A Study on the Behavior of Reinforced Clay Subjected to Direct Shear

직접전단을 받는 보강점토의 거동에 관한 연구

Yoo, Han-Kyu*
유 한 규

요 지

본 연구에서는 강 함유재에 의한 점토에서의 전단강도 증가를 예측하기 위하여 직접전단하에서 힘의 한계평형에 근거한 보강점토 모델이 제안되었다. 본 모델은 함유재의 방향과 길이, 함유재와 점토사이 부착응력 및 함유재의 이동에 따른 흙의 수동저항력이 보강점토의 거동에 미치는 영향을 고려하였다. 이론적인 예측과 비교검토하기 위하여 개폐된 전단박스로 구성된 직접전단장치를 이용하여 직접전단시험을 실시하였다. 또한 함유재와 점토사이의 부착응력을 산정하기 위하여 인발실험을 실시하였다. 시험결과 보강점토의 전단응력의 증가 또는 감소는 함유재의 방향과 점토의 함수비와 관련되어 있음을 알았다. 이론적인 예측과 시험결과를 비교한 결과 본 이론적인 모델은 함유재의 방향과 함유재의 이동에 따른 흙의 수동 저항력이 보강점토의 역학적인 거동에 미치는 영향을 비교적 잘 예측 해주고 있음을 알 수 있었다.

Abstract

In this study, a reinforced clay model based on the limit equilibrium of forces under dircet shear was proposed to predict shear strength increase in clays induced by the steel inclusion. The model accounted for the effects of orientation of inclusion, length, bonding stress between clay and indclusion, and passive soil resistance induced by the inclusion movement, on the behavior of reinforced clays. In order to compare with the theoretical predictions, direct shear tests were performed using a direct shear apparatus formed of an open shear box. Also pull-out tests were conducted to determine the bonding stress between the inclusion and clay. From the experimental results, the increase or decrease in shear strength of reinforced clay samples was found to depend on the orientation of inclusion as well as water content of clay samples. From the comparison of theoretical predictions and experimental results, it was found that the theoretical model predicted reasonably well the influence of orientation of the inclusion as well as passive soil resistance induced by the inclusion movement on the mechanical behavior of reinforced clays.

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* 정회원, 삼성건설 토목설계 ENG팀 과장

1. Introduction

Early civilizations used mixtures of straw and mud for building bricks. Although ancient straw-mud materials can be classed as a type of composite material, the modern concept of soil reinforcement was introduced by Vidal[15]. He defined Reinforced Earth as a composite material composed of soil strengthened by the inclusion of metal rods, bars, or strips which interact with the soil by means of frictional resistance.

Recently many researchers investigated the effects of reinforcing material on the strength of soil. Most of these studies have been conducted on sands reinforced with natural or synthetic fibers, plastic grid, roots, and polymeric mesh. It has been shown that the reinforcement improved peak stress of sand, increased strain at failure, and reduced post-peak loss of strength when the reinforcing materials were placed at optimum orientations to the failure plane.

Very few studies have been conducted on the effects of reinforcing materials on the mechanical behavior of clays. Most of these experimental studies involved use of plastic grids, porous plastic materials, long steel plates and polymeric meshes to study their effects on the strength of clays. It was observed that the strength of the clay and its strain to failure were increased by the presence of reinforcing materials when they had an optimum orientation. The results of these limited tests were analyzed using a relatively simple theoretical model based on limit equlibrium of forces.

The purpose of the present investigation is to study theoretically as well as experimentally the effects of steel inclusion reinforcement on the mechanical behavior of clays. To accomplish the purpose of the present study, a theoretical model based on limit equlibrium of forces is developed to predict the shear strength increase in clays induced by the steel inclusion and to identify important test parameters. Also direct shear and pull-out tests are performed to investigate the effects of test parameters such as orientation of the inclusion as well as water content of clay samples and to evaluate bonding stress between inclusion and clay, respectively.

2. Theoretical Model for Reinforcement under Direct Shear.

2.1 Limit Equilibrium of Forces Model

The states of stress and strain in reinforced clay during deformation and failure are non-uniform and complex. Models based upon limit equilibrium of forces have been used to describe such states. The reinforced clay model used in the present investigation is an adaptation of a similar model proposed by Jewell[7]. The model accounts for the effects of inclusion orientation, length, bonding stress between inclusion and clay, and passive soil resistance induced by the inclusion movement, on the mechanical behavior of intact clay samples. In this study, the central horizontal plane is assumed to be the critical plane under direct shear.

In this modelling analytical expression is derived for three cases of interest : (1) vertical reinforcement ; (2) reinforcement in compression: (3) reinforcement in tension. For each case, the shear resistance on the critical plane τ_{cp} provided by clay and reinforcement is derived from the unreinforced clay τ_s and the combination of the reinforcement and the clay τ_{ex} is given by:

$$\tau_{cp} = \tau_s + \tau_{ex} \tag{1}$$

The overall stress resultants acting on the critical plane in driect shear for each reinforcement case are considered in the following section.

2.2 Vertical Reinforcement

In the case of vertical reinforcement, the overall stress resultant is shown in Fig. 1.

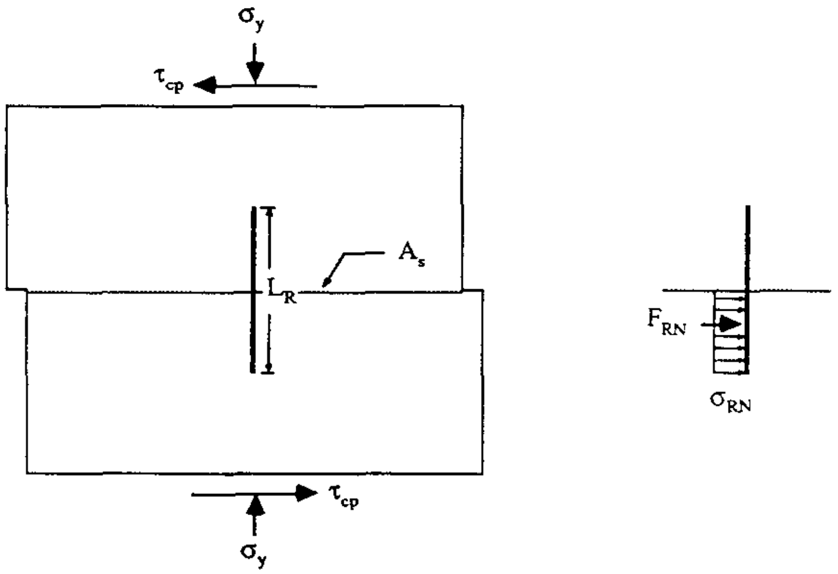


Fig. 1 Total stress resultants for a vertical reinforcement

When the normal stress σ_y and the shear stress τ_{cp} are applied at the sample boundaries, the resultant force F_{RN} induced by the inclusion movement as well as provided by boundary stresses can be expressed as follows :

$$F_{RN} = \frac{\sigma_{RN} A_R}{2} = \frac{A_R}{2}[\sigma_y + 2C\tan(45+\frac{\phi}{2})] \tag{2}$$

where A_R is the cross-sectional area of inclusion. The cohesive intercept of clay C and internal friction angle of clay ϕ can be obtained from the results of direct shear tests on unreinforced clay. The second term in the right hand side of Equation (2) is referred to as the Rankine passive soil pressure. Hence, the shear stress supported by the clay is given by :

$$\tau_s = C + \sigma_y \tan\phi \tag{3}$$

And the extra shear resistance provided by the reinforcement can be expressed as follows:

$$\tau_{ex} = \frac{F_{RN}}{A_s} \tag{4}$$

where A_s is the plan area of clay on the critical plane.

2.3 Reinforcement in Compression

The overall stress resultants on the critical plane of reinforced calys with an inclusion at an angle of β_c towards the right with respect to the direction of normal loads, designated as reinforcement in compression, are shown in Fig. 2.

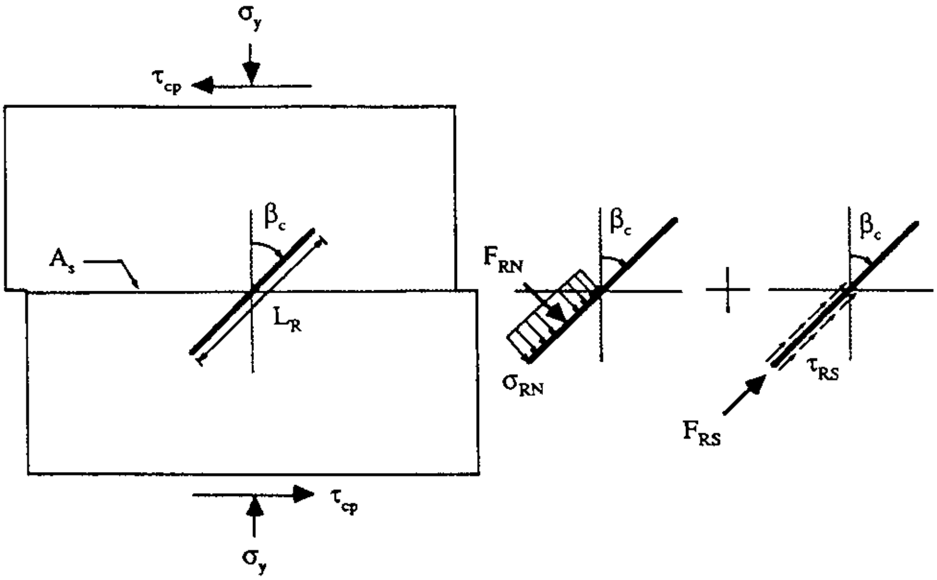


Fig. 2 Total stress resultants for a reinforcement in compression

The resultant force F_{RN} normal to the inclusion induced by the inclusion movement as well as provided by the boundary stresses is given by :

$$F_{RN} = \frac{\sigma_{RN} A_R}{2} = \frac{A_R}{2}[\sigma_n + 2C\tan(45+\frac{\phi}{2})] \tag{5}$$

where σ_n is the normal stress acting on the plane of inclusion induced by boundary stresses. Another resultant force F_{RS} induced by shear stress (bonding stress) between the inclusion and clay is expressed as follws :

$$F_{RS} = \frac{\tau_{RS} A_e}{2} = \frac{A_e}{2}[C_{RS} + \sigma_n \tan\phi_{RS}] \tag{6}$$

where A_e is the effective surface area of the inclusion and is equal to the product of the perimeter and length of the inclusion. C_{RS} and ϕ_{RS} are the adhesion factor and friction angle between the inclusion and clay. The values of C_{RS} and ϕ_{RS} can be obtained from the results of pull-out tests on clay samples with a sand glued inclusion. Using above two resultant forces, the shear stress supported by the clay is given by :

$$\tau_s = C + \sigma_y' \tan\phi \tag{7}$$

where normal stress σ_y' acting on the critical palne provided by boundary normal stress σ_y as well as normal components of two resultant forces is given by :

$$\sigma_y' = \sigma_y + \frac{F_{RN}}{A_s}\sin\beta_c - \frac{F_{RS}}{A_s}\cos\beta_c \tag{8}$$

And the extra shear resistance provided by the reinforcement is expressed as follows:

$$\tau_{ex} = \frac{F_{RN}}{A_s}\cos\beta_c + \frac{F_{RS}}{A_s}\sin\beta_c \tag{9}$$

2.4 Reinforcement in Tension

The overall stress resultants on the critical plane of reinforced clays with an inclusion at an angle of β_t towards the left with respect to the direction of the normal loads, designated as reinforcement in tension, are shown in Fig. 3.

Using Equations (5) and (6), the resultant forces F_{RN} and F_{RS} can be obtained. In this case, the shear stress supported by the clay can be expressed as follows :

$$\tau_s = C + \sigma_y'' \tan\phi \tag{10}$$

where normal stress σ_y'' acting on the critical plane provided by boundary normal stress σ_y as well as the normal components of two resultant forces is given by :

$$\sigma_y'' = \sigma_y - \frac{F_{RN}}{A_s}\sin\beta_t + \frac{F_{RS}}{A_s}\cos\beta_t \tag{11}$$

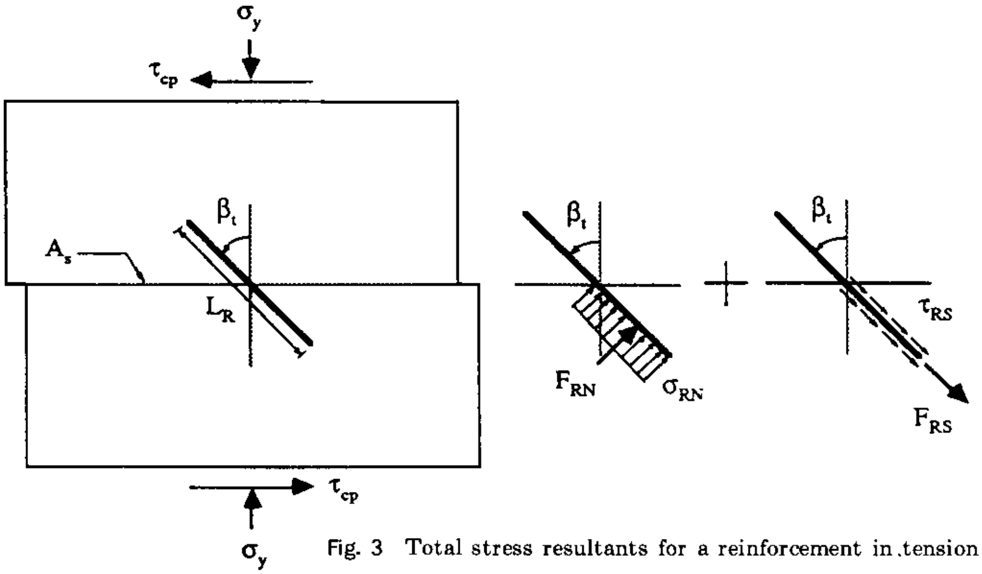


Fig. 3 Total stress resultants for a reinforcement in .tension

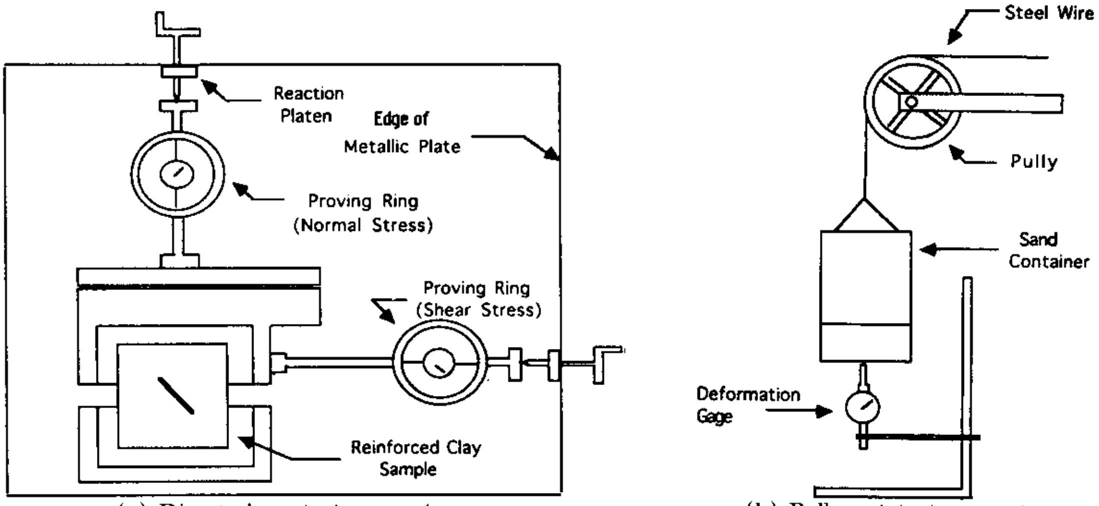
The extra shear resistance provided by the reinforcement is expressed as follows :

$$\tau_{ex} = \frac{F_{RN}}{A_s}\cos\beta_t + \frac{F_{RS}}{A_s}\sin\beta_t \tag{12}$$

3. Direct Shear Tests

3.1 Test Equipment

Tests were conducted using a new version of direct shear apparatus developed in the Geotechnical Engineering Laboratory of the University of Pittsburgh[14]. The direct shear apparatus is shown in Fig. 4(a).



(a) Direct shear test apparatus　　(b) Pull−out test apparatus

Fig. 4 Description of test apparatus

The apparatus has an open shear box formed of two U-sections that enclose a prismatic reinforced sample. The top section of an open shear box is a moving section that transmits the normal and shearing loads to the sample. The loads are genetrated by the rotation of a hand crank-screw system. The movable top section rests on a metallic plate. The area between the movable section and the metallic plate contains ball bearings designed to reduce friction. The lower part of the open shear box is fixed to the metallic plate. The amounts of normal and shearing loads transmitted to the sample are measured by proving ring dial gage systems. Displacements during the shearing process are measured by the use of dial gages attaced to the moving section of the open shear box. The open shear box facilitates the studying and recording the development of failure surface as well as the effects that reinforcement has on this surface.

3.2 Test Materials and sample Preparation

For this laboratory investigation, a commercial powdered kaolinite clay was used to prepare clay samples. This material was chosen because it was very homogeneous and therefore facilitated the study of effect of reinforcements without the adverse effect of micro-scale heterogeneities. The clay had a liquid limit of 58% and a plastic limit of 28%. The reinforcement consisted of steel inclusions. The inclusions were made of stainless steel and had rough surfaces. The rough surface was made by glueing a layer of Ottawa sand to the inclusion. The physical properties of the reinforcement are summarized in Table 1.

Table 1. Physical Properties of Reinforcement

Type of Reinforcement	Length (in)	Width (in)	Thickness (in)	Tensile Strength $(lb/in^2)x10^3$	Elastic Modulus $(lb/in^2)x10^6$
Steel	1.0	1.0	0.035	58−80	29

For the sample preparation, dry powdered kaolinite caly was mixed with water to form a soft soil paste with a water content of about 35%. The clay-water mixture was then placed into plexiglass molds which dimensions were 5inch in width, 4.25inch in length, and 1.5inch 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 inclusion was then placed into the clay-water mixture at the desired location and orientation. After placement of the inclusion 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. At the end of loading period, the samples with and without reinforcement were removed from the molds and were allowed to dry in air.

3.3 Test Proceduren

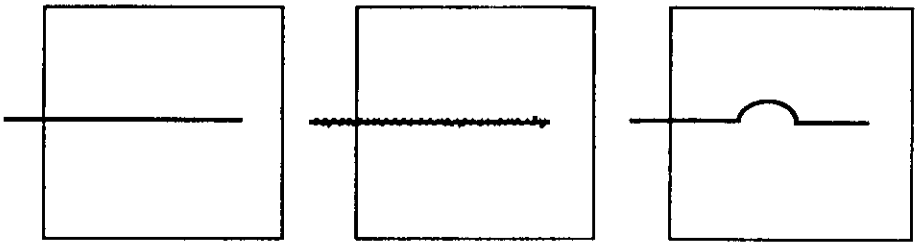
Tests were performed on the clay samples with and without a steel inclusion. One sample was made without an inclusion and five samples had different inclusion inclinations with respect to the direction of the normal load. The inclusions were inclined at either 30°

towards the left (designated as reinforcement in tension) 30 and 60° towards the right (designated as reinforcement in compression) as well as 0 and 90°. This is illustrated in Fig. 1 through Fig. 3. Each sample was loaded and sheared at a selected normal stress. The selected normal stress was 5, 10, and 20 psi for the unreinforced clay samples. The normal stress of 20 psi was used for the reinforced clay samples. For each selected value of normal stress, the shear stress was increased until the sample failed. Both shear load and horizontal displacement were recorded throughout the tests. For each set of samples, two different water contents were used. The average water contents in the sample were 3% in the brittle condition and 23.6% in the ductile condition, respectively.

4. Pull-Out Tests

4.1 Test Equipment and Test Materials

The pull-out apparatus consisted of a direct shear apparatus as shown in Fig. 4(a), a pully, steel wires, a sand container, deformation gage as shown in Fig. 4(b). The pull-out tests were stress controlled. Three types of steel inclusions used in the pull-out tests were straight, sand glued, and deformed inclusion. Fig. 5 shows the pull-out test samples. All of the inclusions were 2.75inch in length, 0.24inch in width, and 0.01inch in thickness. The sample used in the pull-out tests were prepared in a way similar to the procedure in which the samples for the direct shear tests were prepared.



(a) Straight (b) Sand glued (c) Deformed

Fig. 5 Pull-out test samples

4.2 Test Procedure

The inclusion was embedded into a clay sample (total embedded length of the inclusion was equal to 2.75inch) and was placed parallel to the pull-out loading direction. The clay sample with inclusion was placed into the open shear box of the direct shear apparatus and the sample was then loaded under a selected normal stress. A short length of inclusion projecting from the clay sample was connected to a sand container using steel wire. After this was done, the inclusion was pulled out of the clay sample by slowly increasing the weight of sand in sand container. The load needed for pulling out the inclusion was then measured and the pull-out distance was measured by a deformation gage placed under the sand container. After the peak pull-out load was measured, the average bond stress (by assuming uniform shear stress distribution along length of the embedded inclusion) was computed from the peak pull-out load divided by the embedded surface area of the inclusion. The embedded surface area is equal to the product of the perimeter and the embedded length of the inclusion.

5. Test Results and Analyses

5.1 Direct Shear Test Results

In order to obtain the shear strength parameters of unreinforced clay samples such as C (cohesive intercept) and ϕ (internal friction angle) needed for a proposed theoretical analysis, the failure envelope corresponding to peak shear stress and normal stress has been plotted in Fig. 6.

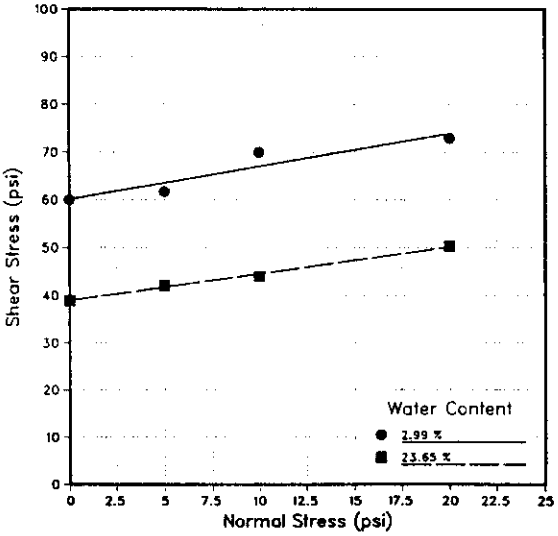


Fig. 6 Shear stress vs normal stress for unreinforced samples

The measured values of C and ϕ were 60 psi and 33.7° for clay samples with a water content of 2.99%. In the case of samples with a water content of 23.65%, the measured values were 38.9 psi and 27.7°, respectively.

The shear stress-horizontal displacement relationship obtained from tests on the brittle as well as ductile sampels with and without an inclusion under a normal stress of 20 psi are shown in Fig. 7 and 8. The water content in brittle and ductile samples was 2.87 and 23.63%, respectively.

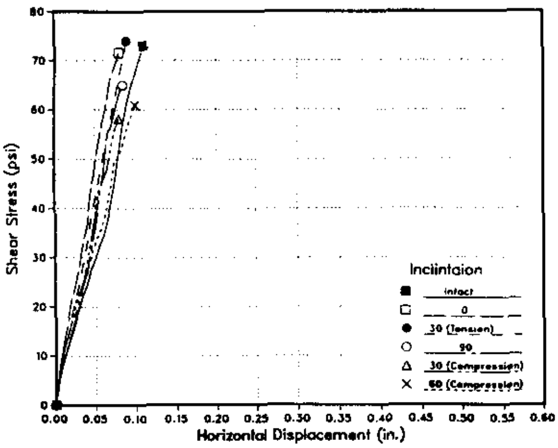


Fig. 7 Shear stress vs horizontal displacement for brittle samples with W=2.87%

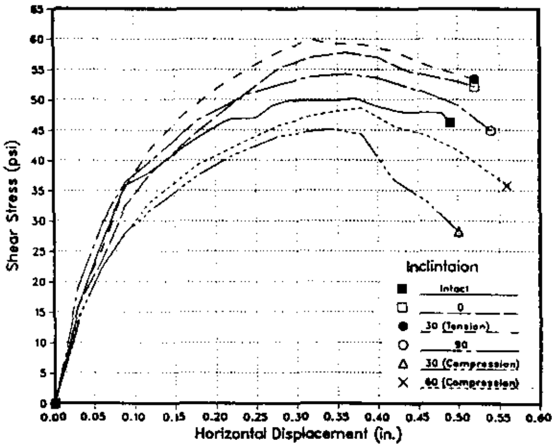


Fig. 8 Shear stress vs horizontal displacement for ductile samples with W=23.63%

As indicated in Fig. 7, the peak shear stress of the brittle sample with an inclusion inclined at 30° to the left (designated as reinforcement in tension) was slightly higher than that of unreinforced (intact) sample whereas the peak shear stress of samples with an inclusion incined at 30 and 60° to the right (designated as reinforcement in compression), 0 and 90° was lower than that of unreinforced sample. For ductile samples, as shown in Fig. 8, the inclusion reinforcements at an inclination of 30 (tension), 0, and 90° enhanced the peak shear stress of clay sample whereas the inclusion reinforcements at other inclinations such as 30 and 60° (compression) tended to weaken the clay sample.

These observations suggest that the increase or decrease in peak shear stress of reinforced clay samples is dependent on the orientation of the inclusion as well as the water content of the clay samples. Generally, the reinforcement of ductile clay samples by an inclusion in tension results in improvements in peak shear stress of the clay sample.

A possible reason for reductions in peak shear stress of clay sample by an inclusion reinforcement in compression seems to be related to the failure behavior of the reinforced clay. It was observed that cracks development at the tips of the interface between clay and inclusion and their propagation led to the sample failure, and therefore weakened the clay sample.

5.2 Pull-Out Test Results

The relationship between bond stress and normal stress obtained from the results of pull-out tests on the sample with straight, sand glued, and deformed inclusions are presented in Fig. 9 and 10. The interface adhesion factor and friction angle obtained from the test results in Fig. 9 and 10 are summarized in Table 2.

The results indicate that the interface adhesion factor and friction angle for the sample with a sand glued inclusion at a water content of 3.82% are higher than those for the

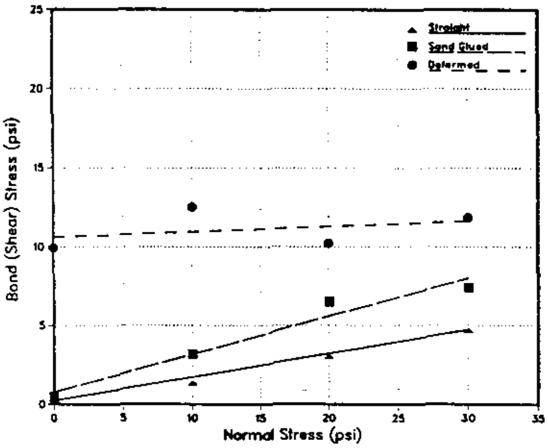


Fig. 9 Bond stress vs normal stress for brittle samples with W=3.3%

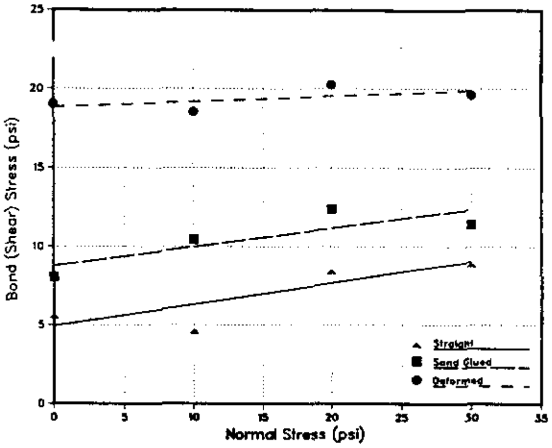


Fig. 10 Bond stress vs normal stress for ductile samples with W=23.26%

Table 2. Pull-Out Test Results

Type of Inclusion	Water Content (%)	Adhesion Factor (psi)	Friction Angle (degrees)
Straight	3.63	0.1613	8.57
	23.24	5	7.35
Sand Glued	3.82	0.8064	13.7
	23.74	8.87	6.75
Deformed	2.45	10.645	1.85
	22.81	18.87	1.85

sample with a straight inclusion at a water content of 3.63%. For a sample with deformed inclusion at a water content of 2.45%, the greatest interface adhesion factor was obtained whereas the lowest interface friction angle was obtained. For samples with three types of inclusion at an average water content of 23.26%, similar results were observed except that the interface friction angle for a sample with sand glued inclusion was slightly lower than that for a sample with straight inclusion. The results also indicate that the interface adhesion factors for all of the inclusions are increased with increasing amount of water in the samples whereas the interface friction angles for straight and sand glued inclusions are decreased with increasing amount of water in the samples and it remained constant for deformed inclusion.

These observations suggest that the bond stress (adhesion and friction) is dependent on the surface roughness and the shape of the inclusion as well as the water content of the clay sample. For straight and sand glued inclusion, the resistance to the pull-out load is primarily provided by menas of friction between the inclusion and clay in the brittle clay samples whereas it is provided by means of adhesion in the ductile clay samples. However, the mechanical interlocking is the predominant factor to provide the resistance to the pull-out load for deformed inclusion.

5.3 Comparison of Theoretical Predictions and Experimental Results

A theoretical reinforced clay model was used to predict and analyze the influence of steel inclusion on the mechanical behavior of clay samples. In this analysis, the strength increase in clay samples induced by reinforcement is expressed in terms of strength increase ratio and the ratio is defined as follows:

$$\text{Strength Increase Ratio} = \frac{\tau_{cp} - \tau_s}{\sigma_y} = \frac{\tau_{ex}}{\sigma_y} \tag{13}$$

There are three values of strength increase ratio corresponding to the value of τ_{ex} (extra shear resistance provided by reinforcement). One value of τ_{ex} is directly calculated using Equations (4), (9), and (12) whereas the other two values of τ_{ex} are obtained from the values of τ_{cp} and τ_s. The value of τ_{cp} is obtained from the results of tests on reinforced clay. The value of τ_s is obtained from the results of tests on unreinforced clay as well as from calculations using Equations (3), (7), and (10).

Fig. 11 through 14 present the relationship between strength increase ratio and inclusion inclination obtained from experimental results and theoretical predictions with or without consideration of the passive soil resistance.

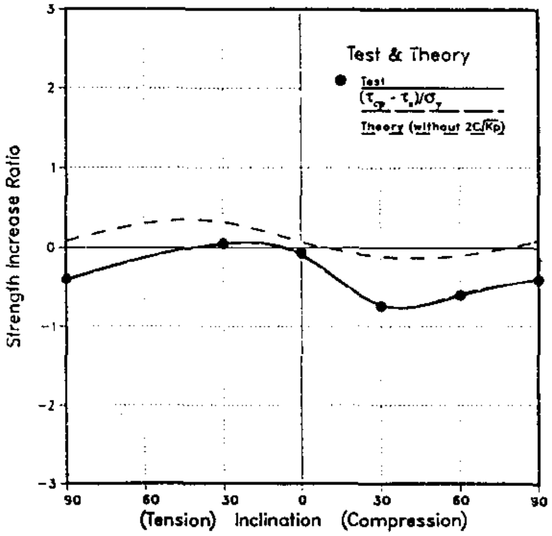


Fig. 11 Comparison of experimental and theoretical results without passive soil resistance for brittle samples with W=2.87%

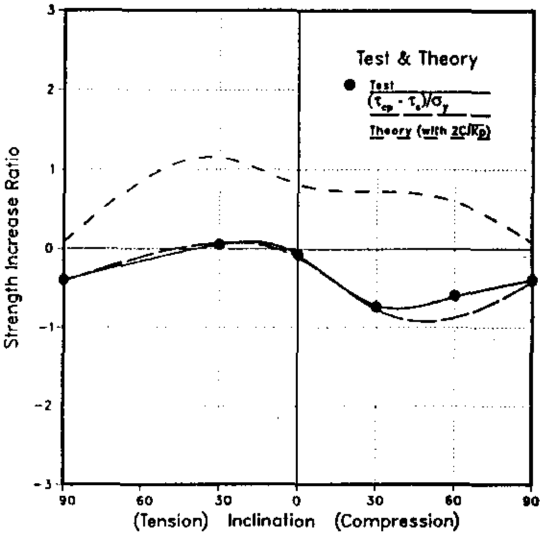


Fig. 12 Comparison of experimental and theoretical results with passive soil resistance for brittle samples with W=2.87%

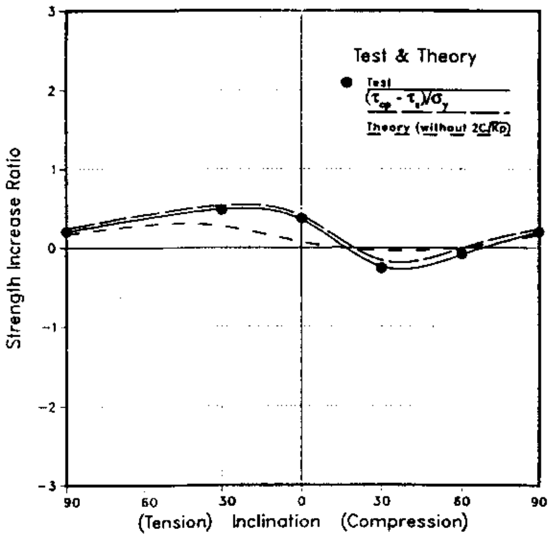


Fig. 13 Comparison of experimental and theoretical results without passive soil resistance for ductile samples with W=23.63%

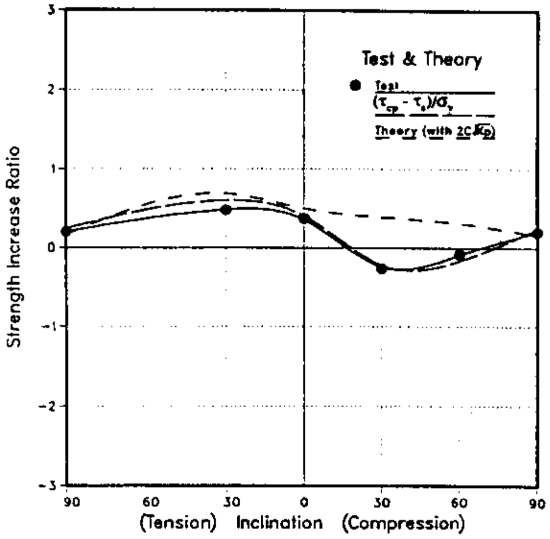


Fig. 14 Comparison of experimental and theoretical results with passive soil resistance for Ductile samples with W=23.63%

These results indicate that the reinforcements in tension enhance the strength of clay compared with unreinforced clay whereas those in compression weaken clay. The dependence of shear strength of clay on the orientation of the reinforcement may be attributed to the tensile resistance that developed in the reinforcement. When the clay sample is sheared, the tensile force that develops in the reinforcement can be divided into a tangential component which directly resists the shear and a normal component which increases the normal stress on the shear plane. Theoretical and experimental investigations conducted by McGown et al[9] and Jewell[8] have indicated that the reinforcement should be placed in tension in order to gain maximum tensile resistance of reinforcement.

For the brittle samples as shown in Fig. 11 and 12, the experimental results are close to the theoretical prediction without consideration of the passive soil resistance induced by the inclusion movement. This is due to the fact that the passive soil resistance is not fully mobilized in the samples because of very low shear deformation of sample at failure.

In the case of ductile samples, as shown if Fig. 13 and 14, the strength increase ratio obtained from experimental results agrees reasonably well with the theoretical prediction with consideration of passive soil resistance. The results may be attributed to the development of passive soil resistance induced by the inclusion movement when water content of the clay sample is increased. As the shear load increases passive soil resistance is developed due to the movement of inclusion and opposite to the direction of shear loads. This passive soil force directly resist shear load applied to the sample and therefore increases the shear strength of the clay samples. Also the increase in shear strength of the reinfroced clay as a result of increasing water content in clay samples may be attributed to the increase of bonding stress. As observed in pull-out tests, the adhesion between inclusion and clay increases with increasing water content of clay sample and therefore increases bonding stress.

The discrepancy between the theoretical predictions and experimental results may be attributed to the effects of the crack develpoment and their propagation from the tips of the interface between inclusion and clay on the failure behavior of reinforced clay which the present theoretical model does not account for.

6. Conclusions and Recommendation

The influence of steel inclusion reinforcement on the mechanical behavior of clay was investigated experimentally and theoretically. The following conclusions can be drawn from the results reported herein :

(1) The increase or decrease in shear strength of reinforced clay samples was found to depend on the orientation of inclusion as well as the water content of clay samples. The reinforcement of ductile clay samples by a steel inclusion resulted in improvements in shear strength of the clay sample.

(2) The bonding stress between steel inclusion and clay was found to depend on surface roughness of inclusion, shape of inclusion, and water content of caly. The bonding stress was generally increased with increasing surface roughness of the inclusion by glueing a sand to the inlcusion as well as with increasing water content of clay up to 23.26%.

(3) A reinforced clay model based on limit equlibrium of forces under direct shear predicted reasonably well the influence of parameters such as inclusion orientation and the passive soil resistance induced by inclusion movement on the shear strength increase of reinforced clays.

(4) The reductions in shear strength of the clay by an inclusion reinforcement in compression was related to the effects of cracks development and their propagation from the tips of the interface between inclusion and clay on the failure behavior of reinforced clay. These effects should be investigated for further development of reinforced clay model.

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