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Multi-stage creep test analysis of mudstone

L'analyse d'essais de fluage à plusieurs étapes pour la glaise

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SYNOPSIS In order to understand creep deformation and long-term strength of mudstone, a new laboratory test method has been developed. This report details the test procedure, and includes discussion of data collection, simplicity of operation, rationality of test results concerning deformation and strength, the amount of samples covered and theoretical importance of the data.

INTRODUCTION

In order to deal with problems of settlement and to understand the phenomenon of delayed or progressive failure, many studies have been done concerning time-dependent strength and visco-elasto-plastic deformation of geologic material (Murayama & Shibata, 1956; Mitchell, 1976; Singh and Bamford, 1971). It has recently been established that soft sedimentary rock has these deformation-strength properties, and that the concept of effective stress can be introduced (Adachi & Takase, 1981; Ohtsuki et. al, 1981; Nishi et. al, 1983). However, further research is necessary to clarify these properties.

This paper presents data concerning creep deformation and long-term strength of mudstone based on various laboratory tests. Mudstone is sedimentary rock from the Neogene Pliocene. Laboratory test methods used to obtain the data are discussed and compared to ordinary test methods. The method selected for this research is intended to simplify and rationalize future research on the visco-elasto-plastic deformation and strength of sedimentary rock.

TEST PROCEDURE

The principal tests are oedometer tests, tri-axial compression tests for various strain rates, and triaxial compression creep tests. According to the new test method developed for the research, after isotropic consolidation the deviatoric stress is increased stage by stage until rupture occurs. These are called multi-stage creep tests. For these tests the increment of deviatoric stress is held constant. The current experiments used an incremental value of 196 kPa. Time intervals are also held constant for each experimental condition. Intervals used are 15, 60, and 1440 minutes.

Concerning drainage, both the consolidated drained and consolidated undrained conditions are used. The multi-stage creep test method is generally said to be one type of stress control test method. Almost the same method is proposed

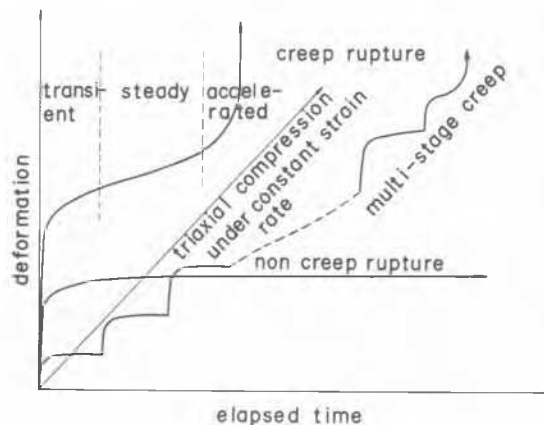


Fig. 1 General Outline of the Multi-stage Creep Test and Various Tests Methods

TABLE I

Physical Properties and Results of Oedometer Tests

γ	(kN/m^3)	Ave. 16.28	$\sigma = 0.20$
W	(%)	Ave. 51.9	$\sigma = 1.8$
P_c	I-D Vertical	3920, 4710, 4610, 4810	
	I-D Horizontal	4423, 3920, 4020, 4220	
	isotropic	3480, 3430, 3290, 3580	

by Murayama & Shibata (1956). For this research however, data are collected continuously. Also, there is greater attention paid to interpretation and possible application of experimental conclusions.

The samples used in this study consist of fresh and intact mudstone. The physical properties of these samples are listed in Table 1.

TEST RESULTS

Principal test results are shown in Table 1 and Figure 2. Table 1 shows the results of standard (1-D) oedometer tests and isotropic consolidation tests. For these tests the test samples are arranged so as to stand in the vertical and horizontal directions against the loading plane. Consolidation yield stress (P_c) obtained from isotropic consolidation tests is slightly smaller than that obtained from 1-D tests, but the distribution of P_c is localized around 3300-4800 kPa.

Fig. 2 shows the strengths of CD and CU as data derived from triaxial compression tests. It is clear that the strength of mudstone is affected by strain rate, and that the rupture envelope curve is not linear.

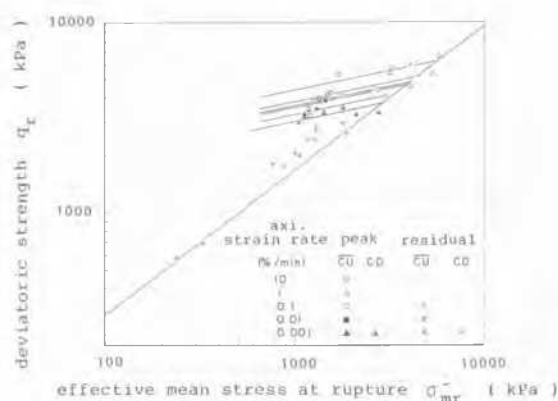


Fig. 2 Strengths established by Triaxial Compression Test

CREEP DEFORMATION

To obtain creep deformation, the multi-stage creep tests are employed in the following data form manner. While there is no problem in the 1st stage, in the 2nd and subsequent stages the deviatoric stress is increased. Thus, the problem of how to assess elapsed time emerges. It was decided that elapsed time starts at the point of loading in each stage.

Fig. 3 shows the relation between strain rate and elapsed time in creep deformation. In the transient creep state, the following relation generally exists.

$$\log(\dot{\gamma}/q) = -m \log t + k \quad (1)$$

where $\dot{\gamma}$ is shear strain rate, q is deviatoric stress, t is elapsed time and m and k are material constants. Results of the multi-stage creep tests confirm the existence of this relation. In the steady creep state, the relation between $\dot{\gamma}$ and t deviates gradually from relation (1) as deviatoric stress increases in multi-stage creep tests. Fig. 4 shows the relation between strain rate and elapsed time at steady state. The results of the multi-stage creep tests are in near agreement with those of the creep test. Similar conclusions can be derived from Figure 4, which shows the relation in the accelerated creep state.

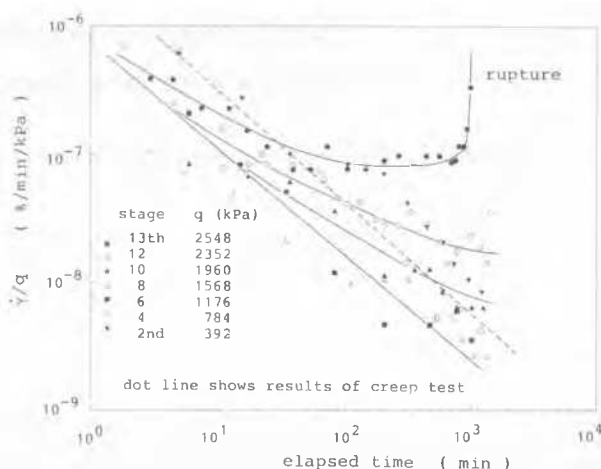


Fig. 3 Change of Creep Strain Rate with Elapsed Time: Multi-stage Creep Test Method

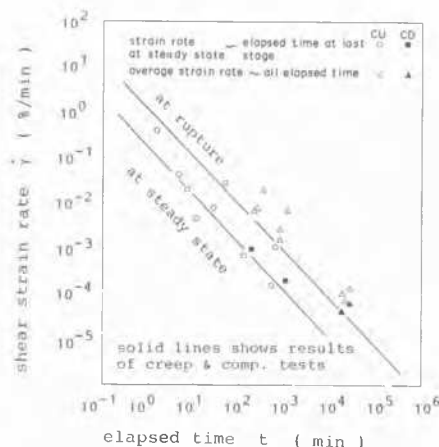


Fig. 4 Relation between Strain Rate and Elapsed Time for Steady and Accelerated Creep States

YIELD VALUE

The yield property of ground materials is generally expressed in terms of consolidation yield stress or yield function. Plastic flow is also important factor in material mechanics. Here we discuss yield value.

From the results of the multi-stage creep tests, yield values are obtained by the following methods, and then results of each method are compared. One method obtains the upper yield value according to procedures established by Murayama and Shibata. The other method obtains so-called Bingham yield value from the relation between the strain rate and deviatoric stress (Fig. 5 & Fig. 6). Where σ_{mo} is effective mean consolidated pressure.

The yield values obtained according to Murayama and Shibata's method fall intermediately among various strengths. As for the Bingham yield values obtained from the strain rates, some belonged to a region of values relatively low when

compared with the strength, while others belonged to a region of relatively large mean stresses (Fig. 7). If this phenomenon is examined in detail, the former are almost equal to the residual strength, and the latter are nearly equal to the consolidation yield stress (Fig.7).

It is clear that viscous deformation will increase as the stress point takes on values above residual strength. This occurs to a greater extent than it does when the stress point is below residual strength. Therefore, time-dependent strength ranges above residual strength (Fig. 8). In contrast, as the stress point approaches the normal consolidated region, viscous deformation will increase considerably. Consolidation yield stress is time-dependent. But if the stress point falls below residual strength, the strength is time-dependent strength or normal consolidated (or residual) strength.

Multi-stage creep tests are simpler than creep tests, which require various deviatoric stress values. Multi-stage creep tests developed in this research provide a way to clarify the physical meaning of the Bingham yield value.

LONG-TERM STRENGTH

In order to understand the long-term strength of mudstone using the concept of effective stress, the following two relations must be expressed. They are the relation between the strength and strain rate at rupture, and the relation between the rupture time and the strain rate at rupture.

In this case, the rupture criteria are expressed as a power function.

$$q_r = \alpha_r (\sigma_{mr}')^{\beta_r} \quad (2)$$

where q_r and σ_{mr}' are deviatoric stress ($=\sigma_1 - \sigma_3$) and mean stress ($=(\sigma_1 + 2\sigma_3)/3$) at rupture, respectively and where α_r and β_r are material constants.

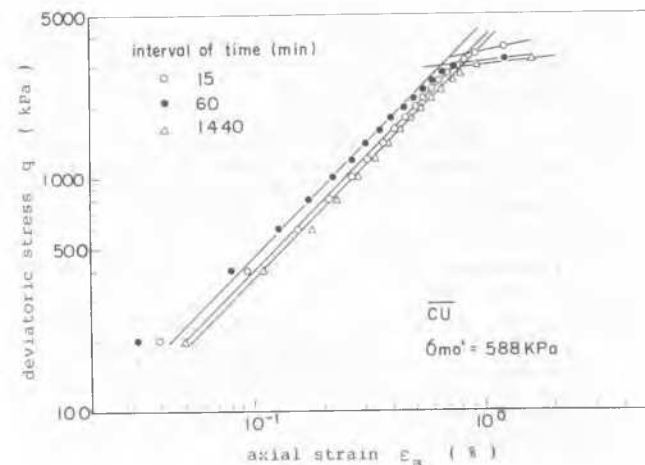


Fig. 5 Yield Values obtained from Method established by Murayama & Shibata

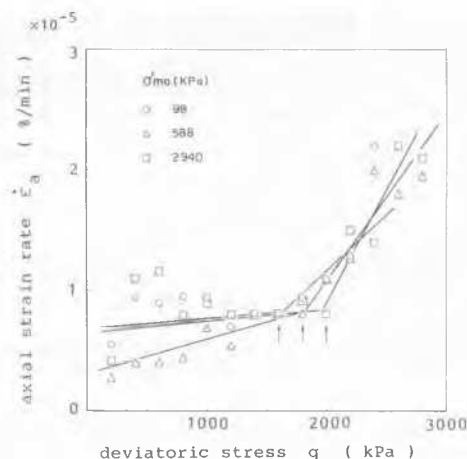


Fig. 6 Bingham Yield Values obtained by Strain Rate

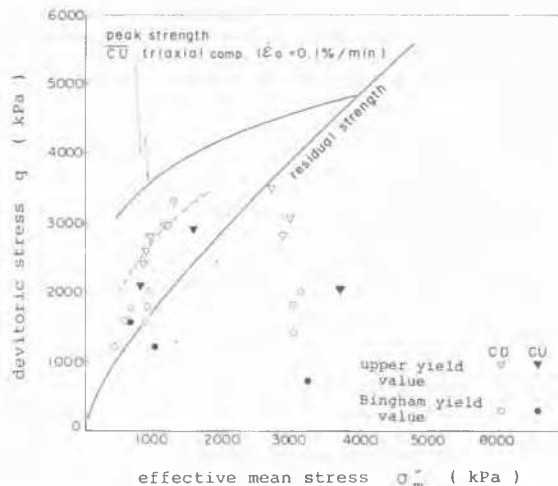


Fig. 7 Position of Yield Values on Stress Space

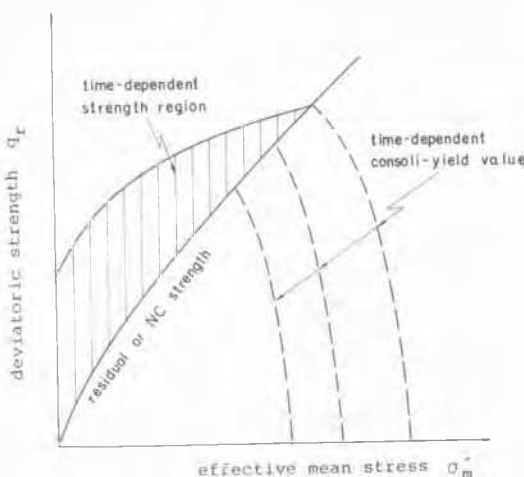


Fig. 8 Time-dependent Strength and Yield Value

One of the two strength constants β_r can be held constant (Fig. 2). Therefore, change in the other variable α_r can be traced. As a result, irrespective of the loading method, the two relationships can be said to be unique (Fig. 4 & Fig. 9). So,

$$\alpha_r = a \log \dot{\gamma}_r + b \quad (3)$$

$$\log \dot{\gamma}_r = c \log t_r + d \quad (4)$$

where $\dot{\gamma}_r$ is shear strain rate at rupture or minimum shear strain rate (in the steady creep state), t_r is rupture time, and a, b, c and d are material constants. In CU tests, $\dot{\gamma} = 1.5 \epsilon \dot{\epsilon}$ because volumetric strain is zero after consolidation where $\epsilon \dot{\epsilon}$ is equal to axial strain.

The strain rate at rupture can be eliminated. So as to obtain the relation between the rupture time and the strength (Fig. 10).

$$\alpha_r = \{ a (c \log t_r + d) + b \} (\sigma_{mr}^i)^{\beta_r} \quad (5)$$

Thus, the long-term strength can be obtained. However, these relation can be obtained only by multi-stage creep tests. Furthermore, since multi-stage creep tests allow for determination of the strength as well as the creep deformation, they are a simpler and more convenient method.

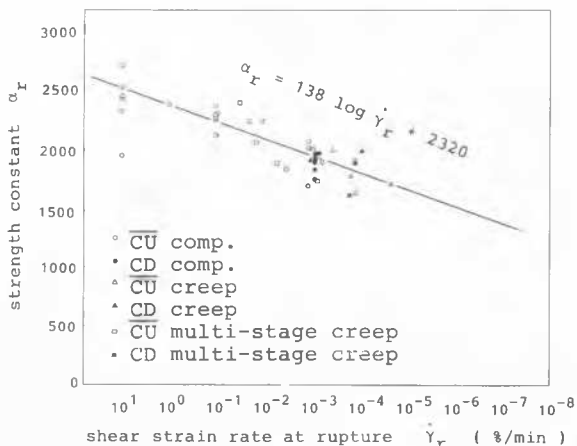


Fig. 9 Dependence of the Strength Constant α_r on Strain Rate

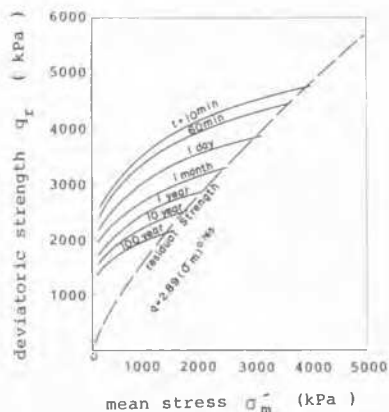


Fig. 10 Change of Strength with Elapsed Time

CONCLUSION

As Mentioned above, the results of multi-stage creep tests can be used to obtain creep deformation and long-term strength. Furthermore, the data they produce allows for assessment of residual strength or consolidation yield stress. Also, the number of samples can be small in case of multi-stage creep tests. This is important because ground conditions may preclude sufficiently extensive sampling. When compared to former methods, the advantages of the multi-stage creep tests are numerous and significant. Multi-stage creep tests are more easily conducted, and they provide a better assessment of deformation and strength using fewer samples than other methods.

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