SHEAR STRENGTH OF MONTMORILLONITE AND KAOLINITE RELATED TO INTERPARTICLE FORCES

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ABSTRACT

Shear strength of saturated, remolded clay mineral samples was measured in an attempt to relate strength to forces acting between clay particles. The fine fractions of the clays, purified when necessary, were consolidated to different void ratios and subjected to quick, translatory shear in a direct shear device. Relative values for shear strength were obtained in this way. Interparticle forces in the clays were altered and the effect on shear strength was observed.

For a high-swelling, Na-saturated montmorillonite, strength at constant void ratio decreased with increasing salt concentration. To explain the decrease in strength with decrease in force of repulsion between particles a model is suggested where strength results from the force of repulsion resisting displacement of particles in the shear plane. Addition of small amounts of dispersing and of soil-conditioning chemicals had little effect on shear strength.

Calcium montmorillonite had a lower strength than sodium montmorillonite when compared at the same void ratios. This is related to the lower surface area of interaction and lower repulsion found with divalent ions.

Water content at the liquid limit showed the same dependence upon interparticle forces in the montmorillonite clays as did shear strength.

In kaolinite, interparticle forces of attraction result in a structure or particle arrangement which has the major influence on shear strength. A clay at low pH which was flocculated in a network, edge-to-face structure owing to presence of positive edge-charge had higher strength than a dispersed clay, but a clay flocculated by electrolyte which produced a lamellar, face-to-face structure had a lower strength.

INTRODUCTION

Shear strength of clays usually has been analyzed on the basis of the principles of mechanics that were found useful for cohesionless granular soils. Recently interest has grown in the physico-chemical particle interaction that gives rise to these observed mechanical properties (Lambe, 1958;

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Rosenqvist, 1959). Shear strength is considered to result from the difference between the interparticle forces of attraction and repulsion, with interparticle attraction due mainly to van der Waals forces, and repulsion to the charge on the clay mineral surface. This study is an attempt to test this concept experimentally and to relate measured shear strength of two well-defined clays to the interparticle forces of attraction and repulsion and the resulting particle arrangement.

Relative values of shear strength have been measured for samples of remolded clays treated in various ways to alter the interparticle forces. Differences in measured strength have then been related to differences in these forces. The natural structure of clays, in which other forces would contribute to shear strength, is not present in these samples.

ACKNOWLEDGMENTS

EXPERIMENTAL PROCEDURES

Clays

Two lots each of kaolinite and montmorillonite were used. Montmorillonite I was the $< 0.2\ \mu$ fraction separated from Volclay Wyoming bentonite, obtained through the courtesy of the American Colloid Co. This bentonite sample contained carbonate which had to be removed to achieve good dispersion. The clay in 5 percent suspension was acidified to 1 N with HCl, allowed to react for 10 min, separated from the supernatant liquid by centrifuging, and neutralized with NaOH. The clay was washed with NaCl and finally with water until it began to disperse. It was then made to 2 percent suspension and the coarse fraction allowed to settle out. A Ca-saturated clay was obtained by percolating this suspension through a resin exchange column. Salt concentration in the pore water was further reduced to $< 10^{-3}$ M by pressure filtration.

Montmorillonite II was the $< 0.2\ \mu$ fraction obtained from a Black Hills Western bentonite sample after allowing the coarse fraction to settle out. This was converted to homoionic Na-clay by passing it through an exchange resin, and freed from salt by pressure filtration.

Kaolinites I and II were two lots of Peerless no. 2 kaolin obtained at different dates through the courtesy of the R. T. Vanderbilt Co. A 7 percent clay suspension was adjusted to pH 9 with NaOH, where the clay remained dispersed. The $< 2\ \mu$ fraction was siphoned off. This was the dispersed sample. The flocculated sample was prepared by acidifying the dispersed

sample to pH 4, where it flocculated immediately. Free salt was reduced to $< 10^{-3}$ M in all samples by pressure filtration.

Shearing Methods

The clays were made up to a water content above the liquid limit, introduced into consolidation rings with porous stones at each end, and consolidated by the standard engineering procedure of static loading.

Two direct shear methods were used. In the first, $2\frac{1}{2}$ in. diameter samples were pushed from the consolidating rings into the chamber of a direct shear machine and subjected to quick, translatory shear. The results will be referred to as "standard shear" values. Later a special device was made in which $1\frac{1}{4}$ in. diameter samples were consolidated and sheared in the same
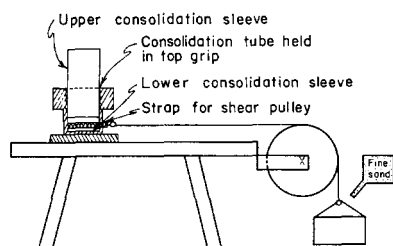

FIGURE 1.—Schematic diagram of cylinder consolidation–shear device where lower cylinder is sheared relative to the upper.

ring without sample transfer. This device consisted of an upper consolidation cylinder resting on a shear cylinder, both held in place during consolidation by restraining sleeves. After consolidation the restraining sleeves were removed and the lower cylinder sheared relative to the upper in the pulley system shown in Fig. 1. These results will be designated as "cylinder shear" values.

Water content of the clay at the failure plane was determined and void ratios were calculated using a particle density of 2.5 g/cm³. Strength values are compared only within one method of shear since the special cylinder gave a higher shear strength value than the standard shear. These strength values are considered as only relative values because of the limitations of the testing procedure.

Liquid Limit

The water content at the liquid limit was determined as the 25 blow point on a line drawn through three measured points in the range from 10 to 40 blows on a plot of water content vs. logarithm of the number of blows (Lambe, 1951, pp. 22–28).

RESULTS AND DISCUSSION

Montmorillonite

Studies with montmorillonite saturated with monovalent ions have shown that some physical properties of this clay, such as swelling in water, can be predicted from diffuse ion-layer theory alone (Warkentin, Bolt and Miller, 1957). The presence of diffuse ion-layers around the particles leads to inter-particle repulsion due to osmotic activity of the ions. This force of repulsion is decreased with increasing distance between clay particles, with increasing electrolyte concentration, and with increasing valence of the exchangeable ion. This repulsion alone does not describe properties of montmorillonite saturated with divalent ions. A Ca-saturated montmorillonite paste con-
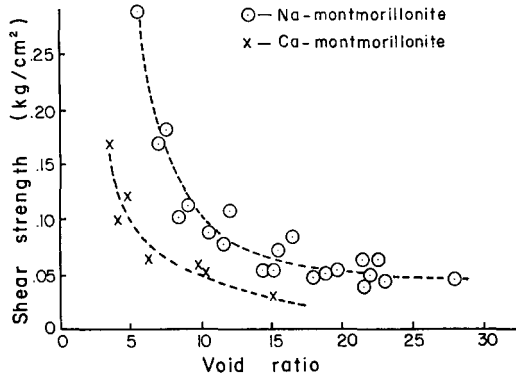

FIGURE 2.—Measured shear strength of Na- and Ca-montmorillonite.

sists of packets of particles having interparticle distances of 9 Å. If a diffuse ion-layer is present, it will be on the outside of these packets (Aylmore and Quirk, 1959; Blackmore and Warkentin, 1960) and the clay will have the properties of one with a much lower surface area. As a result, particle inter-action is confined to smaller volumes. The arrangement of the packets also influences the properties.

Shear strength of montmorillonite saturated with calcium or with sodium at different salt concentrations in the pore water was measured by the standard shear method. Measured strength at different void ratios is shown in Fig. 2 for Na- and Ca-saturated montmorillonite I with no added electrolyte. Strength decreased with increasing void ratio and was lower for the calcium than for the sodium clay. Fig. 3 shows the influence of electrolyte concentration on strength of Na-montmorillonite I. Strength at 10^{-2} M NaCl in the pore water was about the same as that with no added electrolyte, but strength at 1 M was lower.

Water content at the liquid limit for the clays is shown in Fig. 4. These results show the same features as the shear strength; the effect of salt concentration on the sodium clay is clearly shown. For the calcium clay there was little influence of salt concentration. This has been found in studies of other properties of the calcium clay, and it leads to the prediction that shear strength will not be influenced by salt concentration.

The shear strength results for montmorillonite pastes can not be explained by considering strength as the net result of forces of attraction
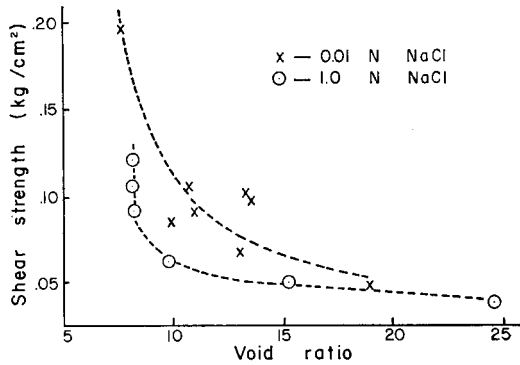
FIGURE 3.—Measured shear strength of Na-montmorillonite at different pore water salt concentrations.
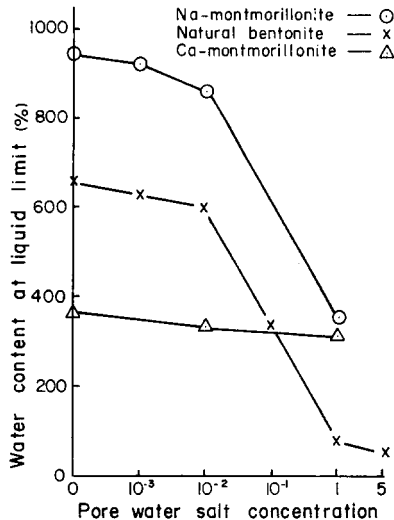
FIGURE 4.—Measured water content at the liquid limit for montmorillonite clays at different pore water salt concentrations. NaCl was added to the natural bentonite and to the Na-montmorillonite and $CaCl_2$ to the Ca-montmorillonite.

minus forces of repulsion. Increasing the salt concentration and the valence of the exchangeable ions decreases interparticle repulsion, and either increases or leaves unchanged the force of attraction. An increased shear strength would be expected on this basis, but the measured strength decreases. The electrostatic force of attraction of positive edge to negative surface also increases as the salt concentration increases, so this can not explain the results. Strength apparently is related to interparticle repulsion.

Interparticle repulsion controls the interparticle spacing or void ratio under any applied load. The particle interaction which determines shear strength at any void ratio can not be specified from these measurements;
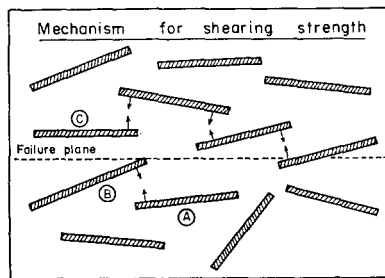

FIGURE 5.—Schematic diagram of interacting clay particles with interparticle repulsion resisting particle rearrangement during development of failure plane.

but if it is due to attraction it requires an interparticle attraction which is higher at higher values of interparticle repulsion. Since the net force as shown by swelling pressure measurements is an interparticle repulsion, can strength arise from a repulsion between particles?

A decrease in strength with decrease in interparticle repulsion can be explained by a model in which strength arises from the force required to readjust particles to form a failure plane. This readjustment is resisted by interparticle repulsion as shown schematically for a few particles in Fig. 5. Any decrease in interparticle repulsion allows an easier particle readjustment and results in a decrease in shear strength at constant void ratio.

No quantitative relationship of shear strength to interparticle repulsion has been obtained. When strength is compared with net force of repulsion as estimated from swelling or rebound curves, the ratio of strength to net repulsion decreases with decreasing void ratio. For the Na-montmorillonite this ratio decreases from 0.5 at a void ratio of 15 to 0.07 at 7. On compression to lower void ratios the particles are forced into more parallel orientation, and less particle movement is required to form a failure plane even though the force of repulsion is greater. The decrease in strength with increasing salt concentration also is not simply related to the decrease in

force of repulsion. At high salt concentration and high void ratio the Na-montmorillonite can form a flocculated structure, and these units rather than individual particles interact, resulting in a higher shear strength.

The influence of dispersing and aggregating chemicals on the strength of Na-montmorillonite II was investigated by the cylinder shear method. The dispersing agent sodium metaphosphate, added as Calgon, was used at 0.5 percent by weight. The soil-conditioning chemical Krilium, a polymer of acrylic nitrile, was used at 0.7 and 2 percent by weight. The samples were not dried following the addition of these chemicals. Krilium did appear to alter the consolidation properties of the clay, but within the large variability between samples in these measurements no influence of either Krilium or Calgon on strength was measured.

Kaolinite

Kaolinite clays have properties that differ at least in degree from those of montmorillonite. They have a low void ratio and exhibit little swelling. Any physico-chemical interparticle forces are smaller because of the low surface area. Kaolinite properties can often be described by reference to physical factors such as size and shape of particles and particle arrangement. However, particle arrangement in remolded samples can be controlled by interparticle forces; the distinction is made between flocculation at high salt concentration which decreases interparticle repulsion allowing face-to-face interparticle attraction, and flocculation due to development of positive edge-charge at low pH resulting in edge-to-face attraction (Schofield and Samson, 1955). By influencing particle arrangement, interparticle forces could influence shear strength.

Shear strength of the fine fraction of kaolinite I was measured by the standard shear method for a dispersed sample at pH 8–9 and for a flocculated sample at pH 4 where edge-to-face flocculation due to positive edge-charge is expected. The samples were both at low pore water salt concentration, although the dispersed sample would be Na-saturated while the flocculated sample would be largely H- and Al-saturated. The results in Fig. 6 show that the flocculated samples had a higher strength at the void ratios investigated. This is in contrast with the montmorillonite where the dispersed samples with the highest interparticle repulsion had the highest strength. For kaolinite, forces of attraction and the resulting particle arrangement increased strength. Both fine fractions had a greater strength than the dispersed coarse fraction, indicating that forces associated with the greater surface area are present in the kaolinite.

Kaolinite flocculated at low pH owing to positive edge-charge can also be dispersed with small amounts of montmorillonite. The smaller montmorillonite particles are attracted to the edges of the larger kaolinite

particles, neutralizing the positive charge and preventing association of the kaolinite particles (Schofield and Samson, 1955). On this basis small additions of montmorillonite should decrease the strength of flocculated kaolinite. It was found with the fine fraction of low pH-flocculated kaolinite II that 1 percent by weight of Na-montmorillonite II decreased the strength measured by the cylinder shear method by about 10 percent. Strength with 2.5 percent montmorillonite was greater, and with 5 percent still
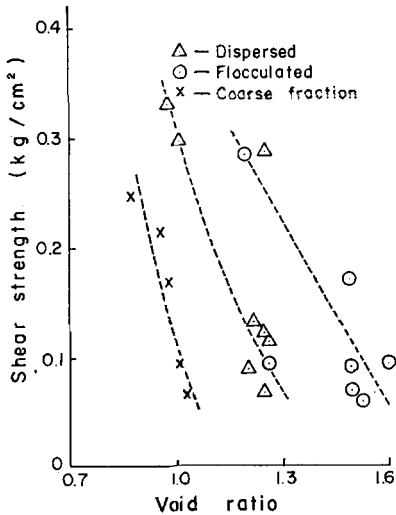

FIGURE 6.—Measured shear strength of flocculated and dispersed kaolinite and of the coarse fraction.
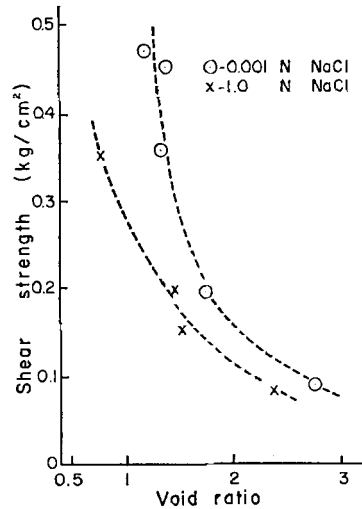
FIGURE 7.—Measured shear strength of dispersed kaolinite at different pore water salt concentrations.

greater, than strength of the flocculated kaolinite at the same void ratio. The higher concentrations of montmorillonite increased strength owing to the properties of the montmorillonite itself, rather than to any further interaction.

There was a decrease in strength of both the dispersed and low pH-flocculated samples of kaolinite II with increasing salt concentration in the pore water. Fig. 7 shows the results for the dispersed sample measured by the cylinder shear method. Similar differences were measured for the flocculated sample. The higher salt concentration resulted in a face-to-face flocculated structure with a lower void ratio and with interparticle forces acting over shorter distances.

Strength of kaolinite can be related to the volume of interaction of particles or units of particles. This volume decreases for the series: edge-to-face flocculated, dispersed, face-to-face flocculated for the samples and

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methods of preparation used. The interaction volume will be influenced by both the average interparticle spacing and the interparticle force range. The difference between low pH-flocculated and dispersed samples may be in the smaller interparticle distance of the latter, while the difference between the dispersed and the salt-flocculated sample may be due to lower values for both interparticle spacing and interparticle force range for the latter. Further work is required to determine whether the interaction between particles or units of particles resulting in shear strength is repulsion as suggested above for the Na-montmorillonite, attraction between units due to unspecified forces, or mechanical interaction between units in the shear plane.

CONCLUSIONS

Differences in interparticle forces in the clay–water–ion system were reflected in differences in shear strength. Interparticle forces may influence strength directly, as in Na-montmorillonite where strength appears to depend upon interparticle repulsion due to osmotic activity of the diffuse ion-layers, or indirectly as for Ca-montmorillonite and kaolinite where forces of attraction and repulsion lead to a structure or particle arrangement that influences strength. The shear strength parameters then have a different meaning in different clays, but they can be related to interparticle forces.

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