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13. ABSTRACT

In this research the effect of rate of strain on shear strength of cohesive soils of marine sediments have been studied.

Vane shear (apparatus) tests have been performed on an ocean sediment at varying permeabilities with various rates of shear. A variation in shear strength as high as 4[illegible].4°/o has been found over the range of rotation rates used in this experiment.

Suggestions for further experimentation in this area have been included.

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"Analysis of Sediment Shear Strength
At Varying Rates of Shear"

A Trident Scholar Project Report

by

Midshipman James E. Halwachs, 1972

U. S. Naval Academy

Annapolis, Maryland

Neil T Monney

Dr. Neil T. Monney
Head of Ocean Engineering
Naval Systems Engineering Department

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ABSTRACT

The vane shear apparatus is a device used to determine the shearing strength of marine sediment. The vane blade is inserted into a sample of sediment and a rotational torque is applied to the shaft of the vane blade. The resistance to this rotation is measured as torque and, knowing the area of the failure surface, is converted to the shear strength of the sediment in terms of lbs/in^2.

The variation in porewater pressure and viscous friction with rate of strain can be expected to affect the value of the shear strength determined by the vane shear test.[1] At present, vane tests are conducted at arbitrary rates of shear with little or no concern for the effect of rate of strain. Some authors even fail to note the rate of rotation of the vane.[2] It has also been stated that rotational speeds of the vane are not a significant factor in the results of vane shear strength analysis.[3] Although results of some tests have shown a variation in strength due to rate of strain,[4] these findings have been largely neglected by researchers working with marine sediments, and little work has been done to determine either the magnitude or the mechanics of the rate effect.

In this attempt to study the effect of rate of strain on shear strength of cohesive soils, vane shear tests have been performed on an ocean sediment of varying permeabilities with various rates of shear. A variation in shear strength as high as 46.4% has been found over the range of rotation rates used in this experiment. Suggestions for further experimentation in this area have been included.

TABLE OF CONTENTS

I. INTRODUCTION

A. Deformation Properties of Sediment

The shear strength of marine sediments is dependent upon the cohesive forces in the particle bed as well as friction between the particles in the slip plane. The strength mechanism of a clayey sediment has been analyzed to include viscoelastic and viscoplastic properties during shear as explained later in this paper.[5] Resistance to shearing forces is initially a result of the inter-particle bonds. Once these bonds are broken and slip planes are formed, the resistive properties of the sediment lie in the friction forces between the slip planes. Previous work shows that particle friction and, therefore, shear strength are reduced with decreasing effective stress.[6] Increased porewater pressure decreases the effective stress between particles and slip resistance will decrease. Conversely, decreased porewater pressures increase the effective stress and, therefore, the slip resistance will increase. It can be seen, then, that sediment should exhibit varying shear strengths

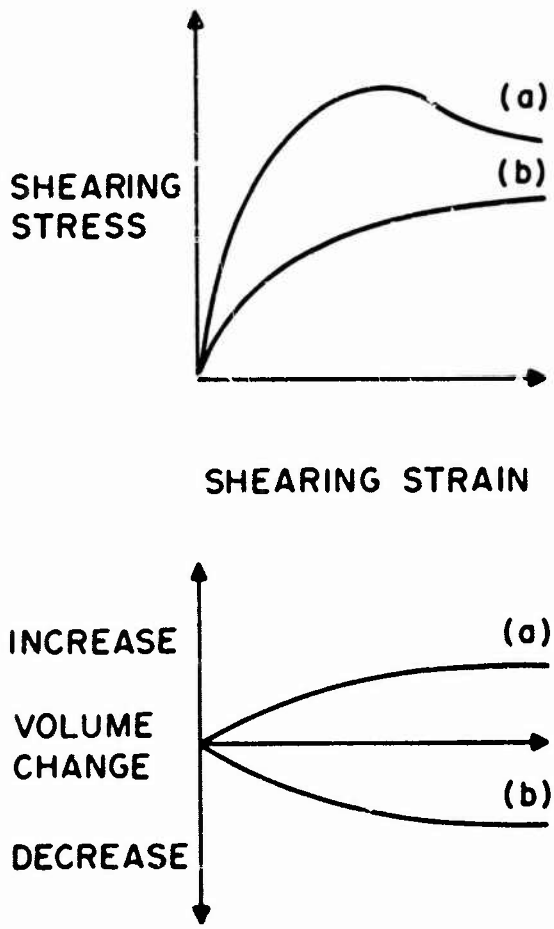


Figure 1

as the porewater pressures (condition of drainage) at the failure surface change.

In a dense and over consolidated sediment bed, shearing forces will result in a stress-strain diagram such as (a) in fig. 1. A loose and normally consolidated sediment will behave as in (b) in fig. 1. The difference lies in the tendencey for dense soils to increase in volume as a shearing force is applied. This in turn reduces the porewater pressure, increasing the effective stress and, therefore, shear strength. The loose sediment, on the other hand, tends to decrease in volume with shear and the opposite effect is noted. Both curves will approach the same shear stress with time, known as the residual stress.

For a better understanding of the deformation properties of a saturated cohesive soil, the following rheological model is presented.[7]

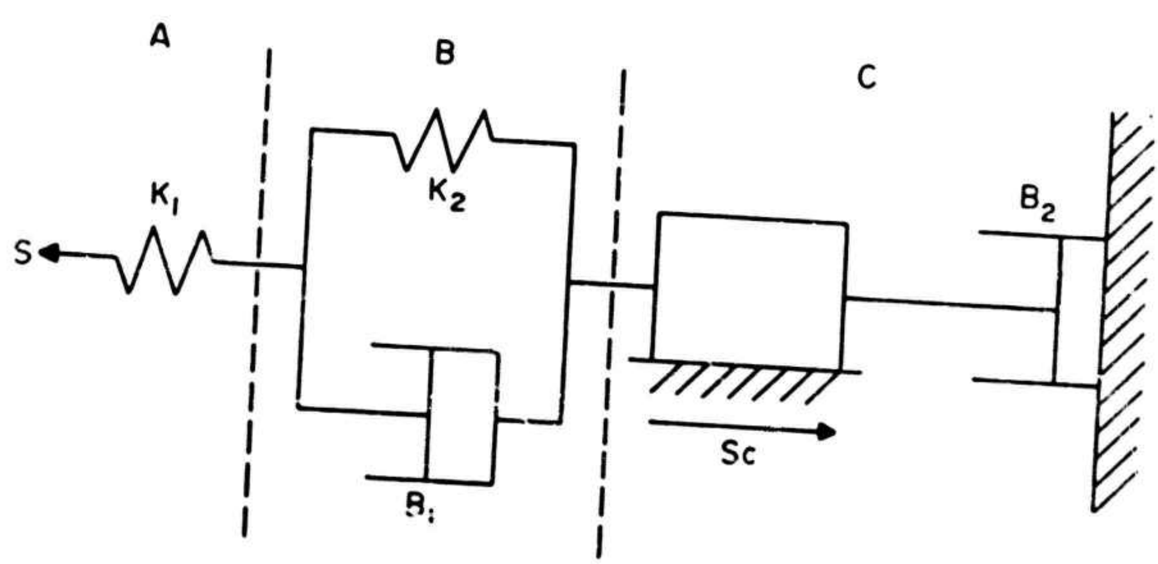


Figure 2

The model can be divided into the pure elastic subsystem A, the viscoelastic subsystem B, and the viscoplastic subsystem C. The initial shear stress S acts on the elastic member K_1 only. As the dashpot B_1 moves with time to effect subsystem B, viscoelastic deformation occurs. If the stress does not exceed the creep strength Sc, then strain will not continue, but will stop at the creep stress-strain limit. The viscoelastic subsystem is rate dependent because of the viscous member B_1. The viscoelastic representation of sediment is consistent with work done on viscoelasticity when it was determined that undispersed sediment behaved like non-Newtonian liquids, viscoelastic in nature.[8] The strain, of course, is very small, and is recovered with time when the stress is removed. If the creep strength Sc is exceeded, then deformation occurs in the viscoplastic subsystem C. The deformation of this subsystem will continue as long as the stress is applied and is purely viscous due to member B_2.

The combination of the purely elastic and the viscoelastic portions of the model are the initial stages of shear where the interlocking forces are being broken, as explained previously. The secondary stages of shear are represented by the viscoplastic portion of the model where the strain cannot be recovered by reduction of stress. If the values of the viscous members B_1 and B_2 change, it will influence the shear strength at varying rates of shear. These values of viscous damping should be different for changing porewater pressures, which should cause a significant difference in shear strength.

B. The Vane Shear Test

The applicability of the vane shear device has been previously tested[9] and generally found to be justified for cohesive soils with relatively low shear strength. The vane test in sand was not justified because of the many other parameters, such as size and rigidity of the container, surface effects, and void-ratio, which effect the value of the shear strength determination.

It was further shown that the laboratory vane test, though commonly considered an undrained test, acquired the characteristics of a drained test in soils of a dilatant nature.[10] Apparently high values for shear strength have been obtained, on occasion, in laminated (varved) soils. It was proposed that this phenomenon could be due to negative porewater stresses induced during shear deformation.[11] These negative porewater stresses caused by volume increase are usually encountered in saturated dense silts just before and during shear failure causing consequent increases in effective stress and, thus, shear strength as noted in the introductory remarks.

II. APPARATUS

A. Vane Shear Device

The vane shear test device was developed and tested in Sweden[12] and an equation was developed to convert the measured torque on the vane shaft to shear strength S; utilizing the following assumptions:

1. The surface of failure is in the form of a right circular cylinder, with dimension equal to those of the vane blade.
2. The stress distribution at maximum torque is everywhere equal and uniform about the surface of the cylinder.

With these assumptions, the equation was developed as follows:

$$T = \pi \left(H \frac{D^2}{2} + \frac{D^3}{6} \right) S$$

Where:

T = maximum torque

H = height of vane blade

D = diameter of vane blade

S = shear strength at maximum torque

With the Wykeham-Farrance Laboratory Vane Tester, the device most commonly used in laboratory tests, the torque is applied through torsion springs. Therefore, the stress cannot be applied at a predetermined rate as the angular strain in the vane blades will affect the applied stress. This has been a common criticism of the vane shear test.[13]

For this experiment, a Wykeham-Farrance Laboratory Vane Tester was modified to be driven by a variable speed D.C. motor with direct chain drive to the vane shaft. With this device, the rate of applied strain was rigidly controlled at predetermined levels. A bonded strain gauge was coupled to the shaft of the vane for direct electrical printout of the torque on the shaft.

B. Other Equipment

Thorough remolding of the sediment was accomplished using a heavy-duty mixer as used in a bakery. A standard lever-arm consolidation unit was used to consolidate the sediment at predetermined pressures. Measurement of the permeability was made using a constant head device attached to the fixed-ring consolidometer cups.

III. THE SEDIMENT

The sediment used in the experiment was an olive gray clayey silt taken from the continental shelf at a depth of 600 feet, off the coast of Santa Barbara, California. It consisted of 3% sand, 25% clay, and 72% silt. The liquid limit was 48.6; the plastic limit, 30.0; and the void ratio, 1.0. This sediment is typical of much of the sediment found on the continental shelf.

IV. EXPERIMENTAL PROCEDURE

The sediment was prepared for testing by thorough mechanical remolding, adding enough salt water to make a thick slurry. The consolidation cups were then filled and loaded to one of three predetermined pressures. The time allowed for consolidation within each pressure range was varied to give a range in permeability for each consolidation load. The samples were then tested for permeability using the device previously described. With this test completed, a divider was placed in the specimen container to make two equal areas in each container for testing. The divider allowed two runs in each sample with its characteristic permeability. A reference rate of 90 deg/minutes was used on one side of the divider for each sample, and on the other side one of 3 other rates was used. The vane blade, as shown in figure 3 was inserted to a one-inch depth for every sample to maintain uniformity in test results.

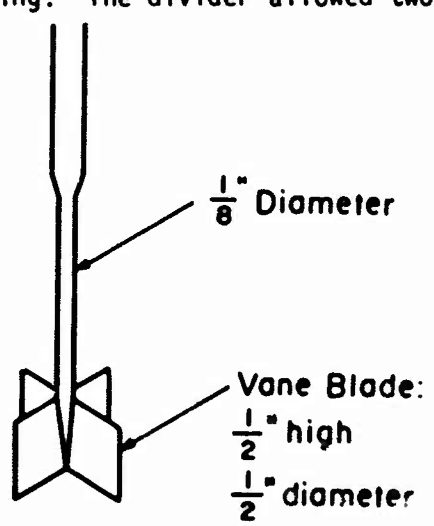
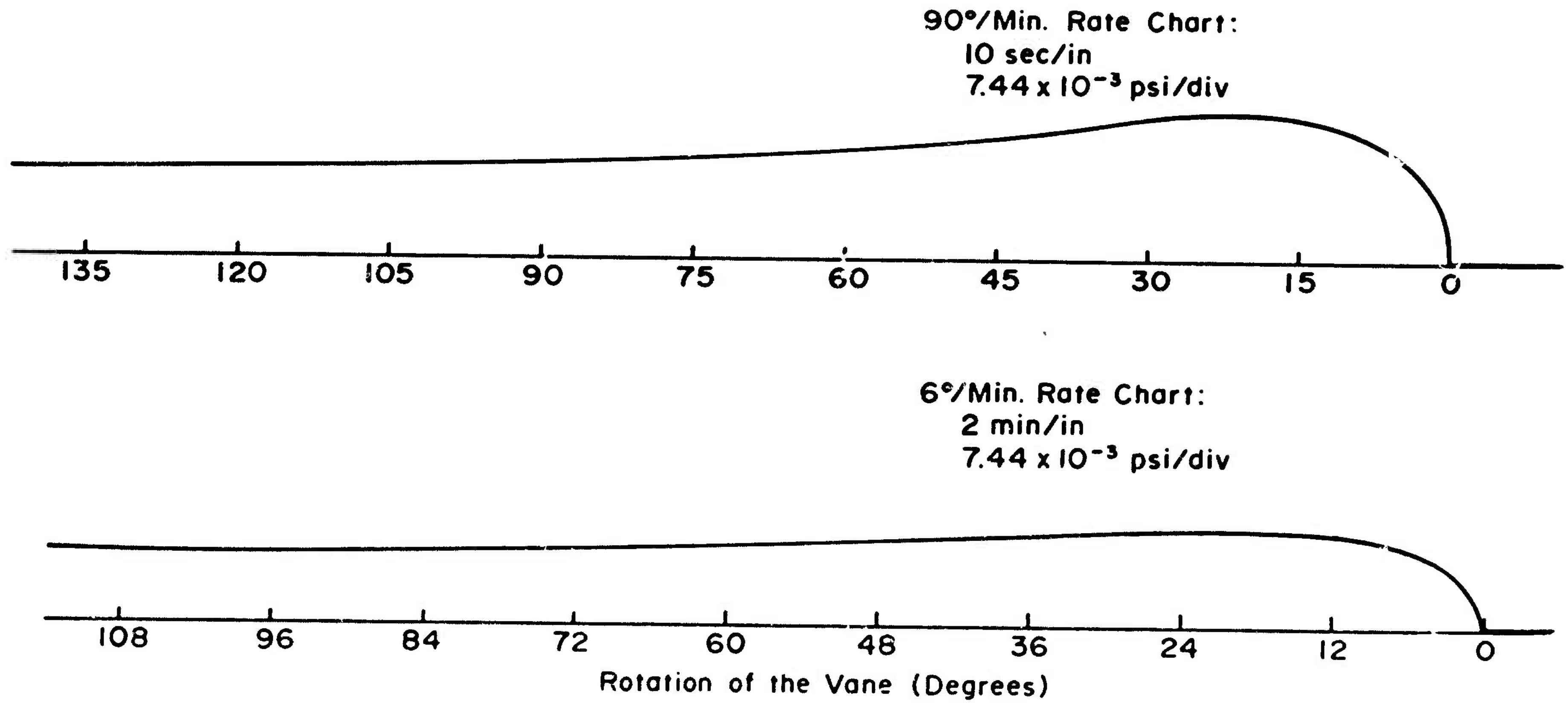


Figure 3



90°/Min. Rate Chart:
10 sec/in
7.44 x 10⁻³ psi/div
135
120
105
90
75
60
45
30
15
0
6°/Min. Rate Chart:
2 min/in
7.44 x 10⁻³ psi/div
108
96
84
72
60
48
36
24
12
0
Rotation of the Vane (Degrees)

Figure 4

Figure 4 shows the direct printout from the strip chart recorder for a run 90 deg/minute and 6 deg/minute on the same sample. The primary concern in testing procedure was to eliminate the uncontrollable variables so that the test results could be reproduced accurately.

V. EXPERIMENTAL RESULTS

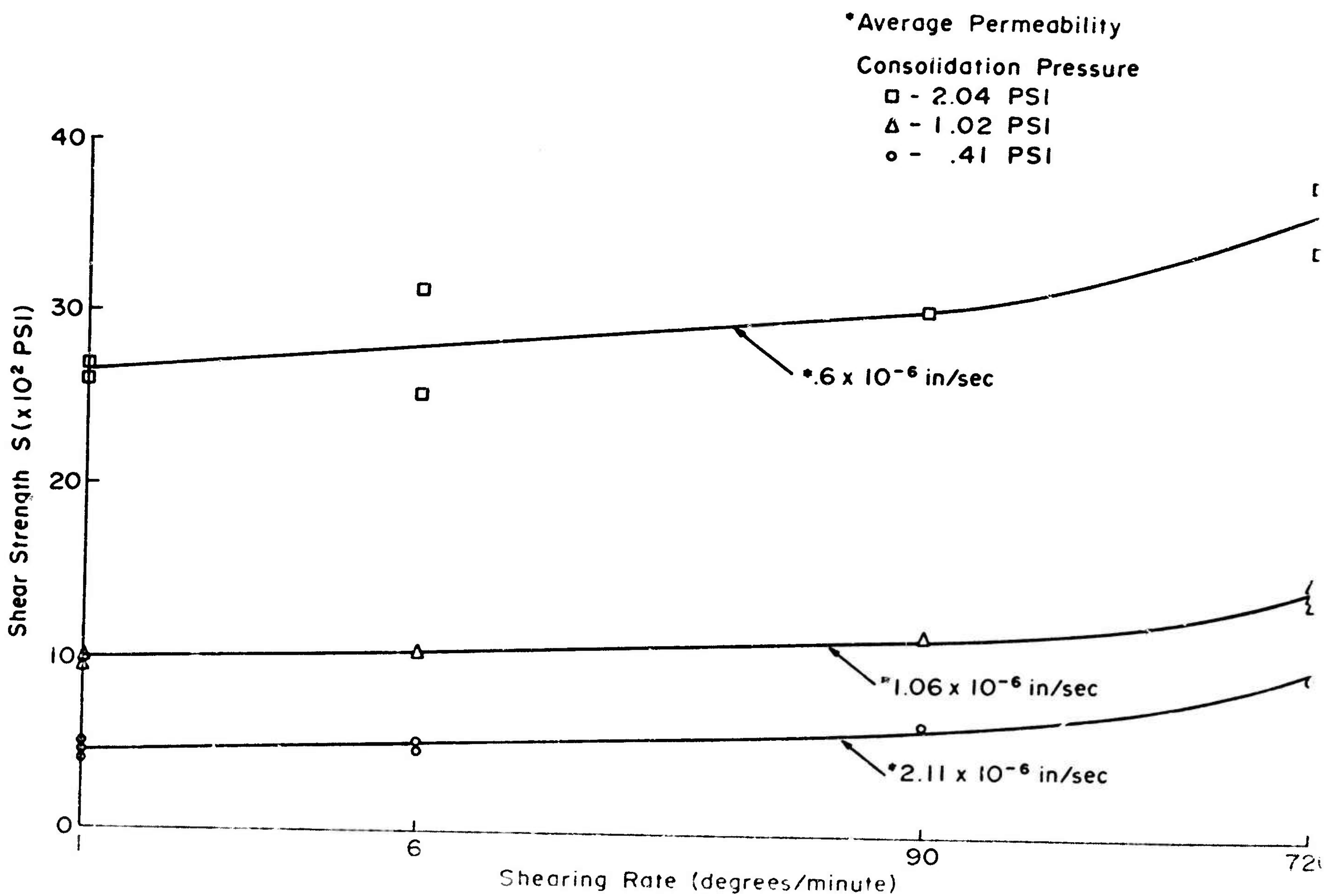
The laboratory vane tests performed on the remolded sediment have shown a significant variation in shear strength with rate of shear. Due to the length of time required for running a complete test series, only about 40 runs were made before this paper was prepared. Additional data will be necessary to permit a detailed analysis of the physical relationships governing the variation in shear strength with changing rates of shear. It is believed that with the good results obtained, however, that the importance of governing the rate of shear when determining sediment shear strength has been established. Other research is being conducted which may be leading to erroneous conclusions because variation in rate of shear is being neglected. For example, in a comparison of laboratory vane shear strength and in-situ vane shear strength, a rate of 21 deg/minute was used for the laboratory vane, giving less strength than the in-situ test using 78 deg/minute.[14] In this case, the total difference was attributed to disturbance in the laboratory vane test rather than to the rate effect.

For each of the three consolidation pressures, there was a range of permeabilities due to the variation in degree of consolidation. All of the shear strengths were normalized to the average reference strength at 90 deg/minute for each of the three consolidation pressures.

resulting in the plot in fig. 5. As is evident, there is one somewhat anomalous point at the highest consolidation pressure for the 6 degree rate, but it is believed that further testing would smooth out the curves. This was the only anomaly in the 40 test runs, and most likely was caused by the vane blade hitting a small lump of sediment that failed to be dispersed during the mixing procedure. The average shear strength at 720 deg/minute was 22.4% higher than that at 90 deg/minute; at 6 deg/minute was 10.0% lower than at 90 deg/minute; and at 1 deg/minute was 16.4% lower than at 90 deg/minute. A difference of even greater significance is seen between the lowest and the highest shear rates, where the average shear strength at 720 deg/minute was 46.4% higher than the average shear strength at 1 deg/minute.

In the analysis of the data, trends were sought which would indicate and identify the mechanism of the rate effect on shear strength. Plots of Shear Strength -vs- Permeability, fig. 6, and Shear Strength -vs- Void Ratio, fig. 7, were prepared. The resulting plots are consistent with work done comparing shear strength to permeability and void ratio in that the data followed a definite pattern, with the lower permeabilities and void ratios giving higher strength. Note that in all but one case, a higher strength was obtained at higher rates of shear for the same permeability or void ratio.

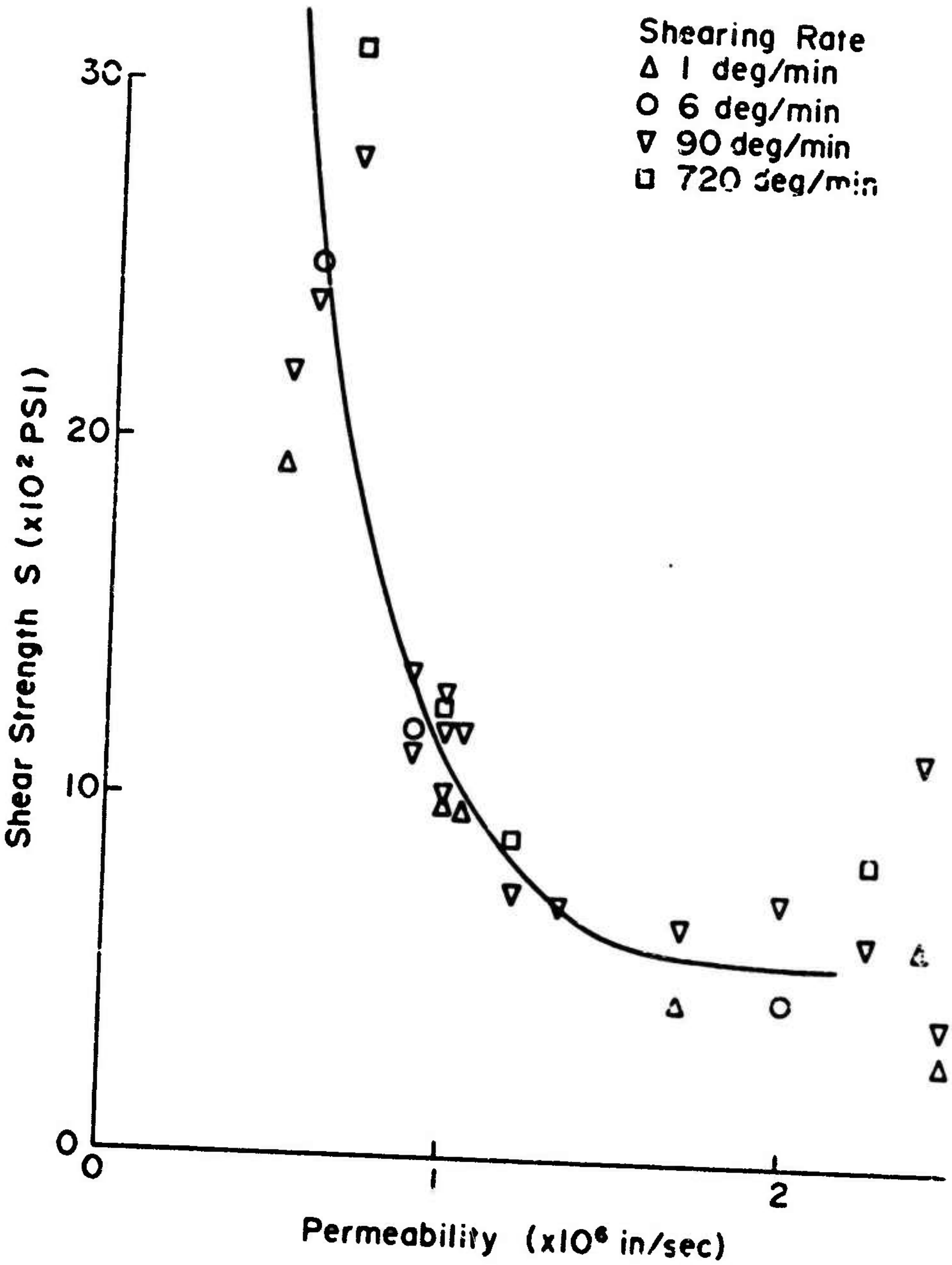
In order to further investigate the relationship between permeability and shear strength at different rates, fig. 8 was prepared. If permeability is to be a factor in the strength to rate relationship, we would expect to find a lower variation in strength at the higher permeabilities for a given rate. This relationship would exist if the porewater pressure changes induced by the rotating vane could be



*Average Permeability
Consolidation Pressure
□ - 2.04 PSI
Δ - 1.02 PSI
○ - .41 PSI
*.6 x 10⁻⁶ in/sec
*1.06 x 10⁻⁶ in/sec
*2.11 x 10⁻⁶ in/sec
Shear Strength S (x 10² PSI)
40
30
20
10
0
1
6
90
720
Shearing Rate (degrees/minute)

Figure 5

10 l



Shearing Rate
Δ 1 deg/min
O 6 deg/min
∇ 90 deg/min
□ 720 deg/min
Shear Strength S (x10² PSI)
Permeability (x10⁶ in/sec)
0
10
20
30
0
1
2

Figure 6

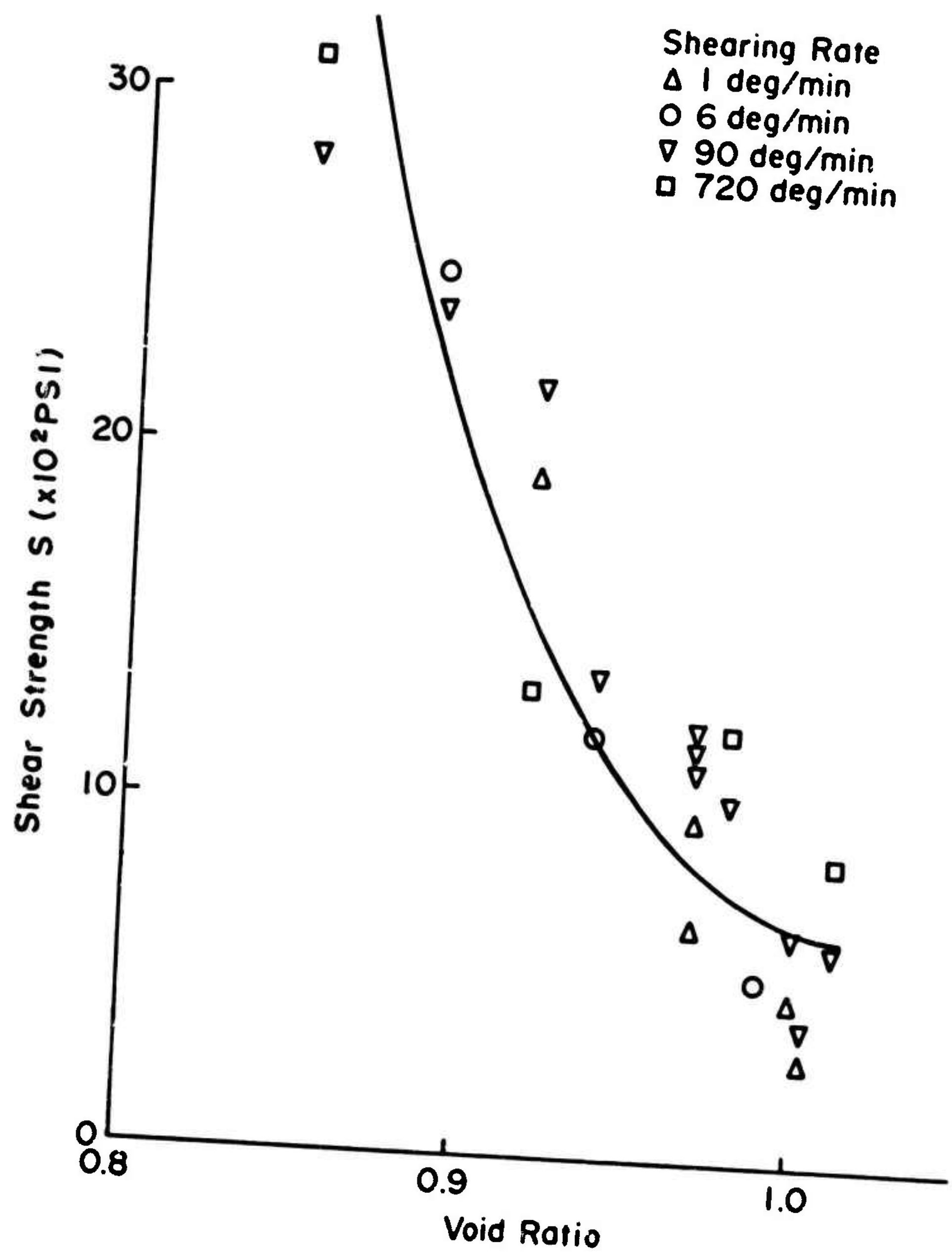

Shearing Rate
Δ 1 deg/min
O 6 deg/min
∇ 90 deg/min
□ 720 deg/min
30
20
10
0
Shear Strength S (x10²PSI)
0.8
0.9
1.0
Void Ratio

Figure 7

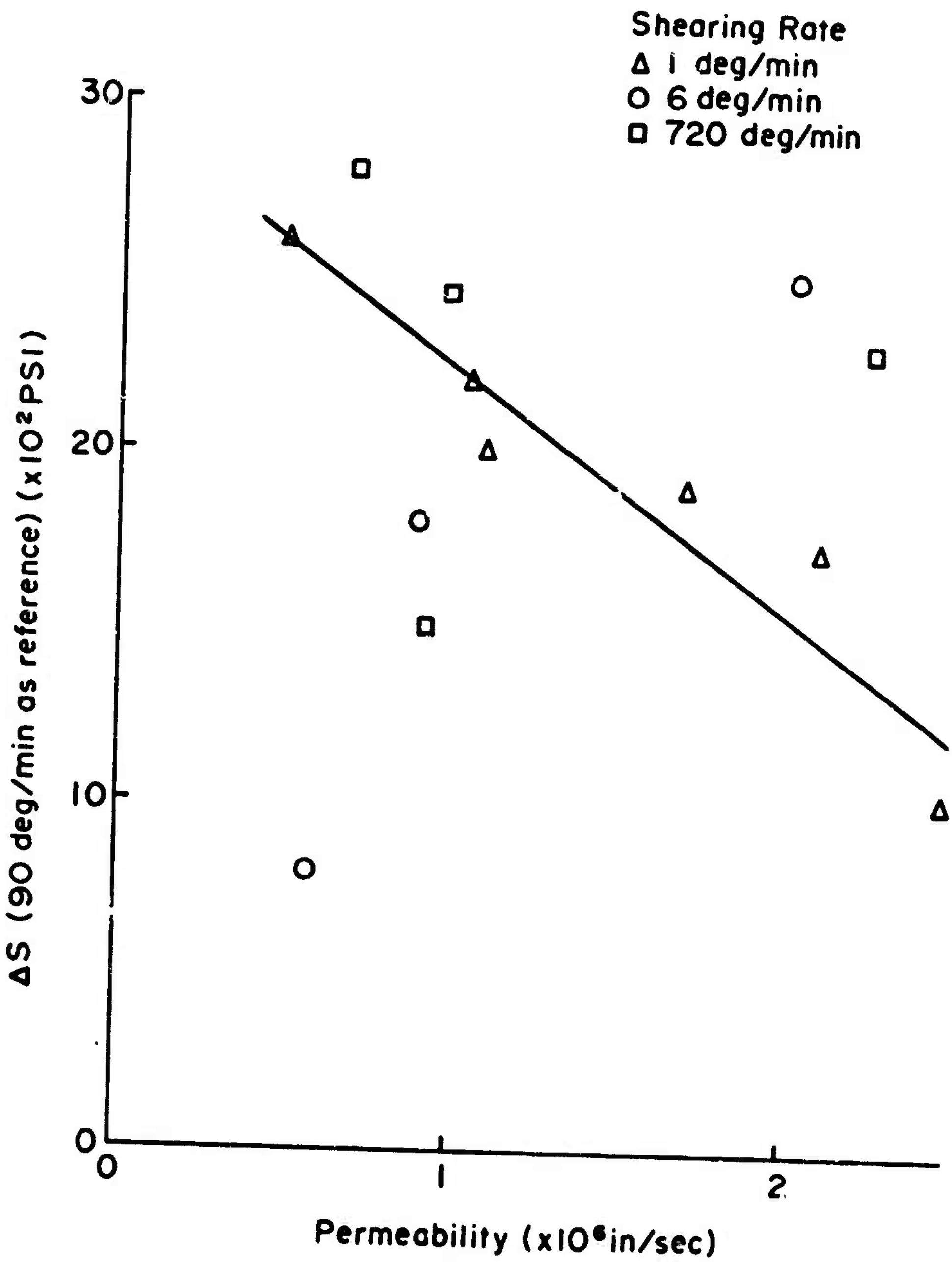

Shearing Rate
Δ 1 deg/min
O 6 deg/min
□ 720 deg/min
30
20
10
0
0
1
2
ΔS (90 deg/min as reference) (x10² PSI)
Permeability (x10⁶ in/sec)

Figure 8

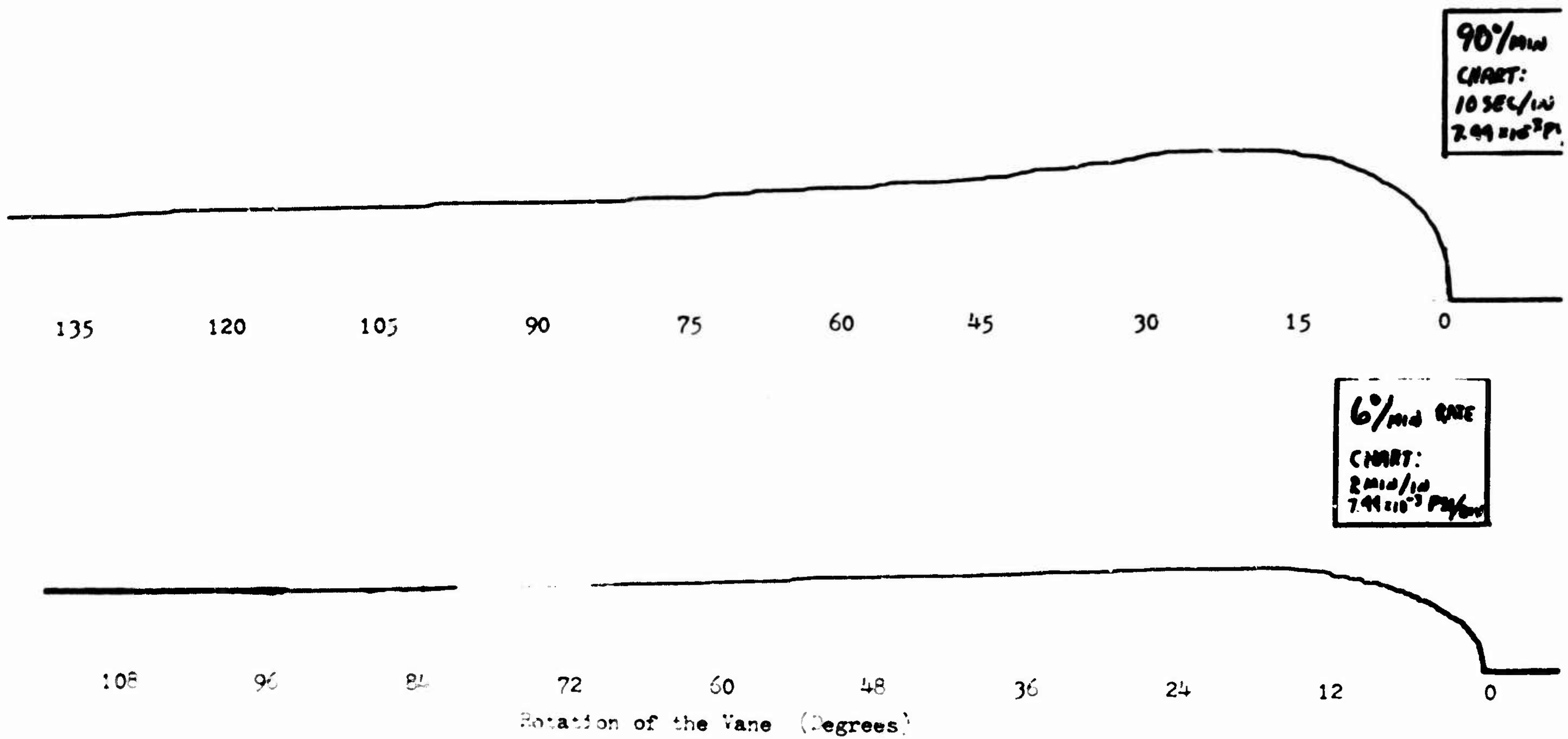
reduced by water escaping from the disturbed area through the pore spaces. The higher the permeability, the faster the porewater pressure can subside; and therefore, the effect on shear strength should be reduced.

Even with the limited data points, a pattern was seen to develop at the lowest shear rate used - 1 deg/minute. If this pattern is substantiated by further experimentation it may be concluded that due to the slow rotation rate used, very little excess pore pressure is developed during the shearing and a drained condition exists at rotation rates lower than 1 deg/minute for this sediment type and consolidation range. The results, as seen in fig. 8, indicate a possible threshold between the drained strength of this sediment and the undrained strength depending on the rate of shear. If this threshold does exist, then we would expect very little change in strength with changing rate due to porewater pressure below 1 deg/minute because it is a drained condition and the values of the viscous damping will only be a function of the viscous nature of the bonds between the sediment particles in shear. Above the threshold, an undrained condition is present where the viscous friction values will be dependent on the pore pressure at the shearing surface.

VI. CONCLUSIONS

The magnitude of the rate effect on shear strength for a clayey silt has been determined and is considered significant. Further tests will greatly improve the analysis of the mechanism of the rate effect on shear strength. The importance of the results of this experiment cannot be over-emphasized. If the habitable environment is to extend onto the continental shelf, the design concepts must be based on a thorough understanding and knowledge of the engineering properties of marine sediments.

In order to insure reliable safety factors when working in the marine environment, the shear strength data which is used to compute slope stability and load bearing capacity of the ocean floor must be reliable and accurate. Now that it is known that the rate of rotation in the vane shear strength measurements will affect the strength, future experimentation can be performed to further investigate the magnitude and the mechanism of the rate effect.



90°/min
CHART:
10 SEC/IN
135
120
105
90
75
60
45
30
15
0
6°/min RATE
CHART:
2 min/in
108
96
84
72
60
48
36
24
12
0
Rotation of the Vane (Degrees)

Fig. 4.

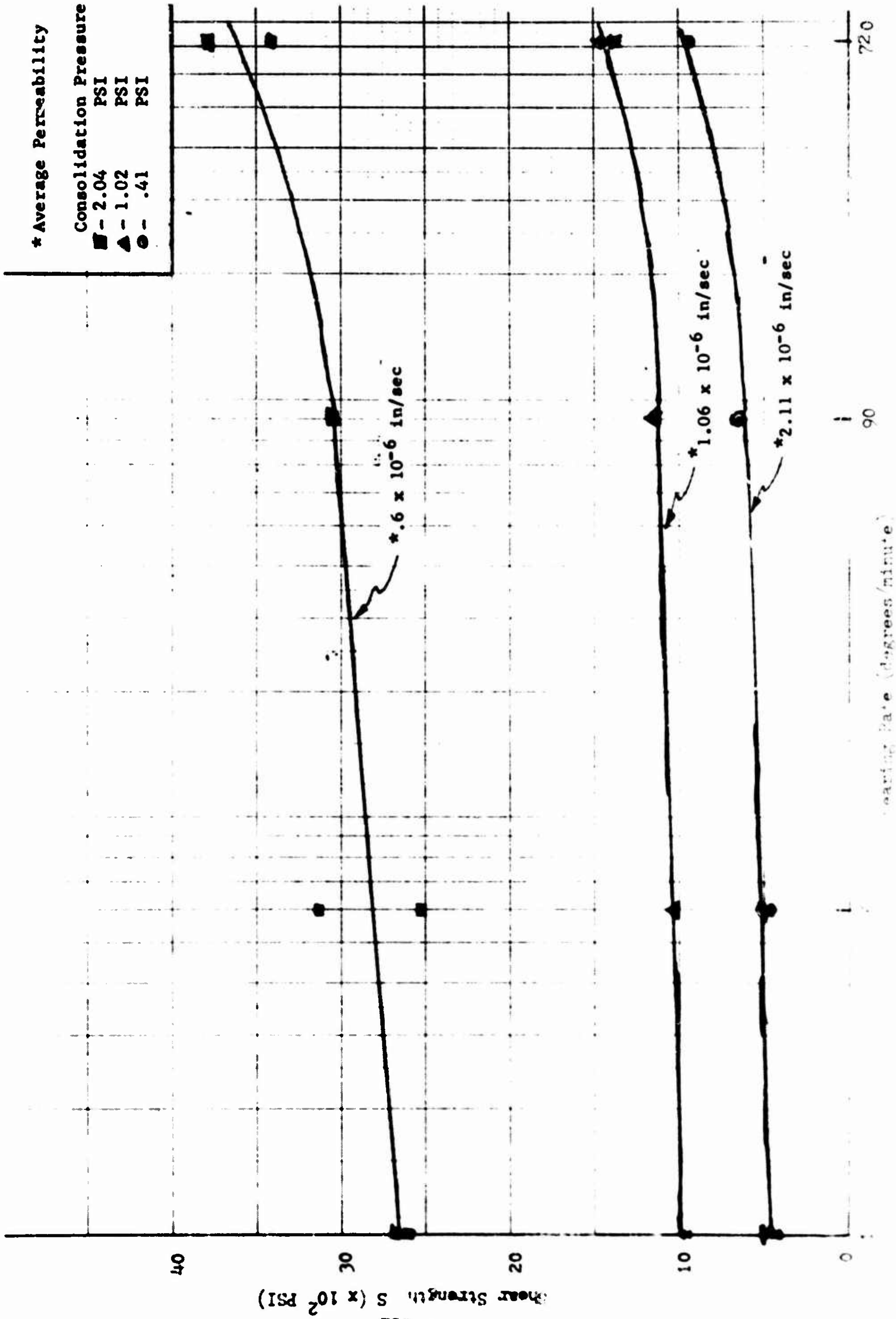

* Average Permeability
Consolidation Pressure
■ - 2.04 PSI
▲ - 1.02 PSI
● - .41 PSI
*.6 x 10^-6 in/sec
*1.06 x 10^-6 in/sec
*2.11 x 10^-6 in/sec
720
90
0
10
20
30
40
Shear Strength S (x 10² PSI)

FIG. 5.

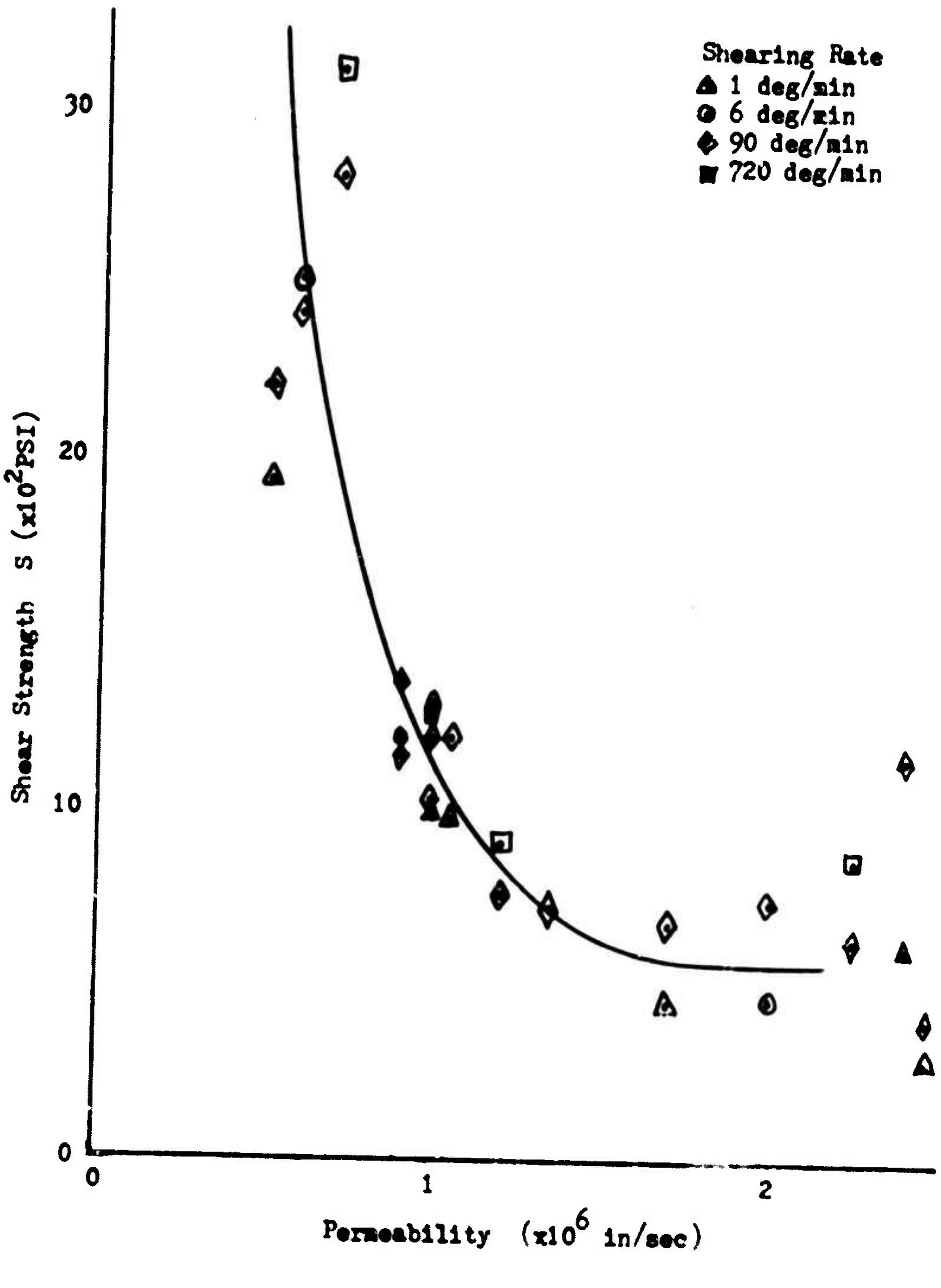

Shearing Rate
1 deg/min
6 deg/min
90 deg/min
720 deg/min
30
20
10
0
Shear Strength S ($x10^2$PSI)
0
1
2
Permeability ($x10^6$ in/sec)

Fig. 6.

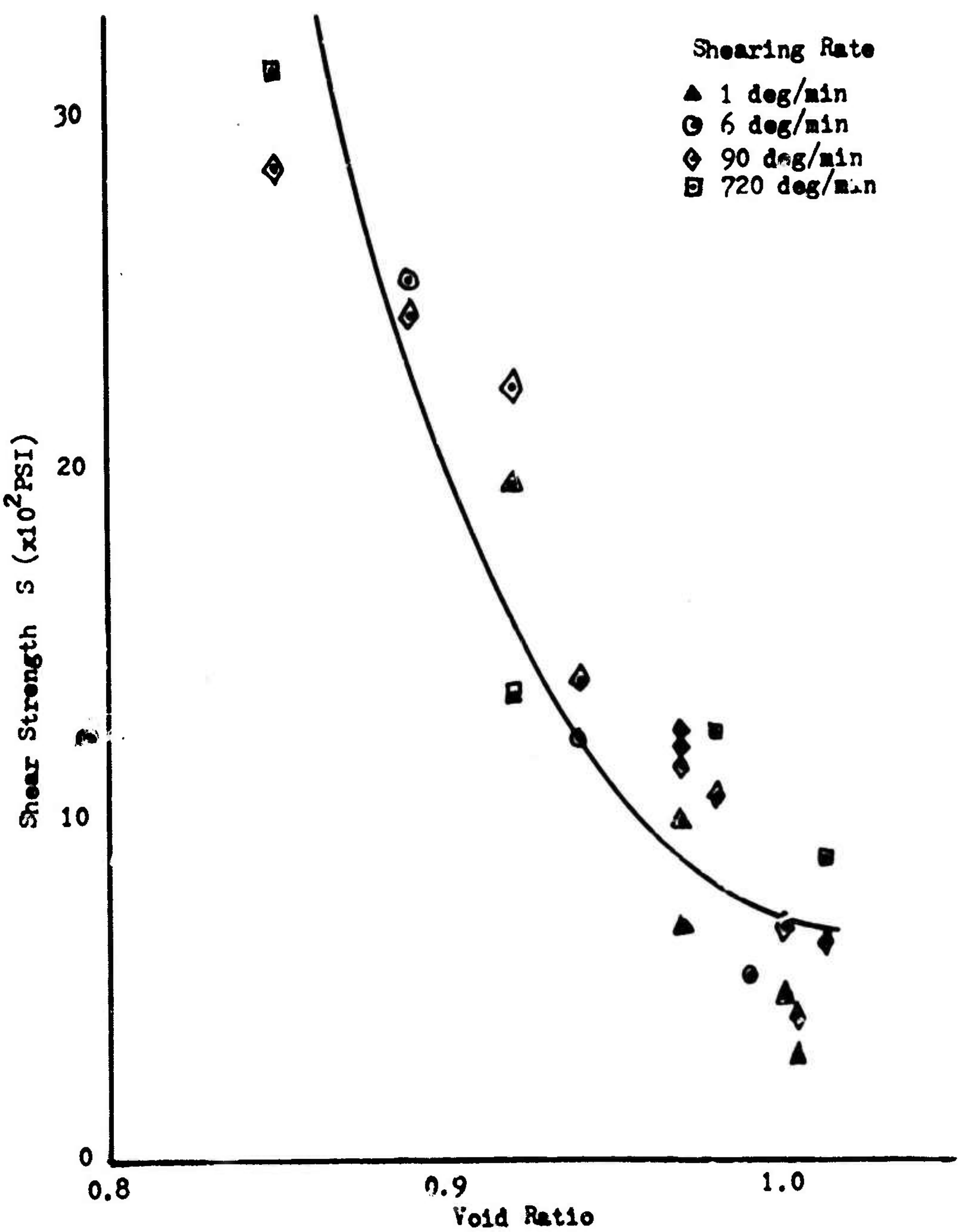

Shearing Rate
1 deg/min
6 deg/min
90 deg/min
720 deg/min
30
20
10
0
0.8
0.9
1.0
Shear Strength S (x10^2PSI)
Void Ratio

Fig. 7.

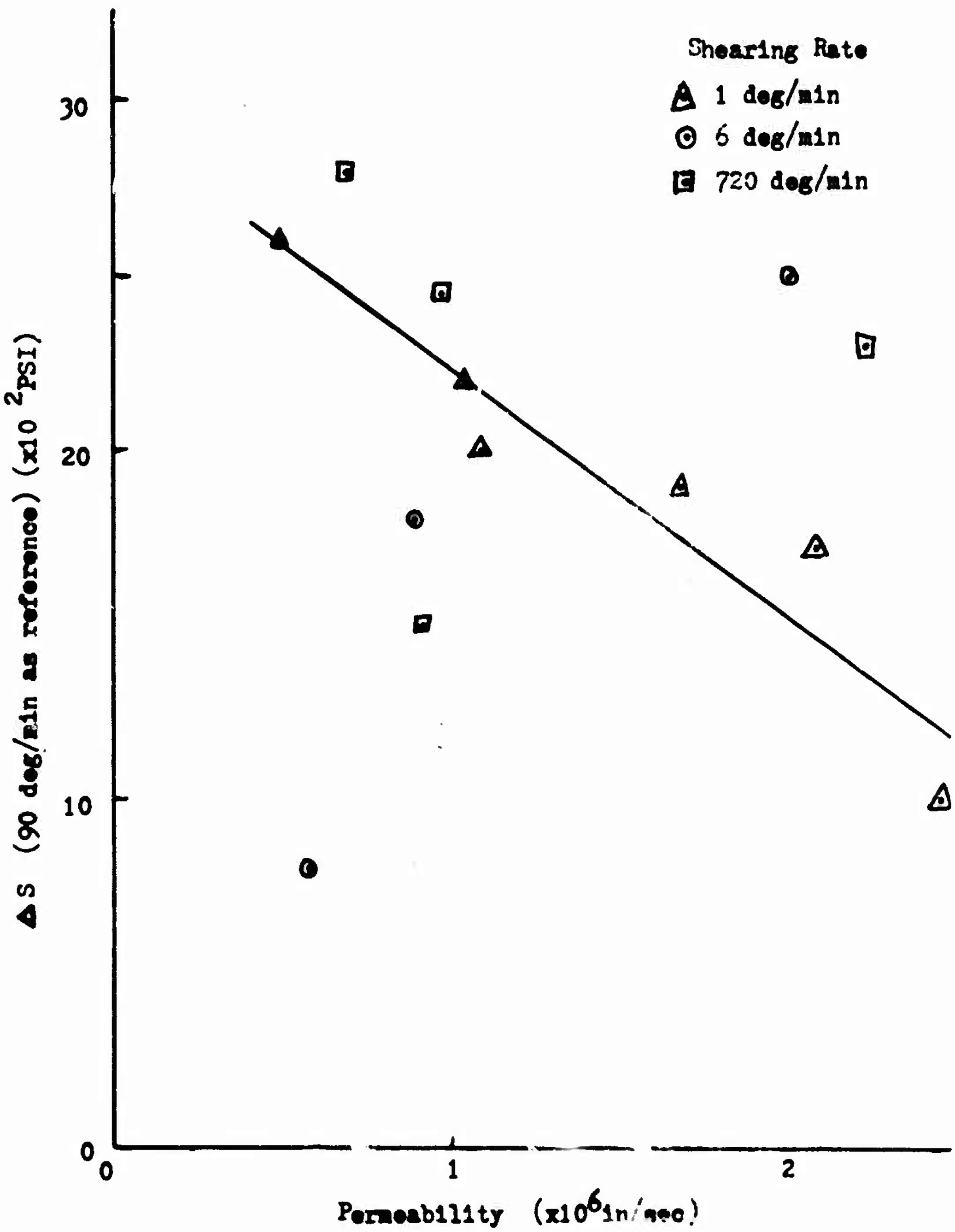

Shearing Rate
1 deg/min
6 deg/min
720 deg/min
30
20
10
0
0
1
2
ΔS (90 deg/min as reference) (x10 ^{2}PSI)
Permeability (x10^{6}in/sec)

Fig. 8.

FOOTNOTES

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2. R. S. Kessler and N. T. Stiles, "Comparison of Shear Strength Measurements with the Laboratory Vane Shear and Fall-Cone Devices," TR No. 68-75, Naval Oceanographic Office, Washington, D. C., 1968.

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10. Ibid., p. 385.

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APPENDIX A

SUGGESTIONS FOR FUTURE EXPERIMENTATION

It is believed that the analysis of the mechanics of the rate effect on sediment shear strength could be greatly enhanced with the addition of porewater pressure measurements. The equipment for this aspect of the experiment is presently undergoing design and will incorporate a miniature pressure transducer with a bonded strain gauge for accurate measurement of the porewater pressure as a function of shear strength and shearing rate.

In order to thoroughly investigate the influence of permeability and void ratio on the rate effect, the experiment should be conducted over larger ranges of permeabilities and void ratios. These ranges can be expanded for the same sediment by increasing or decreasing the consolidation pressure. Other methods of increasing these ranges include varying the grain size distribution of the sediment through the addition of clay or sand.

Assuming that the rate effect is due somewhat to the viscous nature of the deformation properties of cohesive soils, vane shear strength measurements should possibly be determined with the sediment at the in-place temperature. The temperature effects on the viscosity of fluids could be an important factor in the rate effect. This theory could be put to experiment by testing a sample of sediment at varying temperatures holding all other variables constant. Variation in the salinity of the porewater could cause a change in the viscosity, thereby influencing the rate effect. This aspect could also be investigated by experimentation.

All of the variables which could possibly influence the rate effect on the shear strength of marine sediments must be thoroughly investigated before the mechanism of the rate effect can be accurately analyzed.

APPENDIX B

MODIFICATIONS MADE TO EQUIPMENT

A majority of the apparatus used in this experiment is produced for commercial use and was purchased from the manufacturer. It was necessary, however, to adapt and modify much of the equipment to satisfy the needs of this particular project.

In order to maintain uniformity, as described in the Experimental Procedure section, the entire series of tests were run on each sample of sediment while it remained in the consolidometer cup. This procedure required a consolidation cup 1 inch higher than standard for the unit. These cups were machined from brass stock.

For the permeability test, a constant head device was designed incorporating a cylinder to hold the water at a given pressure, a pressure gauge, and a cap to fit over the consolidometer cup. The cylinder and cap were fabricated using brass wherever possible . The consolidometer cups were drilled and tapped so that the cap could be screwed tightly in place.

The vane shear device itself was a standard Wykeham Farrance unit modified by Diversified Marine Corporation of San Diego, California. The modifications included a D.C. powered drive motor with variable output controller, a three-speed gear box, and chain drive to the vane blade shaft. The device as purchased required considerable revision before it could be used with any degree of accuracy. The main problem with the modified unit was that the standard Wykeham Farrance device is operated with a hand crank and torsion springs, while with the modified unit, a sizeable lateral tension was placed on the drive shaft by the chain/gear unit. This lateral tension caused the drive shaft to flex at an internal joint where it connected to a gear in the drive mechanism. The shaft would then bind in the brass brushing/bearing in which it rested. This problem was overcome by machining a new drive shaft and brushing/bearing to much closer tolerances (.001" to .002") and by utilizing a different method of coupling the drive shaft to the worn gear to reduce flexure at this point. These modifications, requiring approximately 125 work hours in the machine shop, resulted in smooth operation of the entire test procedure and therefore improved the accuracy and reliability of the test results.