Effects of Reinforcement of Steel Fibers on the Crack Propagation of Fissured Clays

균열점토의 균열진행에 대한 강섬유의 보강효과

Yoo, Han-Kyu*
유 한 규

요 지

균열점토에 대한 강섬유 사용 가능성을 평가하기 위하여 균열이 있는 보강점토와 비보강점토 시료에 대한 일축압축실험을 실시하였다. 실험결과 강섬유 보강으로 인하여 균열의 시작과 진행에 대한 저항력이 증가하므로써 균열 시작시 응력과 파괴시 극한응력이 증가되었다. 균열의 시작과 진행에 대한 저항력의 증가는 점토시료에서 강섬유에 의한 균열진행의 억제 또는 진행방향의 변경과 관련되어 있음을 알 수 있었다. 파괴역학 이론과 섬유로 보강된 물질에서의 인발미캐니즘을 적용하여 실험결과에 대한 이론적인 해석이 이루어졌다. 해석결과 강섬유의 인발작용을 통한 연결효과로 인하여 시료에서 균열의 진행에 대한 저항력이 증가됨을 알 수 있었다. 이론적인 분석에 의하여 예측된 인발력은 인발실험으로 부터 산정된 값과 비교적 잘 일치되었다.

Abstract

In order to assess the possibility of using steel fibers in the fissured clays, uniaxial compression tests were performed on both unreinforced and reinforced clay samples containing a pre-existing crack. Test results showed that the steel fiber reinforcement increased resistance to cracks initiation and their propagation, and therefore increased both stress at crack growth initiation and peak stress at failure. The increase in resistance to cracks initiation and their propagation was related to the arresting or deflecting the crack propagation in clay samples by steel fibers. A theoretical interpretation of experimental results was made using fracture mechanics theory and pull-out mechanisms in fiber reinforced materials. It was revealed that the steel fibers had bridging effect through their pull-out action that caused an increased resistance to the propagation of the cracks in the samples. The predicted pull-out force based on theoretical analyses agreed reasonably well with the measured values obtained from pull-out tests.

1. Introduction

Clays forming part of zoned and homogeneous earth dams develop fissures or cracks

* 정회원, 삼성건설 토목설계 ENG팀 과장

during and after the construction of the dams. Vallejo[11] has summarized the reasons by which these materials develop cracks. With time these cracks may propagate and interact in the earth dams as a result of gravity induced stresses. The propagation of the cracks takes place when tensile stresses are effective in the cohesive material surrounding the fissures. If short steel fibers are added to the clays during their placement, maybe these steel fibers will stop the propagation of cracks that develop later when the earth dams are completed. No information exists to date in the geotechnical literature on whether or not short steel fibers prevent the crack propagation, and hence improve the strength of fissured clays.

It has been shown that reinforcement of concrete by short steel fibers improved tensile strength, compressive strength, ductility, and crack propagation resistance. Since the vast quantity of cracks in concrete was considered as a major shortcoming of brittle materials, the short steel fiber was primarily used to increase the resistance of concrete to crack propagation. Bentur et al.[1] observed four different types of crack propagation around steel and glass fibers as shown in Fig. 1.

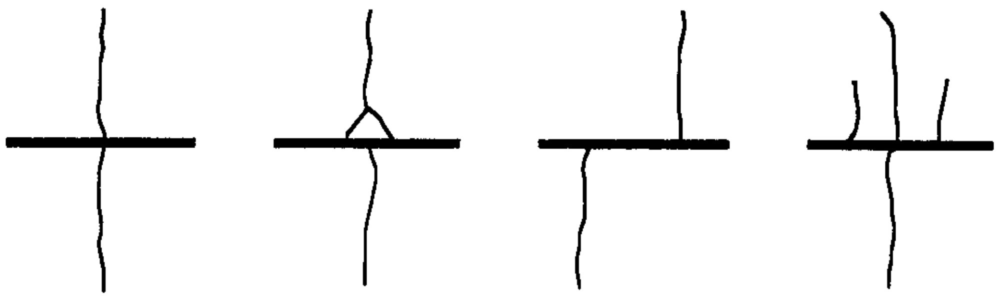


Fig. 1 Four types of cracking process(Bentur, 1985)

Types 1 and 2 were undeviated cracking patterns while type 3 and type 4 involved shifting and branching. The undeviated cracking was found to be very rare. The changes in the path of a crack due to fibers dissipates energy from the stressed system and additional energy is consumed in the interruption. The dissipation of energy and extra energy consumed by interrupted crack yield a resistance to crack growth and ultimately increases the strength of the composite.

Sato et al.[7] investigated reinforcing mechanisms by short fibers for the composite strength by observation of failure process and plastic deformation of the composite matrix. The reinforcing mechanism was considered to be affected by fiber parameters such as surface area, number of fibers, fiber length and separation between the neighboring fibers. The reinforcing mechanisms by short fibers are illustrated in Fig. 2.

The effects of interface, stress interaction, crack path, and plastic deformation were responsible for improving the composite strength and toughness whereas the fiber end caused stress concentration and was primarily responsible for the decrease in the com-

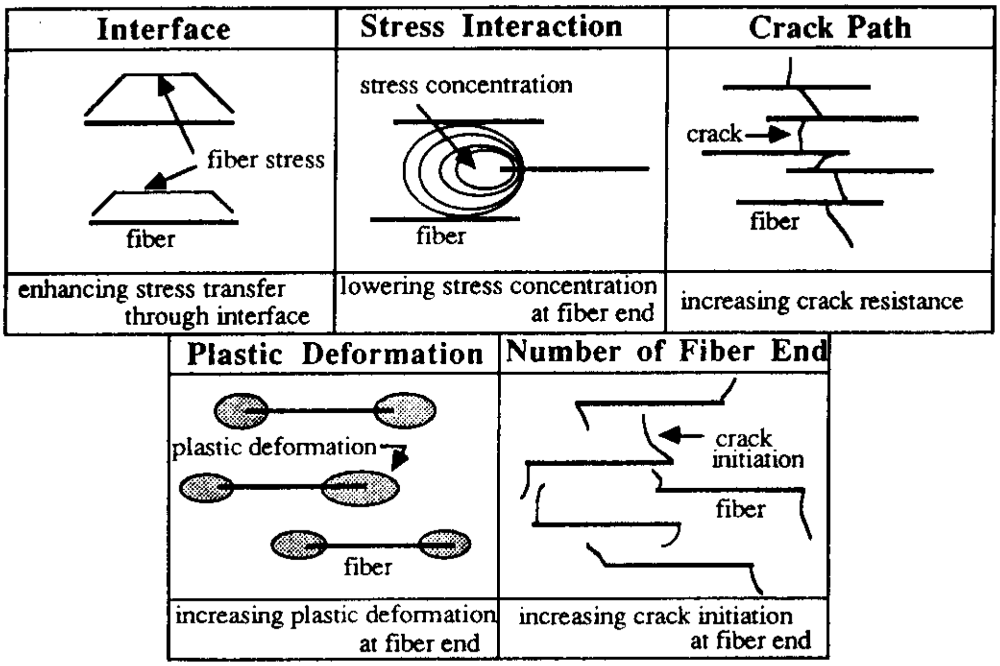


Fig. 2 Reinforcing mechanisms by short fibers(sato, 1988).

posite strength and toughness.

The purpose of present investigation is to assess the possibility of using steel fibers in the fissured clays. In the present study, uniaxial compression tests are performed to investigate the effects of reinforcement of steel fibers on the strength increase and resistance to crack propagation of fissured clay samples. Also, theoretical interpretation of experimental results using fracture mechanics theory as well as pull-out mechanisms in fiber reinforced materials is presented to study how short steel fibers reinforce the fissured clays through their pull-out action.

2. Laboratory Investigation

2.1 Test Materials and Sample Preparation

For this laboratory investigation, a commercial powdered kaolinite clay was used to prepare fissured clay samples. The clay had a liquid limit of 58% and a plastic limit of 28%. The reinforcement consisted of short steel fibers which were smooth and deformed. The fibers had sufficient ductility to permit 180 degree bends without rupture and were available commercially as admixes for concrete reinforcement. The physical properties of the steel fibers are summarized in Table 1.

For the fissured clay sample preparation, dry powdered kaolinite clay was mixed with water to form a soft soil paste with a water content of about 35%. The clay-water mix-

Table 1. Physical properties of short steel fibers

Type of Reinforcement	Length (in)	Width (in)	Thickness (in)	Tensile Strength $(lb/in^2)\times10^3$	Elastic Modulus $(lb/in^2)\times10^6$
Steel Fiber	1.0	0.048	0.01	60－100	29

ture was then placed into plexiglass molds which dimensions were 3 inch in width, 3 inch in length, and 1 inch in thickness. To facilitate easy removal of the samples, the sides of the molds were lubricated prior to placement of the clay-water mixture. The short steel fibers was then placed into the clay-water mixture at the desired location and orientation. After placement of the short steel fibers into the clay-water mixture, the assembly was seated on a porous plate and loaded to a maximum load of 33 pounds for a period of 24 hours. The cracks were artificially made in samples immediately after the samples were removed from the molds. The cracks with different orientations were made in samples by a process of inserting and removing lubricated thin glass sheet (1 inch in length, 0.04 inch in thickness) along the samples's thickness direction. The samples were then allowed to dry in air.

2.2 Test Procedure

Tests were conducted using a standard uniaxial compression apparatus. Both load and deformation were recorded throughout the tests. Also the load at crack growth initiation was monitored and recorded. Photographs were taken of the samples to observe the failure behavior of the reinforced clay samples after they were subjected to uniaxial compressive loadings. From these photographs, the direction of crack propagation with respect to the plane of the pre-existing crack as well as the cracking process at the intersection between the propagating cracks and steel fibers were measured and observed. The pre-existing crack had three inclinations with respect to the direction of the uniaxial compressive loading. These inclinations were 30, 45, and 60°. Eight short steel fibers were placed in the clay zones surrounding a pre-existing crack and oriented perpendicular to the expected crack propagation direction as shown in Fig. 3.

Vallejo[11] presented an analytical method using fracture mechanics theory as well as experimental procedures to determine such a crack propagation direction in samples with a pre-existing crack. His laboratory results consistantly agreed with theoretical predictions, and the angles of crack propagations measured at the tips of the pre-existing crack were 82, 90, and 103° corresponding to the pre-existing crack inclination of 30, 45, and 60°, respectively. In order to test the samples in their brittle state, average water contents of 2.74% were used. In all of the tests, a constant testing speed of 0.03 inch/min was used.

2.3 Test Results

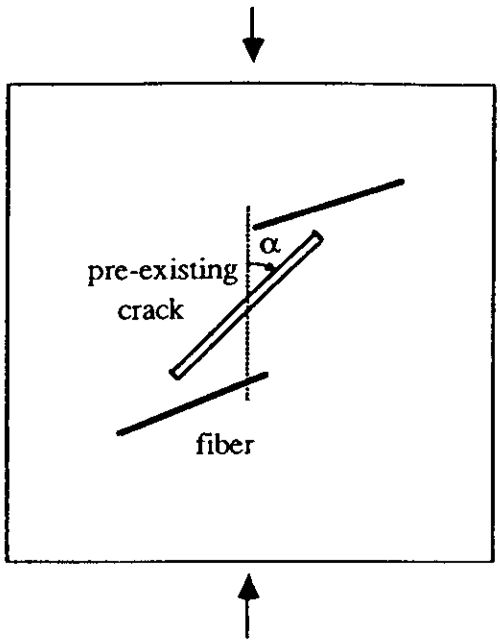


Fig. 3 Fiber reinforced clay sample with a pre−existing crack

Fig. 4 presents relationship between stress and strain for fissured clay samples with or without short steel fibers. In this sample, the inclination of a pre-existing crack was 30° and the water content was 2.77%.

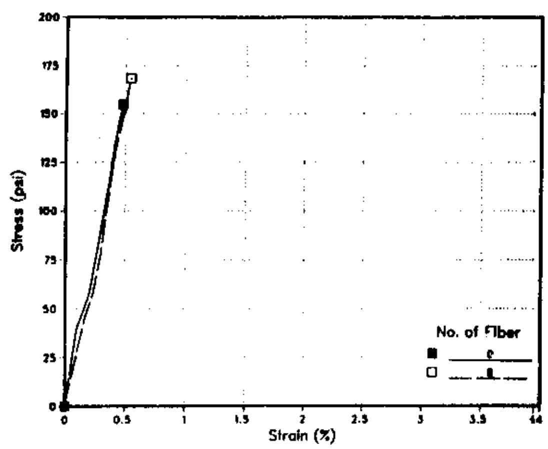


Fig. 4 Stress vs strain for sample with $\alpha = 30^\circ$ and $W = 2.77\%$

It can be seen that short steel fiber reinforcements improved the peak stress of fissured clay sample at failure compared to that at the unreinforced clay sample. The value of peak stress found were 153.86 psi and 167.73 psi for unreinforced and reinforced fissured clay samples, respectively and therefore fiber reinforcements led to 9% improvement compared to the unreinforced fissured sample.

Tests conducted on samples with a pre-existing crack inclined at 45 and 60°, as shown in Fig. 5 and 6, showed similar results.

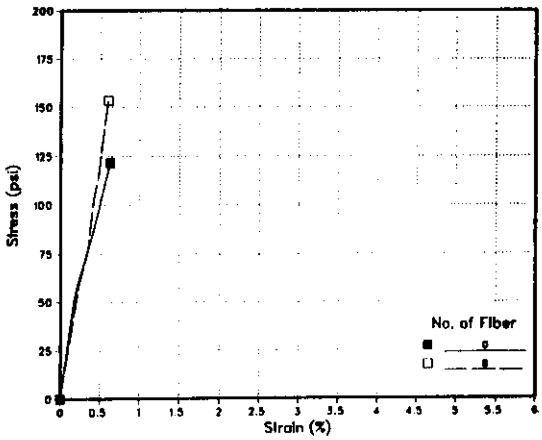


Fig. 5 Stress vs strain for sample with $\alpha = 45°$ and W = 2.81%

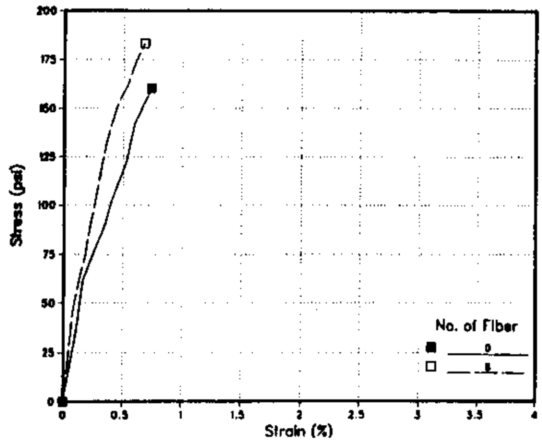
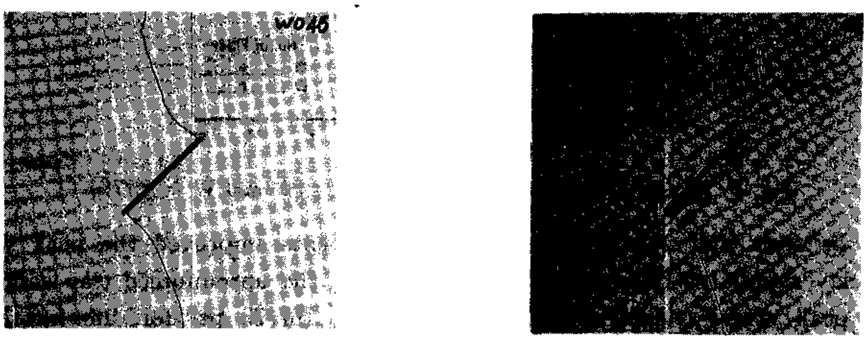


Fig. 6 Stress vs strain for sample with $\alpha = 60°$ and W = 2.70%

This observation suggest that stress-strain behavior of fissured clay tends to be influenced by the presence of short steel fibers. The improvement in the behavior of fissured clays by short steel fibers seems to be related to the propagating mechanics of cracks in the sample.

When the unreinforced fissured clay sample was subjected to uniaxial compression, the cracks developed from either the tips or the edges of the pre-existing crack in a direction that deviated from that of the pre-existing crack. The cracks then propagated very rapidly, upon further increase of loading, in a direction that was parallel to the direction of loading. When the propagating cracks reached the upper and lower boundaries of the samples, the sample failed and divided into two separate pieces as shown in Fig. 7(a). In the case of a fissured clay sample with short steel fibers, as shown in Fig. 7(b), the crack development took place from the tips of a pre-existing crack and followed a direction that deviated from the plane of the pre-existing crack.



(a) Unreinforced Sample (b) Reinforced Sample

Fig. 7 Crack propagation of clay samples with $\alpha = 45°$ and W = 2.81%

When the propagating cracks reached the short steel fibers, they were shifted at the intersection between propagating cracks and short steel fibers. Finally, they propagated in a direction parallel to the direction of loading and led to sample failure. Tests conducted on samples with a pre-existing crack inclined at 30 or 60°showed similar pattern of cracking process at the intersection between propagating cracks and fibers.

Fig. 8 presents the relationship between compressive stress at crack growth initiation and a pre-existing crack inclination in brittle samples with an average water content of 2. 74%.

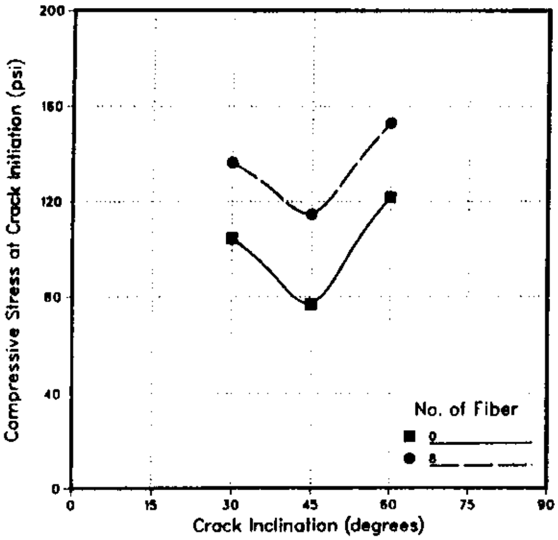


Fig. 8 Relationship between compressive stress at crack growth initiation and crack inclination

This figure shows that the compressive stress at crack growth initiation in reinforced fissured samples is greater than that in unreinforced fissured samples. This observation suggest that the presence of short steel fibers may suppress the crack initiation at the tips of the pre-existing crack, and hence increase the stress at crack growth initiation.

3. Theoretical Analyses

3.1 Fracture Criteria for a Sharp Crack

Erdogan and Sih[2] have analyzed crack propagation in a plate with a central pre-existing crack of length 2a inclined at an angle of α° to the direction in loading under uniaxial uniform stress as shown in Fig. 9.

They state that the crack extends in a radial direction from its crack tip and the direction of crack growth is normal to the maximum tangential stres σ_θ. The polar components of stress σ_r, σ_θ, and $\tau_{r\theta}$ at a point near a single sharp crack, referring to Fig. 9, are given by:

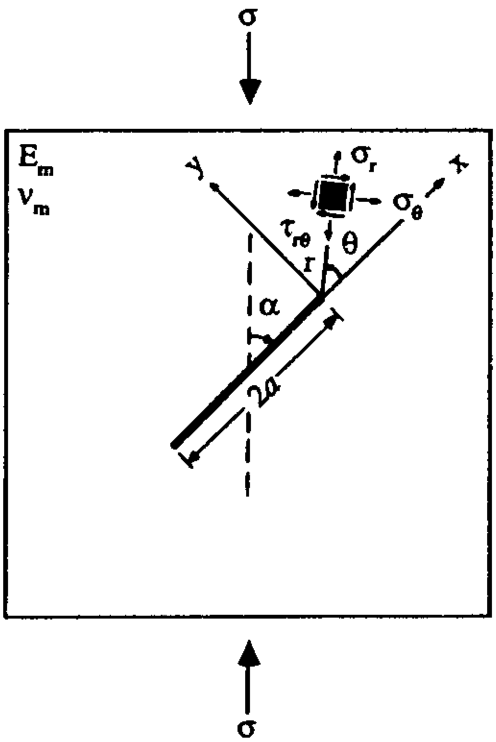


Fig. 9 Stress components of clay sample with a pre-existing crack

$$\sigma_r = \frac{1}{\sqrt{2\pi r}} \{K_I \cos\frac{\theta}{2} [1+\sin^2\frac{\theta}{2}] + K_{II}\sin\frac{\theta}{2} [1-3\sin^2\frac{\theta}{2}]\} \tag{1}$$

$$\sigma_\theta = \frac{1}{\sqrt{2\pi r}} \{K_I \cos^3\frac{\theta}{2} - 3K_{II}\sin\frac{\theta}{2} \cos^2\frac{\theta}{2}\} \tag{2}$$

$$\tau_{r\theta} = \frac{1}{\sqrt{2\pi r}} \{K_I \sin\frac{\theta}{2} \cos^2\frac{\theta}{2} + K_{II}\cos\frac{\theta}{2} [1-3\sin^2\frac{\theta}{2}]\} \tag{3}$$

where the stress intensity factors K_I and K_{II} are given by:

$$K_I = \sigma\sqrt{\pi a}\ \sin^2\alpha \tag{4}$$

$$K_{II} = \sigma\sqrt{\pi a}\ \sin\alpha\ \cos\alpha \tag{5}$$

If a crack in a plate propagates in the direction in which σ_θ, given in Equation (2), reaches its maximum, the direction of crack propagation, θ°, is given by:

$$\frac{d\sigma_\theta}{d\theta} = 0,\ \frac{d^2\sigma_\theta}{d\theta^2} < 0 \tag{6}$$

Applying the conditions expressed by Equation (6) together with Equation (2), the following equation is obtained and given by:

$$K_I \sin\theta + K_{II} [3\cos\theta - 1] = 0 \tag{7}$$

Replacing the value of K_I and K_{II} given by Equations (4) and (5) into the above equation, the following expression can be obtained and given by:

$$\tan\alpha \sin\theta + (3\cos\theta - 1) = 0 \tag{8}$$

There are two solutions of for a given of α, one a positive value, when the applied stress is compressive, and the other a negative value, when the applied stress is tensile.

3.2 Pull—Out Mechanism in Fissured Clays Reinforced by Steel Fibers

Using the fracture criteria for a sharp crack as well as with a knowledge of pull-out resistance of the fiber, a theoretical analysis is presented to study how short steel fiber reinforce the fissured clays through their pull-out action.

Consider a prismatic sample of fissured clay reinforced with short steel fibers in the clay zones surrounding the pre-existing crack of length 2a and subjected to a uniaxial compressive stress σ as shown in Fig. 10.

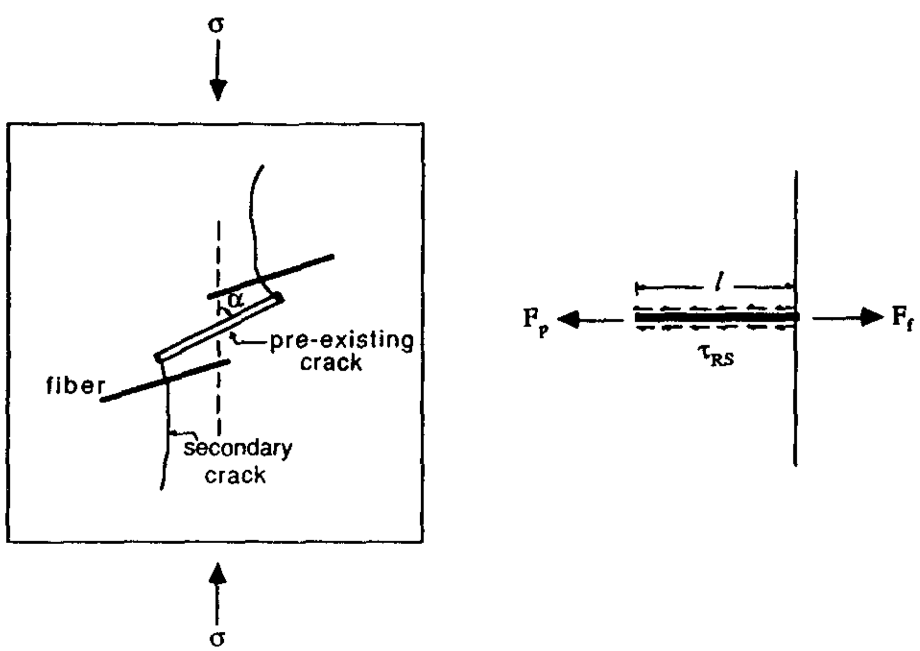


Fig. 10 Force equilibrium in fiber reinforced clay with a pre—existing crack

According to Vallejo[11], crack extension in unreinforced fissured clays takes place in a direction in which σ_θ , given by Equation (2), reaches its maximum value. That is, crack extension occurs when the maximum tangential stress reaches a critical value, σ_{crit}. Therefore σ_θ in Equation (2) for unreinforced fissured clays takes the form:

$$(\sigma_U)_{crit} = \frac{1}{\sqrt{2\pi r}} \{K_I' \cos^3\frac{\theta}{2} - 3K_{III} \sin\frac{2}{\theta} \cos^2\frac{\theta}{2}\} \tag{9}$$

where the stress intensity factors K_I and K_{II} are given by:

$$K_I = \sigma \sqrt{\pi a} \sin^2\alpha \tag{10}$$

$$K_{II} = \sigma \sqrt{\pi a} \sin\alpha \cos\alpha \tag{11}$$

For reinforced fissured clays, the crack extension in fissured clays with short steel fibers is assumed to be goverened by same criteria as those for unreinforced fissured clays. Therefore, σ_θ in Equation (2) for reinforced fissured clays takes the form:

$$(\sigma_R)_{crit} = \frac{1}{\sqrt{2\pi a}} \{K_I' \cos^3\frac{\theta}{2} - 3K_{II}' \sin\frac{\theta}{2} \cos^2\frac{\theta}{2}\} \tag{12}$$

where the stress intensity factors K_I' and K_{II}' are given by:

$$K_I' = \sigma' \sqrt{\pi a} \sin^2\alpha \tag{13}$$

$$K_{II}' = \sigma' \sqrt{\pi a} \sin\alpha \cos\alpha \tag{14}$$

The stress intensity factors for both unreinforced and reinforced fissured clays can be obtained by observing the compression stress at crack growth initiation, σ and σ', from uniaxial compressive tests on fissured clays with and without short steel fibers.

Using $(\sigma_U)_{crit}$ and $(\sigma_R)_{crit}$, the stresses that the short fiber is subjected to can be expressed as follows:

$$\sigma_f = (\sigma_R)_{crit} - (\sigma_U)_{crit} \tag{15}$$

Then the load that the short fiber is subjected to is given by:

$$F_f = \sigma_f \pi r^2 \tag{16}$$

where r is the effective radius of the fiber.

At limit equilibrium conditions, the force F_f in the short fiber is assumed to be equal and opposite to the bonding force F_p (by assuming uniform shear stress distribution along length of fiber) can be expressed as follows:

$$F_p = \tau_{RS} A_{RS} \tag{17}$$

where τ_{RS} is the average bonding stress and A_{RS} is the effective embedded surface area of the fiber.
That is:

$$F_p = \tau_{RS} 2\pi r l \tag{18}$$

where l is the embedded length of the fiber. Therefore, at limit equlibrium conditions, the average bond stress τ_{RS} can'be expressed as follows:

$$\tau_{RS} = \frac{r}{2l}\sigma_f \tag{19}$$

This equation enables the evaluation of the average bond stress τ_{RS} in terms of stress in the fiber σ_f theoretically.

4. Theoretical Interpretation of Experimental Results

Fig. 11 presents comparison of the measured pull－out force of the fiber obtained from the pull－out tests on deformed fiber and the theoretical prediction using fracture criteria for a sharp crack and pull-out mechanisms in fiber reinforced materials. The measured value of pull-out force was 0.65 pounds and the theoretical pull-out force was calculated using Equation (19) with the distance of 1 x 10^{-6}inch from the tips of the pre-existing crack.

It can be seen that the measured pull-out force show good agreement with the theoretical prediction. A possible explanation for this result seems to be related to the contribution of the fibers to increasd stress associated with initial cracking as well as peak stress at failure through their pull-out action. Short steel fibers may provide closing stress to propagating cracks as well as suppression of initial crack growth, and thereby increase such stresses. In other words, the fibers bridge cracks and provide closing stress on the crack until it is actually pulled-out of the clays.

This finding is a good indication of assesing the possibility of using short steel fibers in the earth dams. If short steel fibers are added to clay during their placement and placed with an optimum orientation with respect to the crack propagation direction,

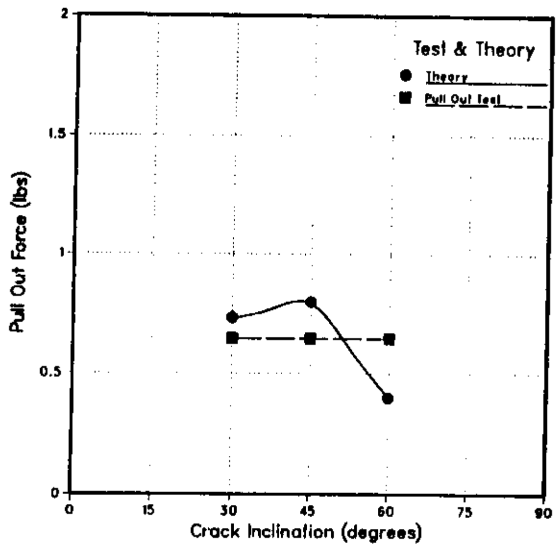


Fig. 11 Comparison of experimental and theoretical pull－qut force

these short steel fibers may arrest or deflect the propagation of cracks that develop later when the earth dams are completed, and hence may improve the strength of fissured clays.

5. Conclusions

From the laboratory investigations and theoretical analyses designed to study the effects of reinforcement of steel fibers on the crack propagation of fissured clays, the following conclusions can be drawn:

(1) When the fissured clay samples reinforced by the short steel fibers were tested under uniaxial compression, reinforcement by steel fibers increased resistance to cracks initiation and their propagation, and therefore increased both stress at crack growth initiation and peak stress at failure.

(2) The crack growth initiation from the tips of the pre-existing crack was suppressed by the short steel fibers and the propagating cracks were shifted at the intersection between propagating cracks and short steel fibers. These observations indicate that suppressing and shifting of cracks are an important mechanism through which fibers increase the resistance to cracks initiation and their propagation.

(3) The pull-out force predicted by theoretical analyses using fracture mechanics theory and pull-out mechanisms in fiber reinforced materials agreeded reasonably well with measured values obtained from pull-out tests. These results indicate that the steel fibers have bridging effect through their pull-out action that causes an increased resistance to the propagation of the cracks in the samples.

References

1. Bentur, A. and Diamond, S. (1985). "Cracking Processes in Steel Fiber Reinforced Cement Paste", Cement and Concrete Research, Vol. 15, pp. 331-342.
2. Erdogan, F. and Sih, G.C. (1963). "On the Crack Extension in Plates under Plane Loading and Transverse Shear", Journal of Basic Engineering, ASME, Vol. 85, pp. 519-527.
3. Fanella, D.A. and Naaman, A. (1985). "Stress-Strain Properties of Fiber Reinforced Mortar in Compression", Journal of American Concrete Institute, July, pp. 475-483.
4. Jenq, Y.S. and Shah, S.P. (1986). "Crack Propagation in Fiber-Reinforced Concrete", Journal of Structural Engineering, ASCE, Vol. 112, No. 1, pp. 19-34.
5. Jennings, H.M. and Lange, D.A. (1988). "Toward High Performance Cement Based Materials", New Horizons in Construction Materials (eds. Lee, D. Y. and Shah, S.P.), ASCE, New York, pp. 4-25.
6. Naaman, A. E. and Shah, S.P. (1976). "Pull-Out Mechanism in Steel Fiber-Reinforced Concrete", Journal of the Structural Division, ASCE, Vol. 102, No. ST8, pp. 1537-1548.
7. Sato, N., Kurauchi, T., Sato, S., and Kamigaito, 0. (1988). "Reinforcing Mechanism by Small Diameter Fiber Composite", Journal of Composite Materials, Vol. 22, pp. 850-873.
8. Shah, S.P. and Rangan, B.V. (1971). "Fiber Reinforced Concrete Properties", Journal of the American Concrete Institute, Feb., pp. 126-135.
9. Shah, S.P. and Naaman, A.E. (1976). "Mechanical Properties of Glass and Steel Fiber Reinforced Mortar", Journal of the American Concrete Institute, Jan., pp. 50-53.
10. Vallejo, L.E. (1986). "Mechanics of Crack Propagation in Stiff Clays", Geotechnical Aspects of Stiff and Hard Clays (eds. Khera, R.P. and Lovell, C.W.), ASCE, Geotechnical SP No. 2, pp. 14-27.
11. Vallejo, L.E.(1989). "Fissure Parameters in Stiff Clays under Compression", Journal of Geotechnical Engineering, ASCE, Vol. 115, No. 9, pp. 1303-1317.

(접수일자 1994. 8. 14)