Slip Fracture and Shear Strength of Bentonite Gels*

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The hydrogel of Wyoming Bentonite shows a charateristic slip fracture under a critical shear stress, *i.e.* the shear strength. The shear strength and the shear modulus of the gel were measured by various methods over a wide range of bentonite concentration. The shear modulus increases with increasing the concentration in the similar manner to the gel of linear polymers. The shear strength (σ_0) is related to the shear modulus (G), as shown by the equation:

$$\sigma_0 = G\gamma_0$$

where γ_0 is the critical shear strain. γ_0 takes values ranging from 1/10 to 1/30, which are in fairly good agreement with the value predicted for an ideal crystal by Mackenzie.

INTRODUCTION

Over a number of years, Gotoh and Hirai[1] have reported briefly that a hydrogel of bentonite clay shows a distinct slip pattern under compression, which inclined at 45° to the direction of the force as shown in Fig. 1. This direction of slipping is that of the maximum shear in the specimen. Such a slip is observed neither for the bentonite dispersed in an organic medium nor for that
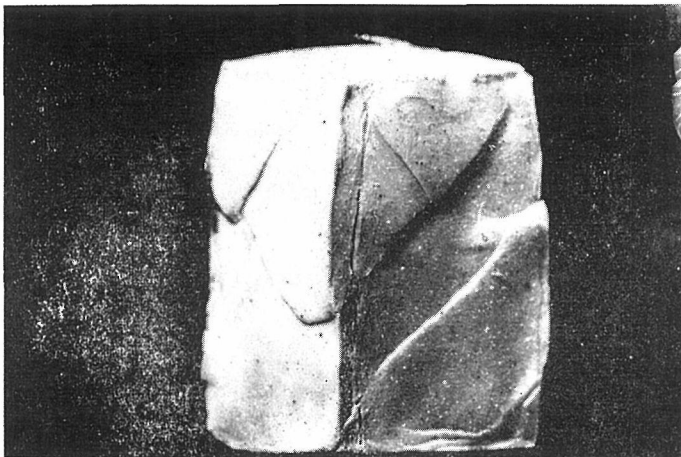

Fig. 1. Slip pattern of bentonite gel compressed vertically.

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Fig. 2. Crack pattern of bentonite dispersed in machine oil.

Fig. 3. Crack pattern of bentonite dehydrated at 800°C.

dehydrated by heating at temperatures higher than 800°C in which crack patterns of fracture as shown in Figs. 2 and 3 were observed respectively; in these patterns we see regular triangles and they should be distinguished from the slip pattern.   This crack pattern seems to be characteristic of the dilatant systems consisting of some liquid medium (organic or inorganic) and lyophobic fine powders.

Aida, Harai and Gotoh[2] investigated the viscoelastic behavior of bentonite gels with a cone and plate viscometer and found that the gel showed an instantaneous elastic deformation followed by a viscous flow or yielding under a relatively low shear stress, while an abrupt slpping of the cone was observed under a shear stress higher than a critical value.

In this paper, the critical shear stress for slip fracture or the shear strength of bentonite gels are measured by three different methods, and the shear modulus by the compression method as well as by the cone and plate viscometer over a

wide range of concentration. The relationship between the shear strength and the shear modulus is discussed, and compared with the theoretical one predicted for an ideal crystal by Mackenzie[7].

EXPERIMENTAL

1. Preparation of the Specimen

Finely ground Wyoming bentonite (400 g) was dispersed 20 l water. After the suspension was kept standing for a week and coarse particles were settled, the upper part (13 l) was taken and evaporated to various concentrations at a temperature below 95°C. Exact concentrations of each specimen were determined by drying at 105°C after each experiments.

2. Measurements of the Shear Strenth

The critical shear stress or the shear strength of the bentonite gel was measured by the following three methods :

(1) **Compression method.** The bentonite gels were molded with a brass cylinder. It was confirmed that the experimental results were independent of the size of specimens but depended mainly upon the concentration, so far as the heights of the specimens were equal to or larger than the diameter. When the height of the specimen was smaller than the diameter, the critical stress or the strength for the slip increased. In this experiment, the height and the diameter of specimens were both 2.5 cm. The cylindrical specimen was placed on the table balance and compressed vertically with a screw device as shown in Fig. 4.
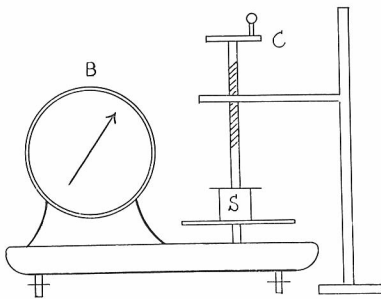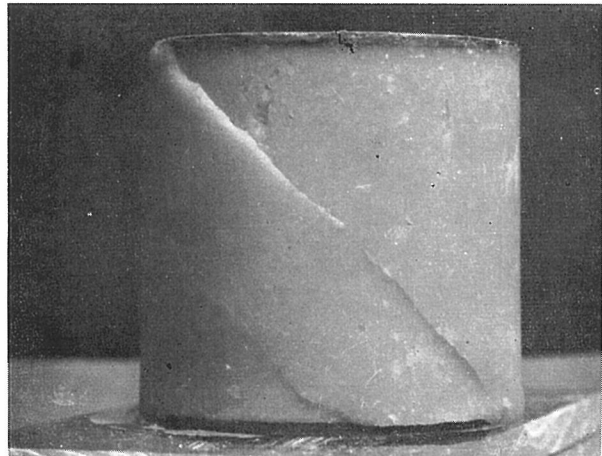

Fig. 4. Apparatus of compression method.

Fig. 5. Slip pattern of a cylindrical bentonite specimen.

The critical compression was detected by the backwark motions of the pointer of the scale board when the slip pattern appeared on the surface of the specimen. Fig. 5 shows an example of the slip fracture. The critical shear stress or the shar strength in the direction of the slip pattern is given by $W/2$ (dyne/cm²) where W is the virtical stress. With this method, Young's meduli (E

dyne/cm^2) of bentonite gels were measured and the shear moduli (G) were obtained by using the relation $E=3G$, the Poisson ratio being assumed to be 0.5. So far as the speed of compression is faster than about 0.2 mm/sec, the bentonite gel showed an elastic deformation for the strain below about 10% and the slip fracture appeared at a critical stress and/or strain. As the bentonite gel is viscoelastic, it shows the plastic deformation or viscous flow in the observation of a longer duration or a slower compression.

(2) **Cone and plate method.** The bentonite gel was placed between the cone and plate, and the cone was rotated by torques caused by various loads through a pulley Fig. 6. The viscoelastic behavior was observed by the deflection of the mirror attached to the axis of rotation of the cone. As shown in Fig. 7, the deflection of the mirror was recorded by a photoelectric tracer and the slip of the cone was observed at a critical stress (F dyne/cm^2); this critical stress was determined at various concentration. The shear moduli of gels could be obtained from the instantaneous deformations on loading or unloading.

(3) **Shearing test box method.** A two-surface shearing test box used for
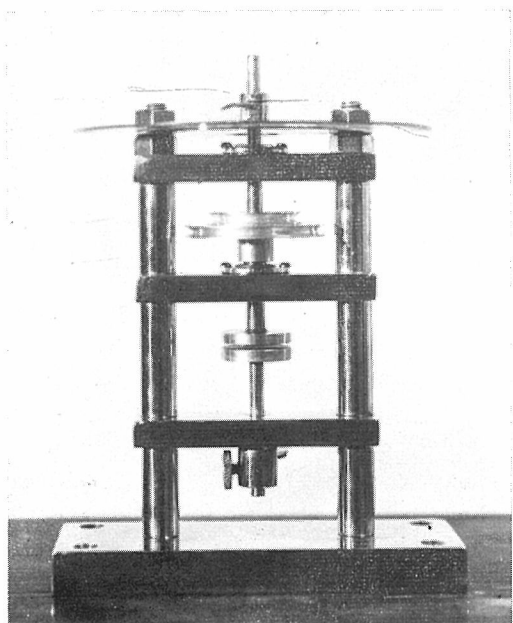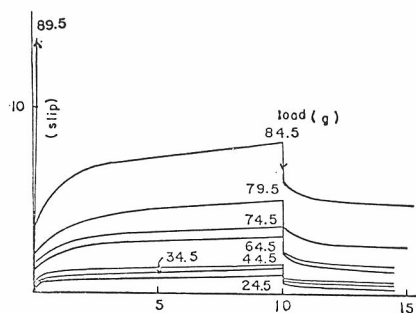

Fig. 7. Viscoelastic behavior and slip of bentonite gel (cone and plate method).

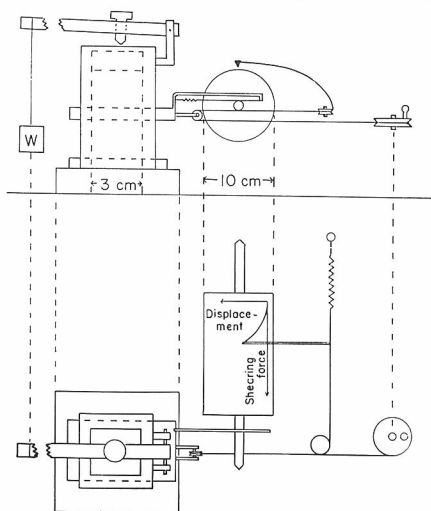Fig. 6. Cone and plate viscometer.

Fig. 8. Shearing test box and recording apparatus.

measuring the shear strengths (S dyne/cm²) under various virtical pressures (Fig. 8). It was confirmed that the shear strength was independent of the vertical pressure as the case of an ordinary clay, but depended upon the concentration of the gel.

RESULTS AND DISCUSSION

1. Dependence of the Elasticity of the Gel on the Concentration

Curve I of Fig. 9 shows the relation between the shear modulus and the concentration of bentonite gels. The experimental fact that the shear moduli (G or $E/3$) obtained by two different methods lie on the same line suggests that Poission's ratio of the gel is nearly equal to 0.5. Curve I consists of three parts having different slopes. This is the general feature of polymer gels as asserted by Hirai[3], who ascribed it to the network structure of polymer gels.
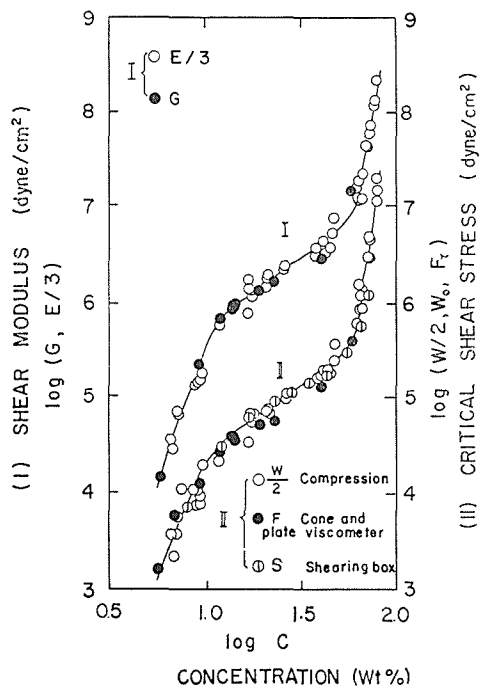
Fig. 9. Relation among shear modulus critical shear stress and concentration.

Gel may reasonably be defined as a state of colloidal dispersions which shows an elastic behavior. Naturally this property leads to the concept of the framework structure of gels. According to the light-scattering, birefringence and viscoelastic studies by M'Ewen[5,5] *et al.*, hydrated bentonite leaflet particles are aligned edge-to-edge in the form of flat ribbons at low concentrations, and make a three dimensional network structure based on a system of cross-linked ribbons at higher concentrations. van Olphen[6] proposed a card-house structure for clay gels which is idealized as an edge-to-face associated cubic network of clay parti-

cles. In short, the bentonite gel has a network structure similar to that of polymers, although the bentonite itself consists of leaflet particles.

2. Dependence of the Shear Strength on the Concentration

The relation between the shear strength and the concentration is shown by Curve II in Fig. 4. Almost all values of the shear strength ($W/2$, F, S) obtained by the three methods lie on the same line over almost whole range of concentration examined. Moreover, Curve II shows a similar trend to Curve I with respect to concentration suggesting that there holds a relation of proportionality between shear strengths and shear moduli. Fig. 10 shows this relationship. It is found that the values of the shear strength fall in general within the range between $G/10$ and $G/30$.
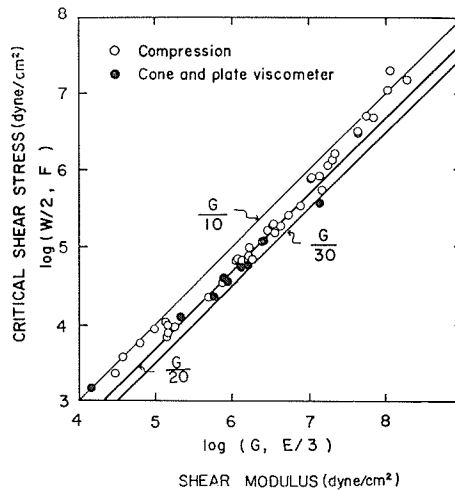

Fig. 10 Relation between critical shear stress and shear modulus.

3. Structure of Gels and Shear Strength

It is well known that the hydrogel of bentonite has thixotropic property and apparent viscosity varies with the rate of shear. Further, the gels yield or creep under very low rate of shear as shown in Fig. 2. These facts suggest that the force of linking between bentonite particles is relatively weak. Thus, it is expected that the framework of the gels is very brittle.

Now, the experimental results in Fig. 5 shows that the shear strength of the gels takes values ranging from $G/10$ to $G/30$. These values agree fairly well with the theoretical one predicted by Mackenzie[7] for the shear strength of ideal crystals. Bragg and Lomer[8] demonstrated that the observed shear strength of a perfect two-dimensional crystal of bubbles agrees with the theoretical value, $G/30$. Futher, Buchdahl[9] pointed out that the ratio of the modulus of elasticity and the yield or beaking strength for a variety of amophous polymers in the glassy state has the smae order of magnitide as the theoretical value. Fig. 11 is the log-log plotting of the strength against the modulus of eleaticity, E or G, the values being taken from the Table of Buchdahl's paper.
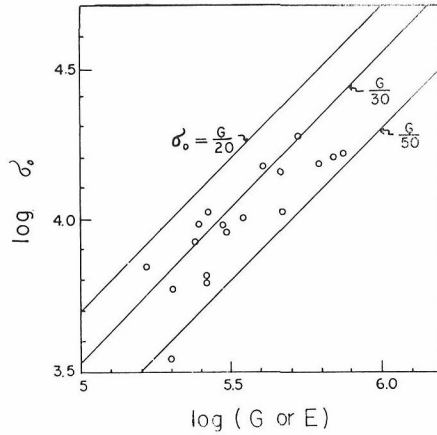
Fig. 11. Relation between shear strength and shear modulus of polymers.

It is concluded from these facts that the relationship between the shear strength and the shear modulus predicted by Mackenzie generally appears to hold for brittle and relatively soft materials, although it may not always be explained by assuming a slip between atomistic layers as proposed by Mackenzie for an ideal crystal.

In order words, the experimental facts shown by Bragg and Lomer, Buchahl and ourselves may be interpreted simply as the brittle fracture at a certain critical stress (σ_0) and/or a critical strain (γ_0). Accordingly, from Fook's law we have

$$\sigma_0 = G\gamma_0$$

where γ_0 takes values ranging from 1/10 to 1/30 in the present experiments.

Furthermore, an instantaneous change in birefringence was detected for the bentonite gel when sheared between two transparent glass plates as shown in Fig. 12. This fact indicates that the bentonite leaflets are oriented on shearing.

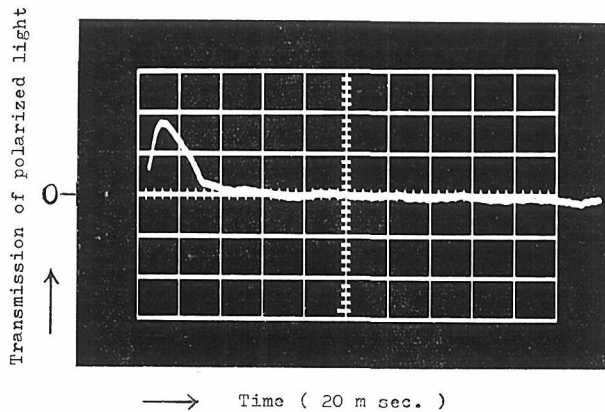Finally, the following mechanism is proposed for the slip facture of the

Fig. 12. Birefringence of bentonite gel on shearing.

bentonite gel : under a critical shear stress, the card-house of the bentonite gel falls down one upon another starting from some point of stress concentration, and leaflets of the gel are oriented in the direction of the maximum shear, when the slipping occurs.

ACKNOWLEDGMENTS

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