CREEP RATE AND CREEP STRENGTH OF CLAYS

RESISTANCE ET VILESSE DE FLUAGE DES ARGILES

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SYNOPSIS New type of data on the creep rate of clays are presented in the first section of this paper. A series of special drained creep tests, during which a water content is practically maintained constant, are performed on the normally consolidated and over consolidated clay samples having the same initial water content. An attempt is made to corelate the both shear and normal effective stresses to the rate of creep strain. In the second section, the time-dependent changes in strength of clays are investigated. The data on the creep strength or yield value obtained by the long-term drained and undrained creep strength tests are presented. These data are analysed on the basis of effective stress concept, and the flexibility of the yield value of clays in terms of effective stress are studied.

INTRODUCTION

The time-dependent deformation behaviour of clays under sustained stresses is a function of a large number of such variables as soil type, soil structure, stress history, effective stress, temperature, etc. Although creep data are now available on saturated clays, the relationship between these variables is as yet only vaguely understood: new types of creep data seen to be needed to provide the essential knowledge for formulating creep theories of clay.

Much of the work has been centered on relating the shear stress τ to creep strain or strain rate, and only a limited amount of data on relating both the shear stress τ and normal effective stress σ' to creep strain has been reported (Šuklje, 1967). One of the purposes of this paper is to investigate the effect of τ/σ' value on the creep rate, in an attempt to provide new data for future formulation of a better rheological theory for clays. A special procedure was adopted in this paper to maintain a constant water content and a constant effective stress on the specimen during creep test.

Another purpose of this paper is to study the time-dependent changes in strength of clays. Many investigators have shown that some types of saturated clays ultimately fail under a sustained load appreciably less than the strength indicated by a normal compressive test. The sustained stresses below which no creep failure occurs are called creep strength, ultimate continuous strength, long-term strength, yield value, etc. The creep strength or yield value, which will be used in this paper, can be obtained by the test in which a load is built up rather quickly and maintained constant until the specimen fails.

The analyses of experimental data on this problem in the past have indicated that the strength at constant water content and under sustained load decreases linearly with the logarithm of time when the clays are saturated. This decrease in creep strength is in part caused by an increase in pore water pressure and a corresponding decrease of the effective stresses and the effective friction component (Hvorslev, 1960). An attempt was made to analyse the data on creep strength on the basis of effective stress in this paper. Results of the undrained creep strength test with pore water pressure measurement and the drained test are presented.

SOILS TESTED AND EQUIPMENT

Four different clays were used for the tests and their classification properties are given in Table 1. Slurries of the clays were first consolidated in a large consolidometer having a diameter of 25 cm to approximately 0.5 kg/sq. cm, and then specimens with an area of 10 sq. cm and a length of 8 cm were cut for testing. The triaxial equipment and pore pressure measuring system developed by the Norwegian Geotechnical Institute were used.

Table 1 Classification Properties of Soils.

Sample No.	LL %	PL %	PI %	% Clay	Activity
1	63.5	27.4	36.1	30.0	1.20
2	54.0	30.0	24.0	28.0	0.86
3	36.0	25.6	10.4	23.0	0.45
4	52.5	23.6	28.9	18.0	1.61

Filter paper strips were placed along the side of the specimens and two rubber membranes separated by silicon grease were used. After further consolidation to the desired pressure in the triaxial cell, the specimens were back-pressured to approximately 1.0 kg/sq. cm. All tests were carried out in a constant temperature room of 20°C.

CREEP RATE OF CLAYS

Except for the special case where the excess pore water pressure remains constant during undrained creep test, it is obvious that the effective stresses continuously change during deformation. On the other hand, if the drained creep tests are employed the specimen drainage is inevitable, and therefore it is very difficult to perform a creep test in which a water content and effective normal stress are maintained constant. Thus for the case of drained condition, one must compare slightly different materials in the initial and final stages of creep. Moreover, the results of tests on specimens consolidated under different magnitudes of stresses do not permit the evaluation of the effect of a given variable, e.g. shear stress, on creep rate, because each specimen has different water content.

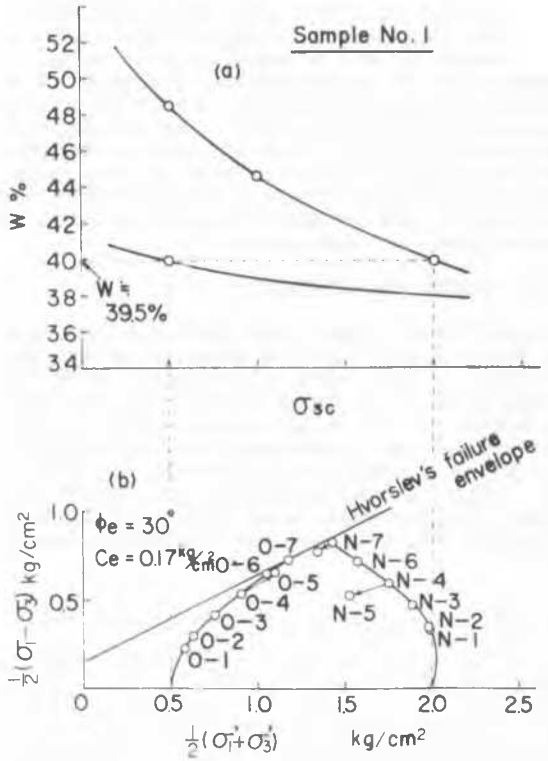

Fig. 1(a) Relationship between Water Content and Triaxial Consolidation Pressure.
(b) Stress States Selected for the Undrained Creep Tests.

One method for overcoming these difficulties is to use the following consolidated drained creep testing procedure. Normally consolidated and over consolidated specimens having the same water content are prepared in the triaxial cell as shown in Figs. 1(a) and 2(a). For example, over consolidated specimens were first isotropically consolidated up to 2.8 kg/sq. cm and then allowed to swell back to 0.5 kg/sq. cm for Sample No. 1. The constant deviator stress is then applied on the specimen, but the selections of stress states in the triaxial cell are made so as to satisfy the conditions of lieing on the effective stress paths, which had been previously obtained by the rather long-term consolidated-undrained triaxial tests on the identical samples. In Figs. 1(b) and 2(b) are shown these testing procedures: the positions indicated by circles on the effective stress paths, with a few exceptions, correspond to the stress states adopted for the creep tests.

In the analysis of the data on drained creep test, the strains defined as follows are used. If the nonuniformities of the stress and strain inside the specimen are disregarded and small strains assumed, Eq. (1) may be established.

$$\varepsilon_v = \varepsilon_1 + 2\varepsilon_3 \tag{1}$$

where ε_v, ε_1 and ε_3 are volumetric, axial and lateral strains, respectively.

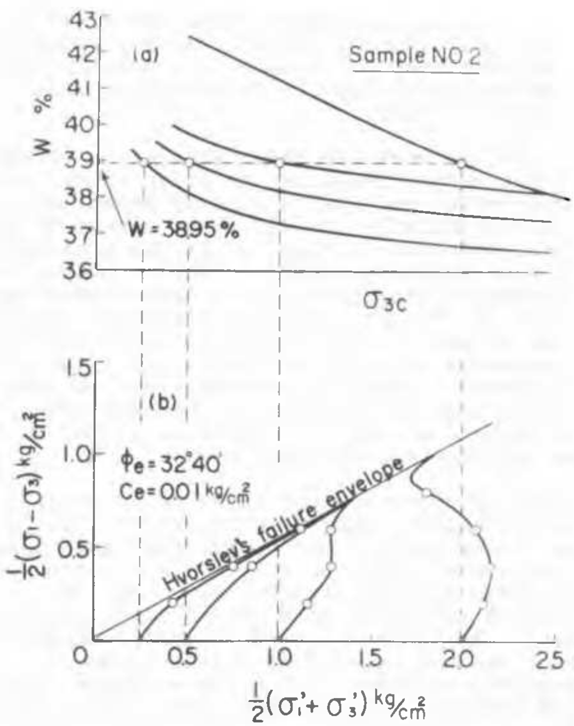

Fig. 2(a) Relationship between Water Content and Triaxial Consolidation Pressure.
(b) Stress States Selected for the Undrained Creep Tests.

Moreover, in triaxial conditions the following Eq. (2) may be obtained.

$$\left.\begin{aligned} \varepsilon_d &= \varepsilon_1 - \varepsilon_o \\ \text{and} \qquad \varepsilon_o &= \frac{1}{3}\varepsilon_v \end{aligned}\right\} \qquad (2)$$

where ε_d and ε_o are the deviatoric and spheric strains, respectively.
The creep deviator stresses were applied on each fresh specimen for about one week, nearly equals 10^4 min, under drained condition. A typical test result is shown in Fig. 3 in the form of deviatoric creep strain ε_d or spheric creep strain ε_o vs. logarithm of time. It is seen from this figure that the creep strain increases with the logarithm of time t for the range $t \gtrsim 100$ min, and that the effect of volume change of specimen on the creep rate may be negligibly small. Mean values of initial and final water contents of all specimens tested are summarized in Table 2, and it may be said that the drained creep tests were carried out at approximately the same and constant water contents for each sample.

The results illustrating the influences of effective stress intensity on the creep behaviour of normally consolidated and over consolidated clays are shown in Figs. 4 and 5: the curves in Fig. 5 are related to the stress states presented in the coordinate system, τ - σ', of effective stress paths at the bottom of the figure. The creep strain ε_d increases linearly with logarithm of time for Sample No. 1, but the simple time law of creep, e.g. strain proportional to log time, cannot be valid for Sample No. 2, and creep strains are plotted against arithmetic time scale.

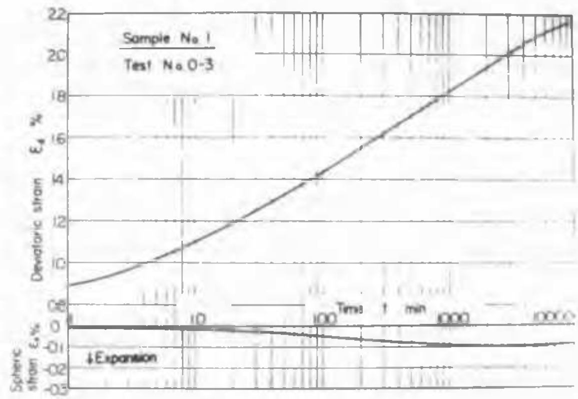

Fig. 3 Time-Dependent Changes of Creep and Volumetric Strains.

Table 2 Mean Values of Initial and Final Water Contents of All Specimens (all data in %).

Stress history	Sample No. 1	Sample No. 2
Normally consolidation	w_i =39.96 w_f =39.45	w_i =39.19 w_f =38.99
Over consolidation	w_i =38.89 w_f =39.92	w_i =38.81 w_f =39.43

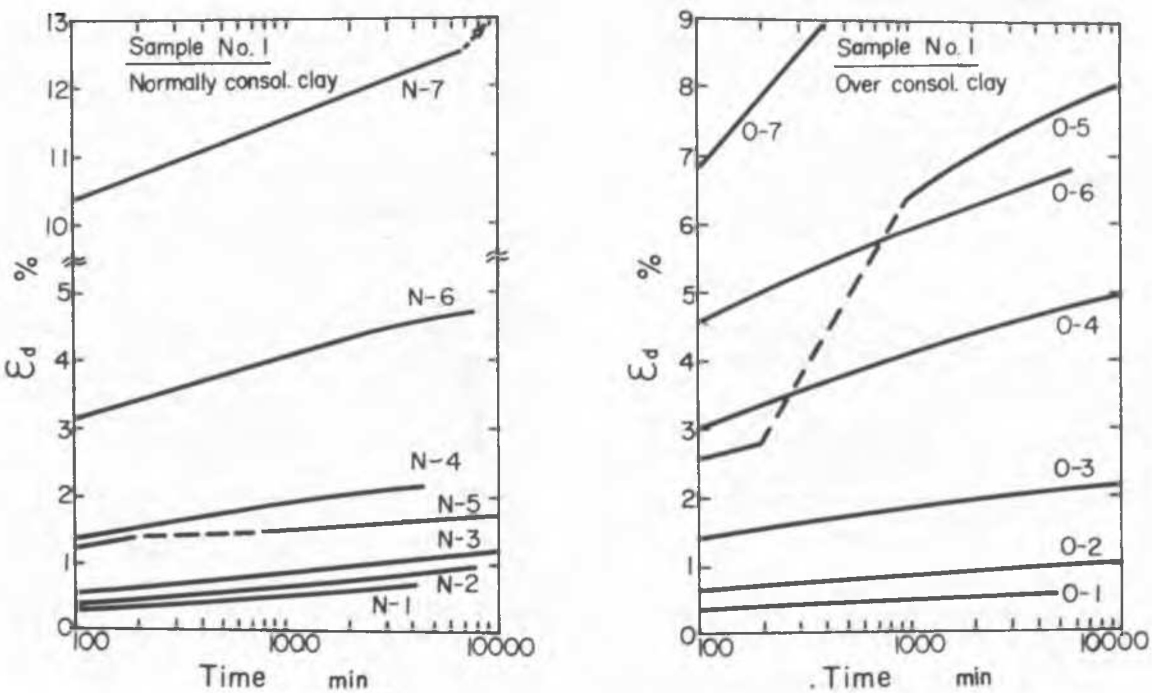

Fig. 4 Creep Deviatoric Strain ε_d vs. Log Time Curves for Drained Creep Test at Approximately Constant Water Content.

Of interest in these test is the fact that any specimen subjected to a stress slightly less than the normal compressive strength shows no sign of creep failure during the drained test. From this fact it seems to be suggested that the creep strength measured in drained condition will coincide with the normal compressive strength, and this will be seen in the next section.

If all variables, such as temperature, effective stress, soil structure, etc., are held constant except deviator stress σ'_d then the creep strain rate $\dot{\varepsilon}_d$ may be written on the basis of rate process theory as:

$$\dot{\varepsilon}_d = const. \times \exp B\sigma'_d \qquad (3)$$

where B is the stress factor and defined as follows.
Andersland & Akili (1967):

$$B = \frac{V_f}{\kappa T}\frac{\sqrt{2}}{3} \qquad (4\text{-a})$$

Mitchell et al (1968):

$$B = \frac{\lambda}{4S\kappa T} \qquad (4\text{-b})$$

where V_f ; volume of flow unit, T ; absolute temperature, κ ; Boltzmann's constant, λ ; distance between equilibrium positions of flow units, and S ; number of flow units. If logarithms of both sides of Eq. (3) are taken, we obtain:

$$\log \dot{\varepsilon}_d = \log const. + B\cdot\sigma'_d \qquad (5)$$

Thus under conditions of constant structure, temperature, and effective stress, the logarithm of the strain rate should be a linear function of the deviator stress. These linear relationships have been observed for a variety of clays for stresses greater than about 20 to 30 % of the initial strength, but below those causing creep failure (Mitchell et al, 1968).

The similar relationships were found in this paper for both normally consolidated and over consolidated specimens, all tested under conditions of constant effective stress and constant water content. Fig. 6 shows the typical test result for Sample No. 1; the strain rate $\dot{\varepsilon}_d$ can be calculated from the value of $\Delta\varepsilon_d/\Delta\log t$ in this figure by

$$\dot{\varepsilon}_d = \frac{\Delta\varepsilon_d}{\Delta\log t}\frac{1}{t}$$

It may be seen from Fig. 6 that the relationship between logarithm of strain rate and deviator stress is linear and the slope is independent of time as postulated by Eq. (5). The slope B is however dependent on the stress history or structure of clay, i.e. the larger value of B is found for the clay having larger over consolidation ratio. From Eq. (4-a) the knowledge of stress factor B provides a basis for obtaining a measure of the volume of the flow unit, but more research is needed to evaluate the nature of stress factor.

In Fig. 7 contours of equal creep strain rate, that is equal $\dot{\varepsilon}_d$, are plotted on the constant water content plane: the contour lines run parallel with the horizontal axis at the lower shear stress levels and run parallel with the failure line at the higher shear stress levels. Therefore it may be seen from this figure that the creep strain rate $\dot{\varepsilon}_d$ essentially depends on the magnitude of shear stress τ irrespective of σ' for appreciably smaller shear stress than the compressive strength, and that $\dot{\varepsilon}_d$ depends on the τ/σ' value for larger shear stress close to the compressive strength. The contours of equal creep strain rate for normally consolidated clay formed a series of straight lines all of which passed through the point close to the origin (the figure is omitted from this paper).

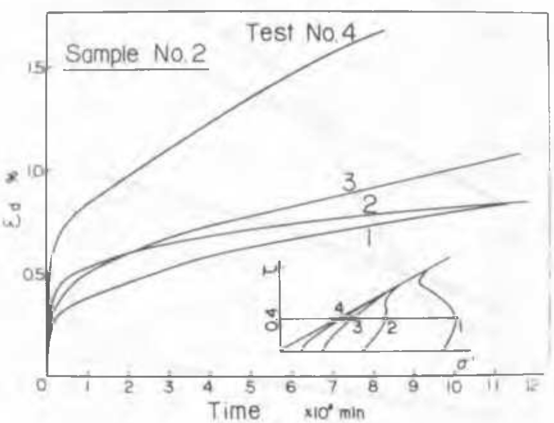

Fig. 5 Creep Deviatoric Strain ε_d vs. Time Curves for Drained Creep Test at Approximately Constant Water Content.

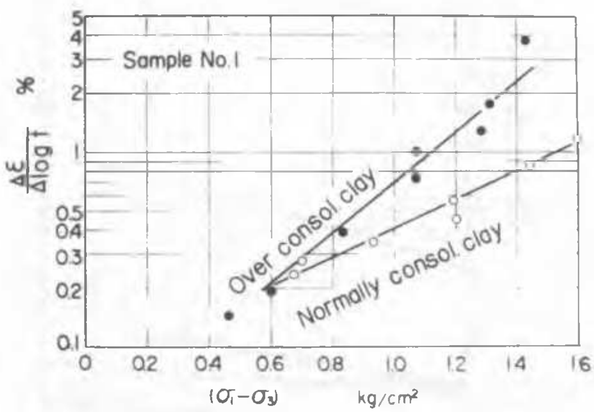

Fig. 6 Relationship between Rate of Creep Strain and Deviator Stress.

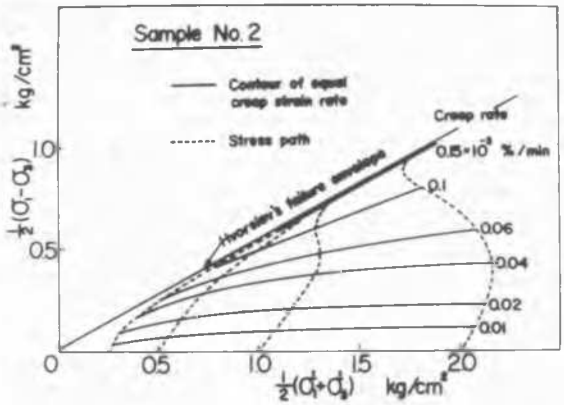

Fig. 7 Contours of Equal $\dot{\varepsilon}_d$ for Drained Creep Test at Approximately Constant Water Content.

CREEP STRENGTH OF CLAYS

Creep strength tests were performed on normally consolidated samples of Nos. 3 and 4 under the undrained and drained conditions. In the undrained test, the cell pressures were held constant and the pore pressure measurements were made to obtain effective stress paths for all stages of creep.

Fig. 8 shows typical creep strain ε_d or excess pore water pressure u vs. time curves obtained by the undrained creep strength test. The rate of creep strain is first rapid, then slower, and finally increasing again to failure: the time to failure is about 15,000 min in this case, where "the time to failure" refers to the elapsed time between application of the final creep load and failure. Although the result on Leda clay obtained by Coates & McRostie (1963) showed that creep deformation lead to failure without significant change in the pore water pressure, the considerable amount of pore pressure changes were observed for the clay tested as shown in Fig. 8.

From the data plotted in Fig. 8 the change of effective stress during the creep test may be obtained and the corresponding effective stress paths are illustrated as shown in Fig. 9. In this figure the creep deviator stress was applied in five increments at time interval of 3 min, i.e. the rate of stress application was 3.3×10^{-2} kg/sq. cm/min. In the creep strength test, as already stated, a load is precedingly built up rather quickly and then maintained constant until the specimen fails. The term "rate of stress application" refers to the rate of stress increasing at the preceding load steps in this section. At the final stage of loading, in which the deviator stress was maintained constant at 1.0 kg/sq. cm, the effective normal stress on the potential failure surface decreased slowly and creep failure occured after about 11 days.

In this figure the solid circle and crossed mark indicate the initial and final states of effective stress at the final stage of loading in the creep strength test. The coincidence of the creep failure point, plotted by the crossed mark in Fig. 9, with the failure envelope obtained by the normal triaxial compression test will be seen later.

In Fig. 10 are shown the summary of undrained test results on Sample Nos. 3 and 4, provided the results for almost the same rate of stress application for each sample were presented. The meaning of points indicated by the solid circles and crossed marks are the same as shown in Fig. 9, but additional symbol of the hollow circle represents the stress states of specimens of which no creep failure was observed in the test duration. Therefore if a line of demarcation was drawn between the groups of solid and hollow circles, it would mean that the line corresponds to the yield value in terms of effective stress of clays.

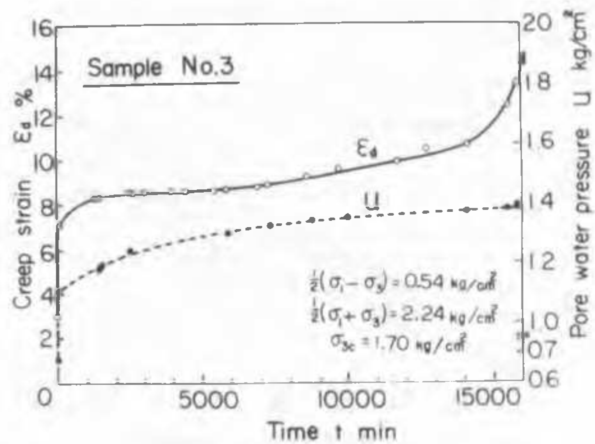

Fig. 8 Creep Strain and Pore Pressure vs. Time Curves for Undrained Creep Strength Test.

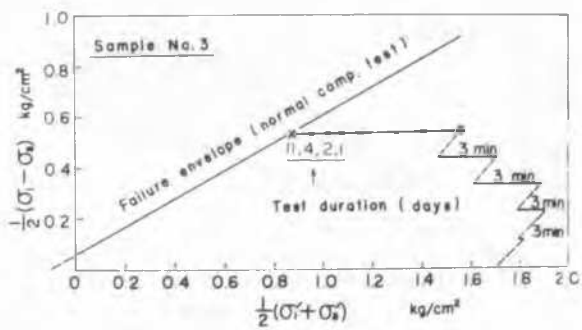

Fig. 9 Effective Stress Path for Undrained Creep Strength Test.

These lines are drawn in Fig. 10 and they can be approximated by a straight line with intercept $-c' \cot \varphi'$ on the axis σ', and slope φ'_y, where c' and φ' are the cohesion intercept and angle of shearing resistance, respectively, with respect to the effective stress. Thus the yield value envelope of normally consolidated clay may be expressed as

$$\tau_y = (c' \cot \varphi' + \sigma') \tan \varphi'_y \qquad (6)$$

Similar form as Eq. (6) has been proposed by Šuklje (1967).

Of interest is the fact that the undrained creep strengths, in terms of effective stress indicated by the crossed marks, lie near the failure envelope, defined as the maximum principal effective stress ratio, obtained by the normal strain-controlled triaxial compression test as shown in Fig. 10. This fact indicates that the maximum angle of shearing resistance φ' is common to the creep strength and normal compressive strength for the clays tested, and that the "rheological component" suggested by Hvorslev (1960) may be negligible for the test duration lasting only a few weeks.

Next, the flexibility of the yield value parameter φ'_y will be studied. Fig. 11 shows the influence of the rate of stress application, or the duration of the preceding load steps, on the value of φ'_y for Sample No.3 (in this figure the yield value envelope for slow rate was reproduced from Fig. 10). It is seen from Fig. 11 that the duration of the preceding load steps certainly influence the yield value parameter φ'_y measured under the undrained conditions: quick loading decreases the parameter φ'_y. On the other hand, the influence on the effective creep strength of the duration will be negligible as shown in Fig. 11.

A series of drained creep strength tests were performed on Sample No. 3. The loading was increased slowly step by step, but the adjustments of deviator and ambient stresses in the triaxial cell were made during the tests so as to maintain a constant value of $(\sigma_1' + \sigma_3')/2$ on the specimen. The durations of tests were from 20 to 30 days. The results of tests are summarized in Fig. 12 and the yield value parameter φ'_y seems to be close to the maximum angle of shearing resistance φ'.

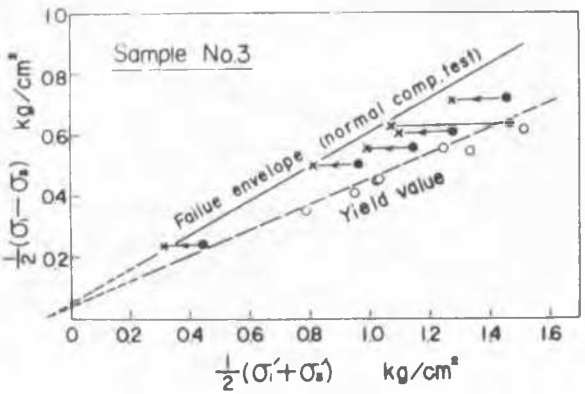

Fig. 10(a) Summary of The Data on Creep Strength and Yield Value for Sample No. 3.

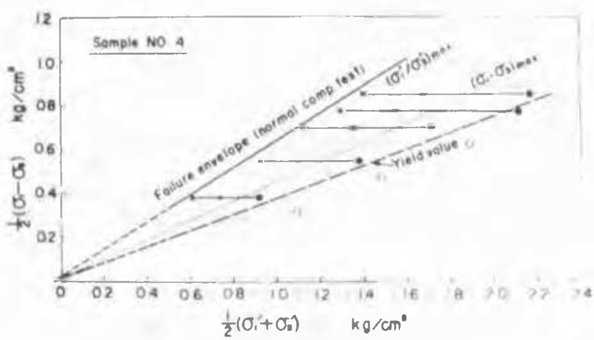

Fig. 10(b) Summary of The Data on Creep Strength and Yield Value for Sample No. 4.

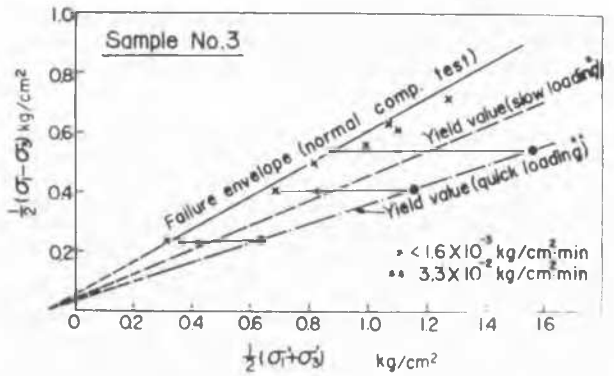

Fig. 11 Influence of The Rate of Stress Application of The Yield Value.

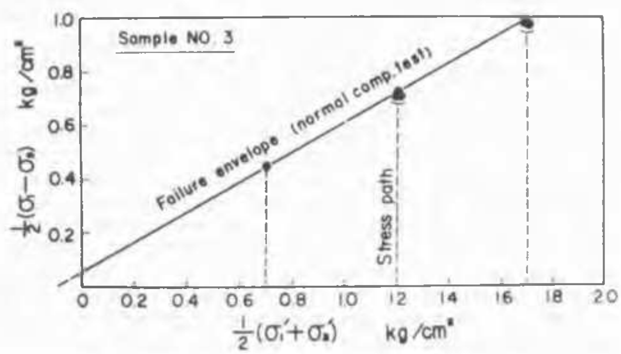

Fig. 12 Results of Drained Creep Strength Test.

CONCLUSIONS

The following tentative conclusions can be drawn from the tests performed during this investigation:

(1) The special creep tests were performed on the normally consolidated and over consolidated clays having the same water content under the condition of approximately no change of effective stress and of water content. The contours of equal creep strain rate plotted on the constant water content plane, Fig. 7, shows that the creep strain rate $\dot{\varepsilon}_d$ essentially depends on the magnitude of shear stress τ irrespective of the effective normal stress σ' for appreciably smaller shear stress than the normal compressive strength, and that $\dot{\varepsilon}_d$ depends on the τ/σ' value for larger shear stress close to the normal compressive strength.

(2) The linear relationships between logarithm of creep strain rate and the deviator stress are found for both normally consolidated and over consolidated clays, all tested under conditions of approximately constant effective stress and constant water content, Fig. 6. The larger value of stress factor B , which is derived from the rate process theory and provides a basis for obtaining a measure of the volume of the flow unit, is found for the clay having larger over consolidation ratio.

(3) The data on yield value, below which no creep failure occurs, are analysed on the basis of effective stress concept. The yield value envelopes of clays plotted on τ - σ' coordinate system can be approximated by the straight lines with intercept $-c' \cot \varphi'$ on the axis σ' , and slope φ_y' , Fig. 10 and Eq. (6). The yield value parameter φ_y' measured by the undrained creep strength test is seen to be a flexible term, but φ_y' by the drained creep strength test seems to be close to the maximum angle of shearing resistance φ' .

(4) Approximately the same value of φ' is obtained for the following three types of strengths: undrained creep strength in terms of effective stress, drained creep strength, and the normal compressive strength defined as the maximum effective principal stress ratio. This means that the rheological component suggested by Hvorslev may be negligible for the test duration lasting only a few weeks.

ACKNOWLEDGEMENT

The authors are indebted to M. Hoshino, who kindly permitted them to make use of some of his experimental results.

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