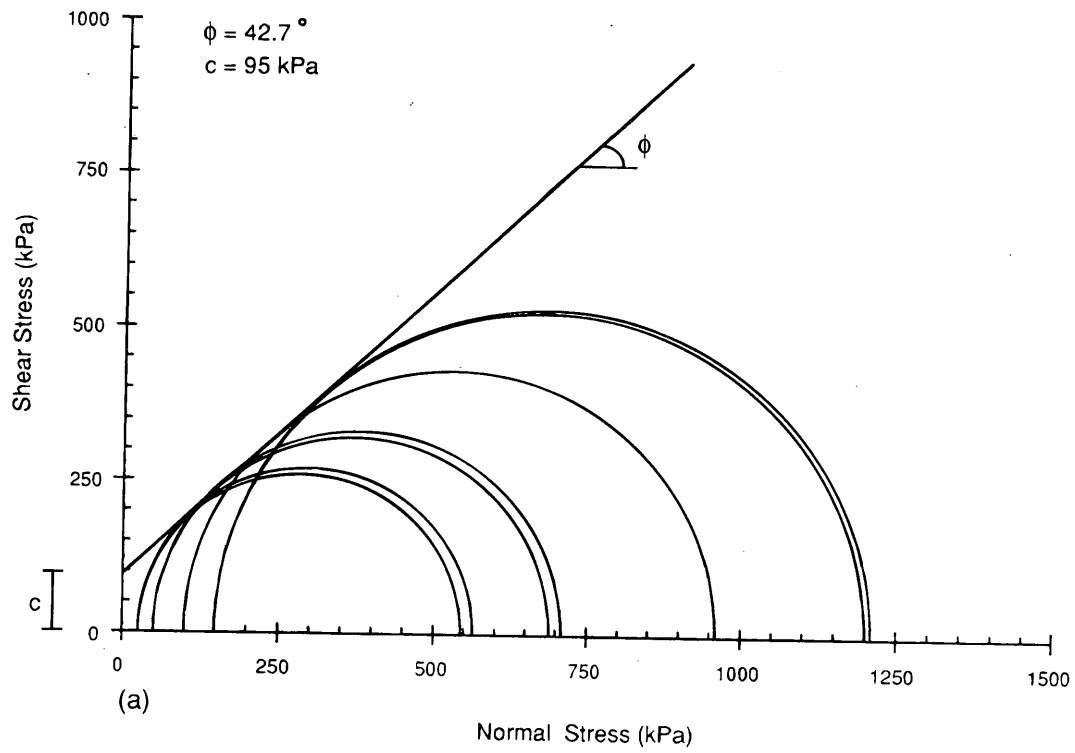


FIGURE 11 Mohr-Coulomb failure envelopes for (a) Mortar sands and (b) Lonestar #3 sands reinforced with continuous filaments.

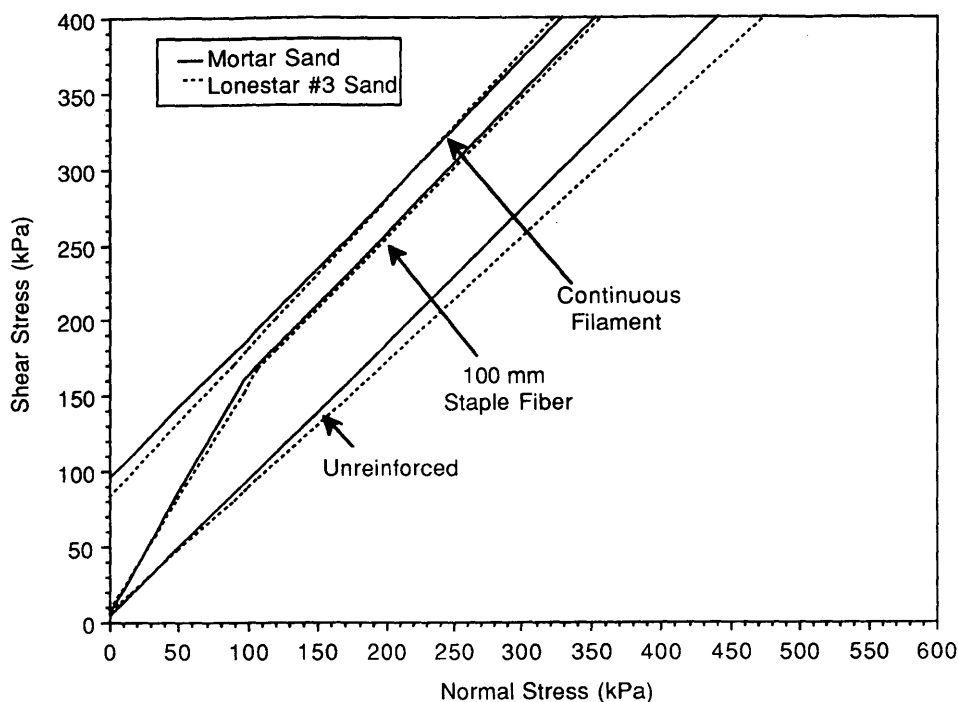


FIGURE 12 Mohr-Coulomb failure envelopes for all composite types.

TABLE 2 Strength Parameters from Mohr-Coulomb Failure Analysis

Reinforcement Type	Sand	Angle of Internal Friction (degrees)	Cohesion Intercept (kPa)
Unreinforced	Mortar	42	4
	Lonestar #3	40	6
100 mm Staple Fiber	Mortar	58	5
		43	70
	Lonestar #3	56	8
		43	68
Continuous Filament	Mortar	43	95
	Lonestar #3	44	83

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