Reinforcement of Fissured Clays by Short Steel Fibers

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The study involved a laboratory and a theoretical analysis designed to understand whether the use of short fibers increases the shear strength of fissured clays. The laboratory experiments involved the direct shear testing of reinforced and unreinforced clay samples containing a preexisting crack. The theoretical analysis used the principles of linear elastic fracture mechanics theory to determine the direction of crack propagation in the fissured clays. The investigation revealed that, if short steel fibers are added to the fissured clays, their shear strength increased. For the case of a clay sample with a preexisting horizontal crack, the addition of short fibers increased its shear strength by 9 percent. For the case of a clay sample with a preexisting crack inclined at 30 degrees with the horizontal, the shear strength increased by 25 percent with the addition of the fibers. Thus, the use of short fibers appears to be a viable technique for increasing the strength of fissured clays. However, many questions remain about how to effectively reinforce fissured clays in the field, the interaction mechanisms of the fibers with multiple cracks of different lengths and orientations, and the durability of the steel fibers in clay.

Reinforcement of intact clays with short fibers is a viable technique for increasing their shear strength. Studies have demonstrated that the inclusion of short fibers significantly improves the response of intact clays under both static and dynamic loading conditions (*1–4*). Many clays, however, are not intact but have fissures in their structure (*5–9*). These fissured clays often form part of earth dams and natural slopes. If these fissured clays are subjected to static or dynamic loads, the fissures propagate and interact in the clays, causing the failure of the slopes and the earth dams (*10–12*).

This study involved a theoretical and a laboratory investigation designed to answer the question: Can the use of short fibers stop the propagation of fissures in clays subjected to static loads? If the short fibers stop the propagation of the fissures, the strength of the reinforced fissured clays should also increase.

PHASES AND GOAL OF THE STUDY

This study involved two phases. In Phase 1, prismatic samples with induced cracks were tested in a direct shear apparatus to understand the propagation mechanisms of the induced cracks. Linear elastic fracture mechanics theory was used to interpret the types of stresses and the direction of crack propagation in the fissured clay samples. Phase 2 also involved the preparation of prismatic samples of clay with induced cracks However, to this second set of clay samples, short steel fibers were added. The short steel fibers were placed in the samples in a direction normal to the propagation direction of the cracks. The direction of crack propagation was obtained in Phase 1 of the testing program.

The findings of this study represent the first step in understanding whether fibers can reinforce fissured clays under controlled conditions in the laboratory. The goal is to implement the laboratory findings in actual field cases.

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PHASE 1: FISSURED CLAYS SUBJECTED TO DIRECT SHEAR

Preparation of the Fissured Clay Samples

For the experimental investigation on the effect of fissures in clays with no reinforcement and subjected to direct shear conditions, laboratory-prepared samples of brittle kaolinite with preexisting cracks were used. The kaolinite clay used in the experiments had a liquid limit equal to 58 percent and a plastic limit equal to 28 percent. Dry kaolinite was mixed with distilled water to form a soft soil mass with a water content of about 40 percent. After the mixing, the clay-water mixture was placed in an oedometer 30 cm in diameter and consolidated under a normal pressure of 25.7 kPa for 5 days. After unloading the oedometer, prismatic specimens measuring 7.62 cm long, 7.62 cm wide, and 2.54 cm thick were cut from the clay block.

Immediately after the prismatic samples were cut, when the water content was equal to 30 percent, cracks were artificially made in the samples by inserting and removing thin glass sheets 1 mm thick and 2.5 cm wide in a direction normal to the samples' free face. Two sets of clay samples, each set having a total of three samples, were prepared in the laboratory. One set of clay samples had the induced crack made at 0 degrees with the horizontal (Figure 1a). The second set of clay samples was prepared with the induced crack inclined at 30 degrees with the horizontal (Figure 1b). The samples were allowed to air dry until their average water contents reached a value of about 3 percent. After this was done, the samples were subjected to direct shear loading in the plane stress direct shear apparatus (Figure 2). This apparatus has been described in detail elsewhere (*9,13*). Under direct shear stress conditions, the cracks in the samples propagated, forming secondary tensile cracks that extended from the tip of the preexisting cracks.

The samples with the horizontal preexisting crack developed secondary cracks that extended in a direction that was inclined at 65 degrees with the plane of the preexisting crack (Figure 3a). The samples with the preexisting crack inclined at 30 degrees with the horizontal developed secondary cracks that followed the direction of the plane of the preexisting crack (Figure 4a). In other words, it

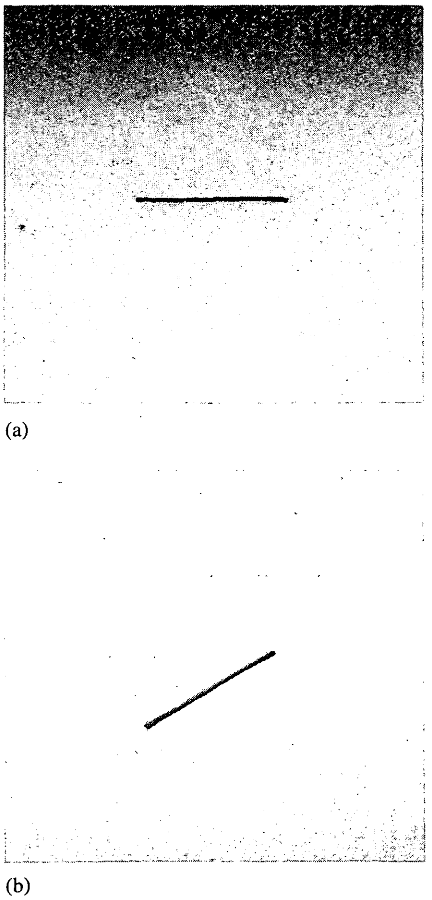

FIGURE 1 (a) Clay sample with horizontal crack; (b) clay sample with a crack inclined at 30 degrees with horizontal.

extended in a self-similar manner. For the case of the samples with a horizontal crack, crack propagation took place when the normal stress, σ_a, in the direct shear apparatus was equal to 69 kPa, and the shear stress, τ_a, was equal to 380 kPa. For the case of the samples with a crack inclined at 30 degrees with the horizontal, the normal stress, σ_a, in the direct shear apparatus at which the crack propagated was equal to 69 kPa, and the shear stress, τ_a, was equal to 276 kPa.

Theoretical Analysis

To interpret the results obtained from the direct shear results (Figure 3a and 4a), linear elastic fracture mechanics theory was used (*14*). By using this theory, the type of stresses causing the crack propagation in the clay samples as well as the direction of crack propagation can be obtained.

The system of stresses acting on a soil element located on the predetermined location of the failure surface are (*15–17*) those shown in Figure 5, where σ_a and τ_a are the normal and shear stresses exerted on the soil element by the direct shear apparatus, and σ_b is the lateral normal stress to the soil element. Note that in the direct shear apparatus the vertical stress σ_a is equal to the lateral normal stress σ_b (Figure 5).

For the theoretical analysis presented in this study, the soil element in the shear zone as shown in Figure 5 will include an open inclined crack. The soil element will be subjected to the same type of stresses as shown in Figure 5. This system of stresses acts on soil elements located in the shear zone of soil samples subjected to direct shear (*15–17*). The soil element with the crack and the system of stresses acting on it are shown in Figure 6.

In the vicinity of the tip of the preexisting crack (Figure 6), an element in the intact clay that surrounds the crack is subjected to the stresses σ_x, σ_y, and τ_{xy}. According to works by Gdoutos (*18*) and Vallejo (*9*), these stresses can be obtained from

$$\sigma_x = \frac{k_1}{(2r)^{1/2}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) - \frac{k_2}{(2r)^{1/2}} \sin\frac{\theta}{2}\left(2 + \cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right) \quad (1)$$

$$\sigma_y = \frac{k_1}{(2r)^{1/2}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) + \frac{k_2}{(2r)^{1/2}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \quad (2)$$

$$\tau_{xy} = \frac{k_1}{(2r)^{1/2}} \cos\frac{\theta}{2}\sin\frac{\theta}{2}\cos\frac{3\theta}{2} + \frac{k_2}{(2r)^{1/2}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \quad (3)$$

where r and θ represent the polar coordinates of the point considered (Figure 6), and k_1 and k_2 represent the stress intensity factors (*18*) that can be obtained from

$$k_1 = \sigma_n c^{1/2} \quad (4)$$

and

$$k_2 = \tau_n c^{1/2} \quad (5)$$

In Equations 4 and 5, σ_n is the stress acting normal to the plane of the crack (Figure 6), τ_n is the shear stress acting parallel to the plane of the crack in Figure 6, and c is half the length of the crack. Both of these stresses can be obtained from the following equations.

$$\sigma_n = \frac{\sigma_a + \sigma_b}{2} + \frac{\sigma_a - \sigma_b}{2}\cos(2\alpha) - \tau_a \sin(2\alpha) \quad (6)$$

Since in the direct shear apparatus, $\sigma_a = \sigma_b$ (*15–17*), Equation 6 simplifies to the following relationship:

$$\sigma_n = \sigma_a - \tau_a \sin(2\alpha) \quad (7)$$

The shear stress τ_a can be obtained from

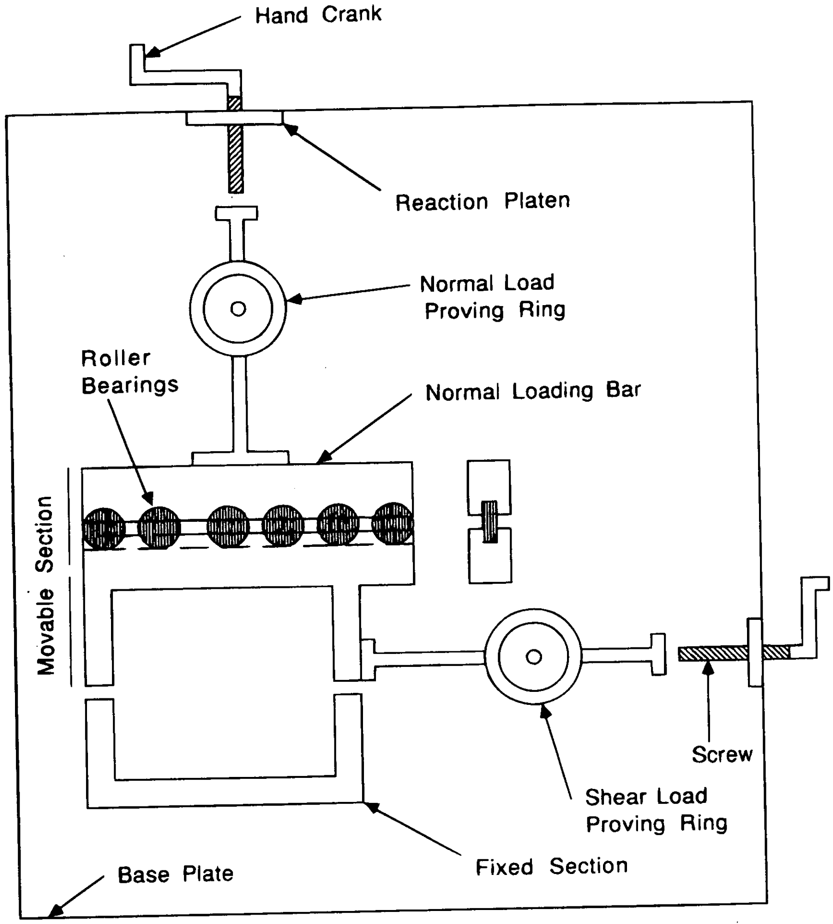

FIGURE 2 **Description of the plane stress direct shear apparatus.**

$$\tau_n = \frac{\sigma_a - \sigma_b}{2} \sin(2\alpha) + \tau_a \cos(2\alpha) \tag{8}$$

Since $\sigma_a = \sigma_b$ (Figure 5), Equation 8 becomes

$$\tau_n = \tau_a \cos(2\alpha) \tag{9}$$

The principal stress σ_1 and σ_3 at points surrounding the crack in Figure 5 can be obtained using Equations 1 through 9 and the following relationship:

$$\sigma_{1,3} = \frac{\sigma_x + \sigma_y}{2} \pm \left[\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\;2}\right]^{1/2} \tag{10}$$

The direction of the principal stresses can be obtained from the following equations:

$$\psi = \frac{1}{2}\tan^{-1}\left(\frac{2\tau_{xy}}{\sigma_x - \sigma_y}\right) \tag{11}$$

and

$$\lambda = \psi + \pi/2 \tag{12}$$

where ψ is the angle of inclination with respect to the X axis (Figure 6) of the principal plane where σ_1 acts; λ represents the inclination with the X axis of the principal plane on which σ_3 acts.

A computer program that uses Equations 9 through 12 was written to calculate and plot the magnitude and direction of the principal stresses around the fissured clay samples shown in Figures 1a, 1b, 3a, and 4a. The principal stresses were calculated using the values of the normal and shear stresses at which the preexisting cracks propagated in the samples.

Analysis of Theoretical Results

Results from the analysis using the computer program are shown in Figures 7 and 8. These figures show the plots of the principal stresses around the horizontal crack and the crack inclined at 30 degrees with the horizontal. The values of σ_a and τ_a that were used to plot Figures 7 and 8 were those at which crack propagation took place when tested in the plane stress direct shear apparatus. For the case of the test that included a sample with a horizontal crack, the values of σ_a and τ_a used were equal to 69 kPa and 380 kPa, respectively. The values of σ_a and τ_a used to plot Figure 8 (the case

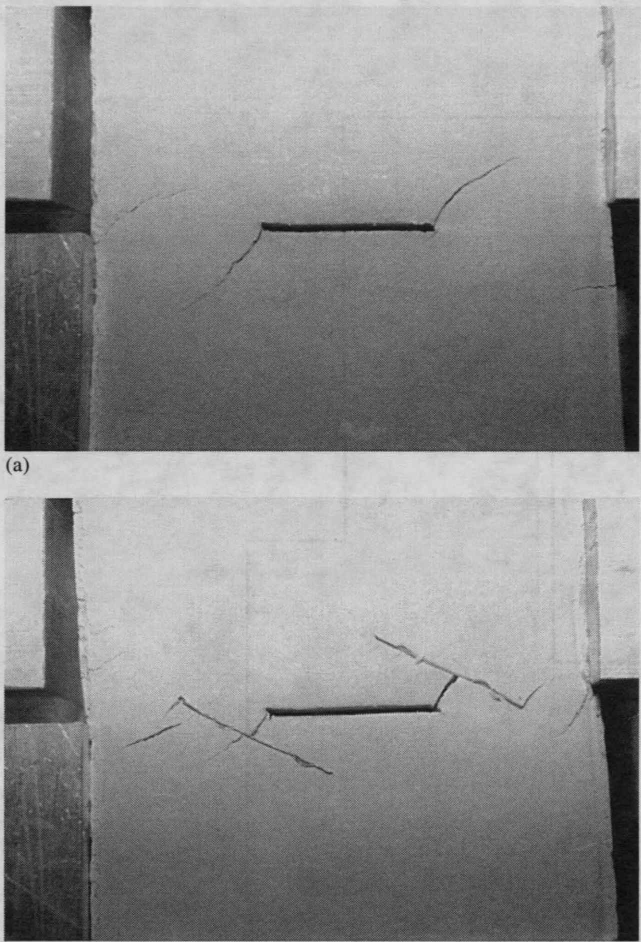

FIGURE 3 (a) Crack propagation in unreinforced clay sample with horizontal crack; (b) crack propagation in reinforced clay with horizontal crack.

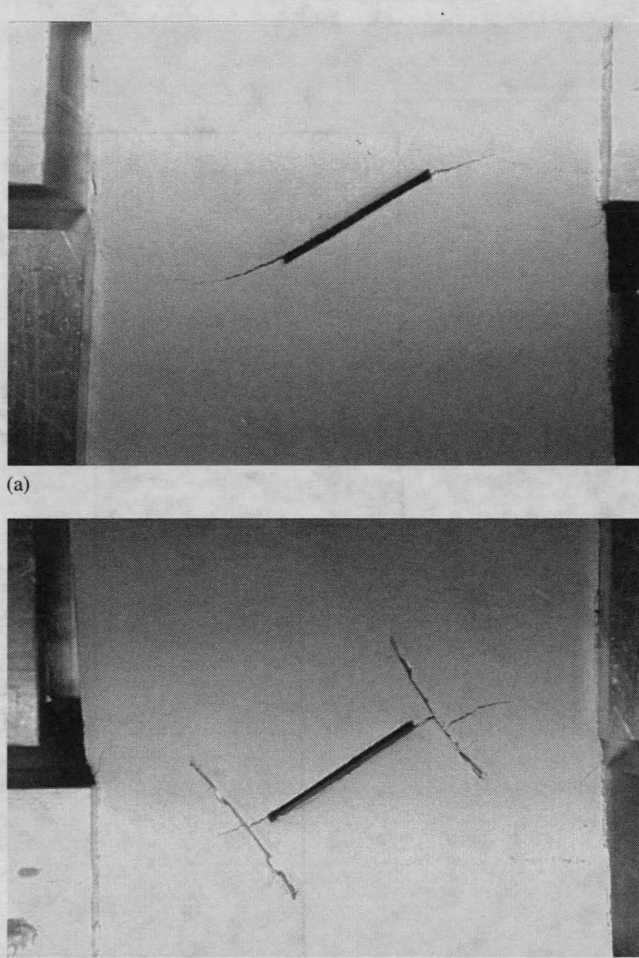

FIGURE 4 (a) Crack propagation in unreinforced clay with preexisting crack inclined at 30 degrees with horizontal; (b) crack propagation in reinforced clay sample with preexisting crack inclined at 30 degrees with horizontal.

with the 30-degree crack) were equal to 69 kPa and 276 kPa, respectively. These are the values for the case of clay samples with one crack and no reinforcement.

An analysis of Figures 7 and 8 indicates that zones of tensile stresses formed around the cracks. For the case of the horizontal crack (Figure 7), the zones of tensile stresses formed in the upper-right and lower-left corners of the preexisting crack. These will be the zones in which the soil fails because clays are weak in tension. The laboratory result (Figure 3a) in fact shows that the zones where the tensile stresses developed experienced cracking. The extended cracks will follow a direction that is normal for the major principal tensile stress (Figure 7). This normal direction is equal to 70 degrees (Figure 7) and is very close to the 65 degrees measured in the laboratory experiment (Figure 3a).

For the case of the sample with the preexisting crack inclined at 30 degrees with the horizontal, the computer results are shown in Figure 8. Zones of tensile stresses developed at the two tips of the preexisting crack. The direction of the major principal tensile stress is normal to the plane of the preexisting crack (Figure 8). Therefore, secondary cracks will extend from the tips of the preexisting crack and will follow a direction parallel to the plane of the preexisting crack. Laboratory results, shown in Figure 4a, confirm the findings of the computer analysis.

PHASE 2: REINFORCED FISSURED CLAYS SUBJECTED TO DIRECT SHEAR

To investigate whether the addition of short fibers is a viable technique to prevent the propagation of cracks in fissured clays, fissured samples similar to the ones shown in Figure 1 (no reinforcement) were prepared in the laboratory. The only difference was that short crimped steel fibers, 2.54 cm long and 0.12 cm wide, were added to the clay (see Figure 9). The short fibers were placed in a direction normal to the expected crack propagation direction (Figures 3a and 4a). The clay samples with no cracks but with steel fibers were subjected in the oedometer to the same level of consolidated pressure (25.7 kPa) for the same duration (5 days) as the samples prepared

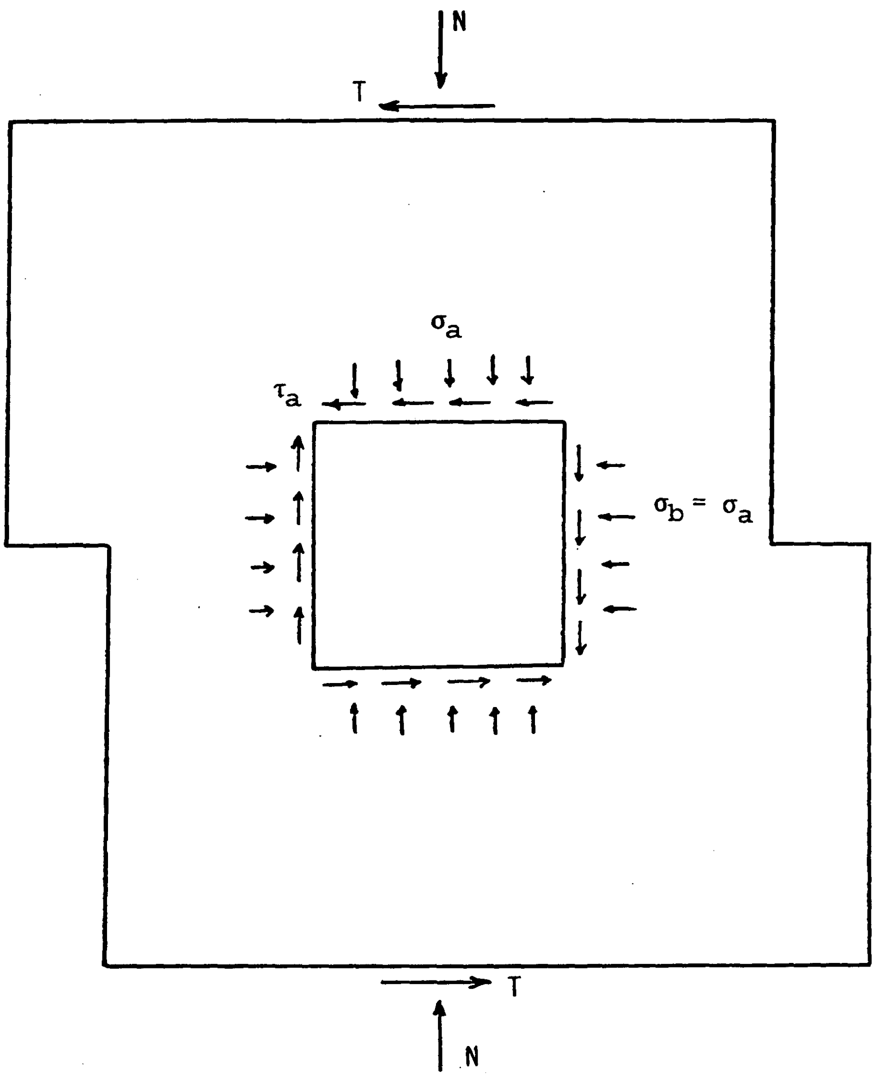

FIGURE 5 Stresses acting on soil element located in shear zone of direct shear apparatus (*15–17*).

for Phase 1 of the testing program. After unloading the oedometer, the cracks were induced in the samples. The steel fibers were not disturbed because their locations were known before the cracks were made in the samples. The samples had a total of eight short steel fibers. The steel fibers were located in two zones, near the tips of the induced cracks, where the secondary cracks developed in the unreinforced fissured clay samples. Each of the two zones had four steel fibers.

The samples with the preexisting fissures were placed in the plane stress direct shear apparatus and were subjected to direct shear. The normal stress, σ_a, in the direct shear apparatus was kept constant and equal to 69 kPa for both samples (one with the horizontal crack, the other with the 30 degree crack). After shearing, secondary cracks developed in both samples. For the case of the sample with the horizontal crack, secondary cracks developed when the shear stress was equal to 414 kPa (Figure 3b). For the case of the reinforced sample with the preexisting crack inclined at 30 degrees with the horizontal, secondary cracks developed when the shear stress in the direct shear apparatus reached a value equal to 345 kPa.

A summary of the laboratory results on the unreinforced and reinforced samples is shown in Table 1. An analysis of the data indicates that the crimped short steel fibers helped increase the shear resistance of the fissured samples. The addition of the short steel fibers to the sample with a horizontal crack increased its strength by 9 percent. When the fibers are added to the sample with a 30-degree crack, its shear strength increased by 25 percent. Thus, the use of short fibers appears to represent a viable technique for increasing the shear strength of fissured clays.

CONCLUSIONS

The use of fibers to increase the shear strength of *intact* clays has been proved by previous research to be a viable technique. The present study extends the research on reinforced intact clays to include

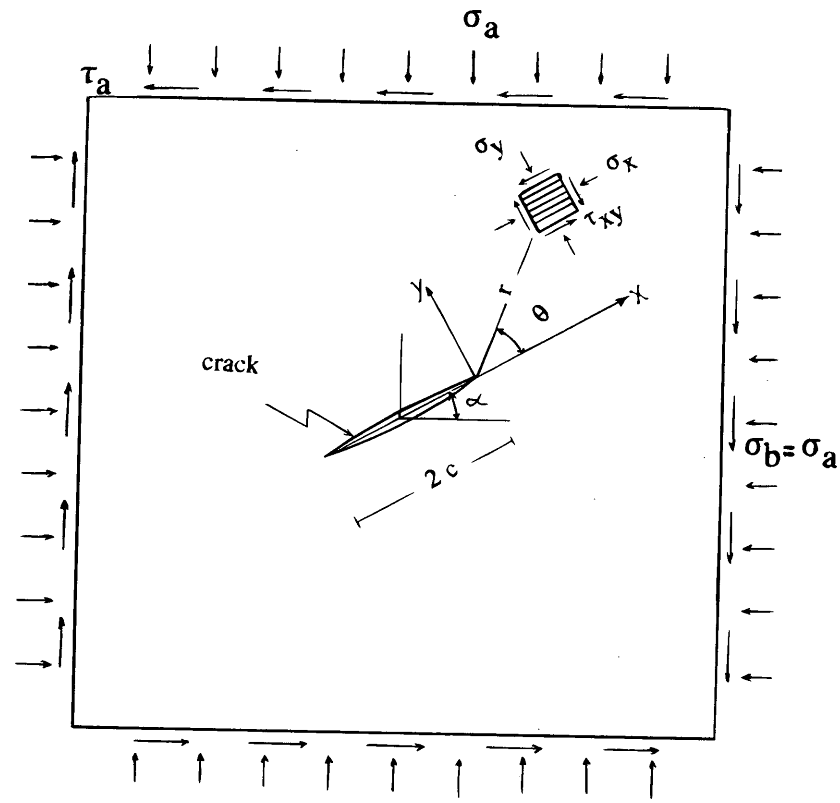

FIGURE 6 System of stresses acting on soil element containing crack and located in shear zone of direct shear apparatus.

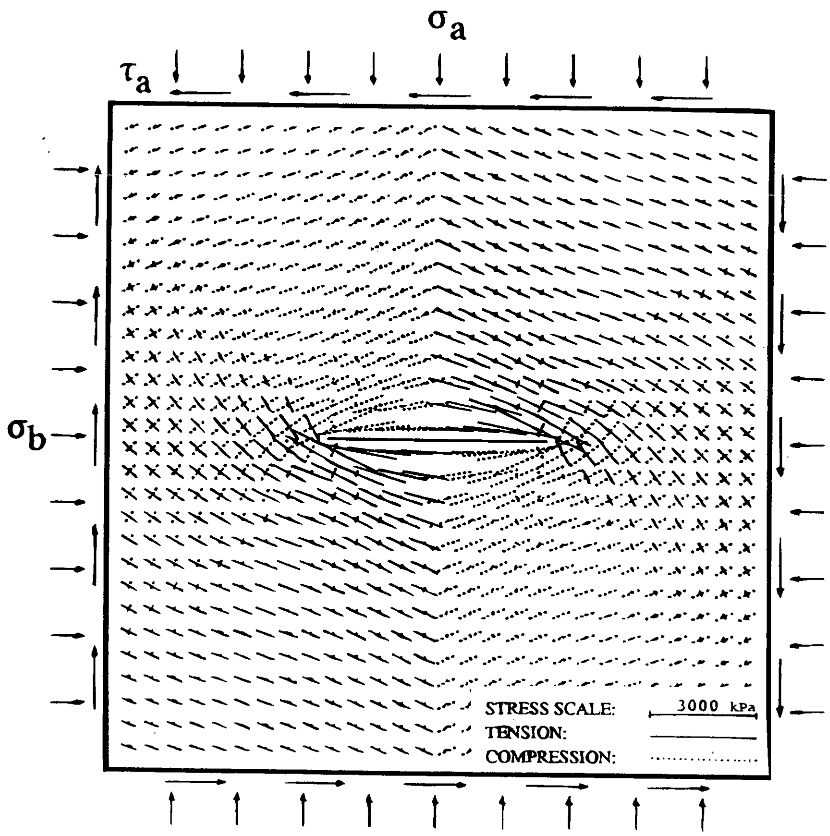

FIGURE 7 Principal stresses around horizontal crack subjected to direct shear stress conditions ($\sigma_a = \sigma_b = 69$ kPa, $\tau_a = 380$ kPa).

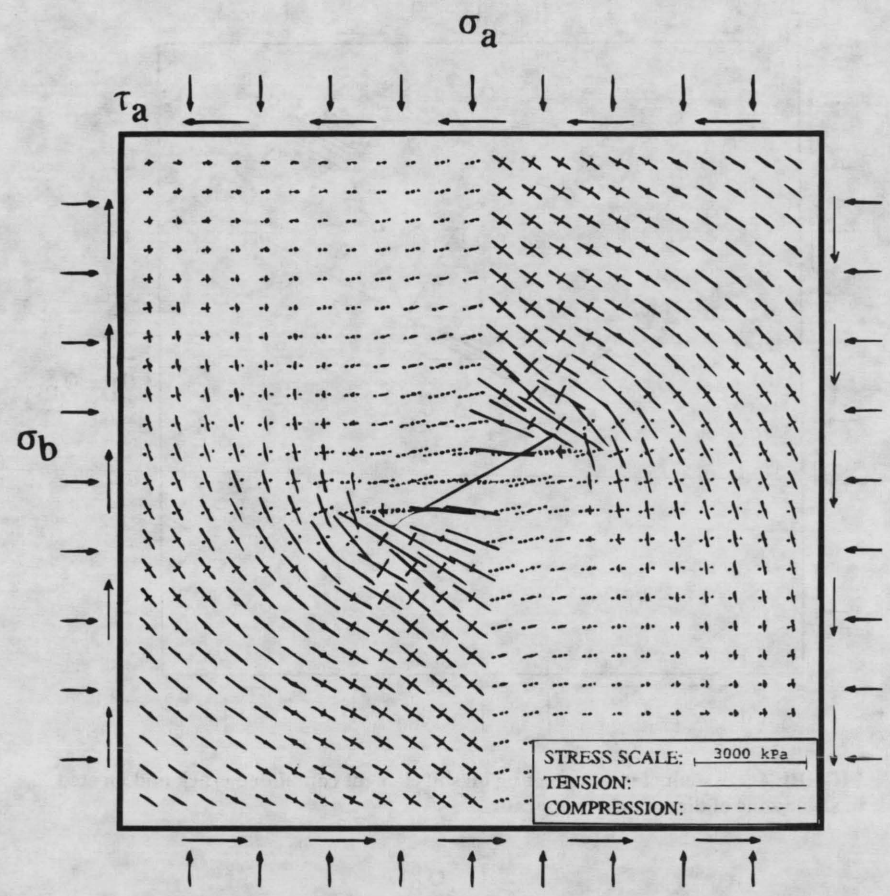

FIGURE 8 Principal stresses around crack inclined at 30 degrees with horizontal and subjected to direct shear stress conditions ($\sigma_a = \sigma_b = 69$ kPa, $\tau_a = 276$ kPa).

fissured clays. By using a laboratory testing program in unreinforced and fissured clay samples, as well as a theoretical analysis that makes use of linear elastic fracture mechanics theory, the following conclusions can be reached.

- The theoretical analysis predicted the type of stresses causing crack propagation and the direction of crack propagation in the clay samples with no reinforcement. The type of stresses that caused the cracks to propagate were tensile in nature, and the direction varied according to the inclination of the cracks in the sample.
- Fibers were added to the samples and were installed in a direction perpendicular to that in which the crack propagated, as determined in the unreinforced fissured clay samples. The addition of short steel fibers to fissured stiff clays increases their resistance to shear stresses. For a sample with a horizontal crack, the addition of the fibers increased its shear strength by about 9 percent. For the sample with a preexisting crack inclined at 30 degrees with the horizontal, the shear strength was increased by 25 percent.
- The short steel fibers appear to be effective in increasing the shear strength of fissured clays if the fibers are placed in the direction normal to the direction of propagation of the preexisting fissures in the clay samples.
- Because the testing program was limited in scope, further research is needed to answer the many important questions that still exist. These questions relate to (a) the repeatability of test results if different types of clay are used; (b) the effect crack structure, such as crack shape, has on the way cracks propagate in the samples; (c) the influence of the orientation and number of the preexisting cracks on the mechanics of crack propagation and interaction in clay samples; (d) the interaction of fibers and multiple cracks in clay samples; (e)

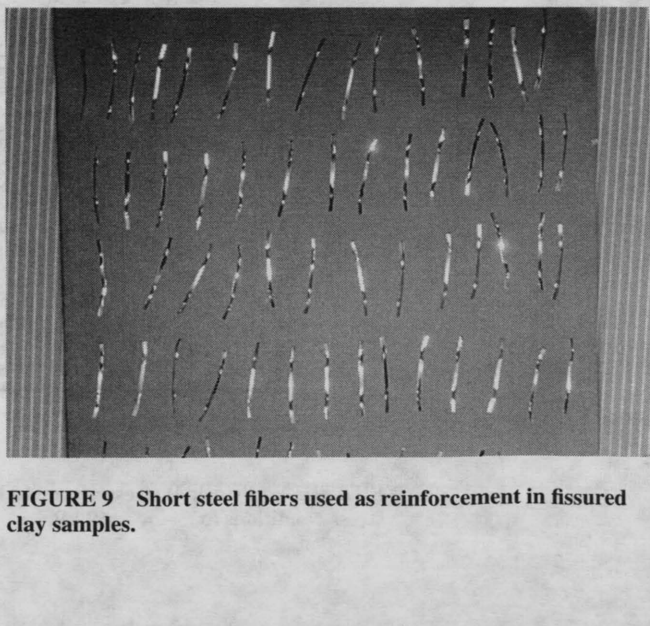

FIGURE 9 Short steel fibers used as reinforcement in fissured clay samples.

TABLE 1 Effect of Reinforcement in Fissured Clays

Sample	Water Content %	Normal Stress, σ_a* (kPa)	Shear Stress, τ_a* (kPa) Without Fibers	With Fibers
With Horizontal Crack	3.0	69	380	414
With Crack at 30 degrees with Horizontal	3.0	69	276	345

* σ_a and τ_a are measured by the direct shear apparatus

the methods to introduce the fibers into the clay under field conditions so the fibers are aligned perpendicular to the direction of crack propagation; and (f) the durability of steel fibers in the clay soil.

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