

CHAPTER 50
EFFECT OF CLAY CONTENT ON STRENGTH OF SOILS

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(Supported by a contract with Office of Ordnance Research
Ordnance Corps, U. S. Dept. of Army)

ABSTRACT

Engineers have worked greatly on measuring the strength of soils but relatively little on the fundamental geologic causes of strength. Strength depends principally upon the content of (1) water, (2) clastic materials and (3) plastic materials. Soils are primarily of two types (1) cohesionless soils in which the strength is produced mainly by the friction of clastic particles against one another, and (2) cohesive soils in which the strength, among other things, is influenced by forces between clay particles. The present investigation is a study of the effect of clay content upon the strength of cohesive soils. The strength was measured by a shear vane device working upon synthetic mixtures of clays of known composition. In each mixture strength varies inversely with water content in a straight line relationship when strength is plotted logarithmically and water arithmetically. Mixtures of glycerine with vol-clay (a montmorillonite) give a curvilinear relationship. For given water content the strength increases with respect to type of clay from kaolin through illite, ball clay to montmorillonite. Strength also increases progressively with increasing clay-sand ratio for all types of clay. In clay-sand mixtures of given clay composition strength increases with increasing fineness of grain of the sand mixed with clay. The liquid limit likewise increases regularly with increasing clay concentration and varies with clay type in the same way as does strength. Strength varies inversely with temperature to a slight extent, changing less than one percent per degree Centigrade. Hydrogen kaolin clay, for given water content is several times stronger than sodium clay.

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INTRODUCTION

The Office of Ordnance Research of the Department of the Army, through a contract with the Institute of Engineering Research of the University of California at Berkeley, has been supporting an investigation of the fundamental geologic causes of strength in soils. Engineers are primarily interested in determining quantitatively the strength of soils, rather than the basic factors that impart strength. The purpose of this investigation is to study the effects of some of the basic factors influencing strength of soils. Strength is caused principally by three factors (1) water, (2) clastic particles, and (3) plastic particles. Soils and sediments are of two types with respect to strength: (1) cohesionless soils, composed mainly of clastic particles and (2) cohesive soils, which contain substantial quantities of plastic particles and varying quantities of clastic particles. In the cohesive soils composed of clastic particles, that is, broken or transported particles of sand or silt size, the strength is caused primarily by the friction of the particles against one another and water is of relatively little effect. In the cohesive soils the strength is influenced by forces of attraction between particles of clay size. It is convenient to think of such particles as plastic particles because they impart plasticity and cohesiveness to soils. If clastic particles are present in cohesive soils they modify the strength. As the causes of strength in cohesive soils are less well understood than the causes of strength in cohesionless soils, the present investigation has been devoted primarily to the causes of strength in cohesive soils, and in particular to the effect of clay content upon strength. The variables that have been studied are (1) clay type, (2) clay-sand proportion, (3) grain-size of the clastic particles mixed with the clay, (4) base exchange effects, (5) temperature, (6) thixotropic effects, and (7) glycerine content in glycerine-clay mixtures. Numerous other variables affect the strength of soils but these are not considered in the present investigation.

METHODS OF ATTACK

MATERIALS STUDIED

The method of approach has been to use clays of essentially pure composition and sands of differing grain-size. The clays that have been used are (1) Edgar China clay from Georgia, which is nearly pure kaolin about midway in composition between a hydrogen sodium clay (Fig. 11); (2) Illinois grundite, which consists of about 80 percent illite and 20 percent of clastic material, which X-ray and Differential Thermal Analysis curves indicate to be mainly quartz;

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(3) Kentucky Old Mine No. 4 Ball clay, a mixture of about 85 percent kaolin and 15 percent silica with an unknown content of organic matter, called Ball clay No. 1 in this report, (4) Kentucky Mine Special, a ball clay estimated to contain 80 percent kaolin and the remainder quartz, called Ball clay No. 2, (5) Wyoming bentonite, a clay estimated to be 97 percent montmorillonite and 3 percent quartz; and (6) Vol clay, a nearly pure bentonite. The median diameter of the clays range mainly between 1 and 2 microns, though precise figures for illite and montmorillonite are not available.

Each of the six types was first tested in the pure condition without the addition of sand. Subsequently, varying amounts of sand were mixed with the clay. Ten grades of sand were used. The median (average) grain diameters of these sands are 1680, 945, 725, 350, 180, 136, 80, 55, 16 and 1.2 microns, respectively. Sedimentary parameters of these sands are given in Table 1. The 16 micron sand is known in the trade as Silica No. 2 sand and the 1.2 micron as DMAF sand. These two sands are made commercially by crushing in a ball mill. They have coefficients of sorting ranging between 1.8 and 2.0. The other eight samples are California beach sands, or mixtures of beach sands, whose sorting coefficients range principally between 1.1 and 1.4. Though mixtures of all these sands with the various types of clay were studied, experiments on clay-sand properties generally were made with 16 micron sand. Four concentrations were used, namely, 20, 50, 80 and 100 percent clay. The corresponding sand contents of these mixtures are 80, 50, and 20 and 0 percent sand. For montmorillonite, which is highly plastic even in small proportions, mixtures of 90 percent sand and 10 percent montmorillonite were studied. The other clays do not have sufficient plasticity to make cohesive soils when only 10 percent clay is present. These clays, when mixed in a proportion of 10 percent clay and 90 percent sand exhibit dilatancy, or increasing shear-resistance with increasing stress, and give anomalous results.

The sands cannot be studied in the pure state, because they are too dilatant. The only investigations of pure sand were on artificial mixtures of 135 micron sand with slightly larger and smaller sized sands to give different coefficients of sorting (Fig. 2). The strength of such samples was measured in a conventional direct shear box under a normal load of 6 pounds per square inch.

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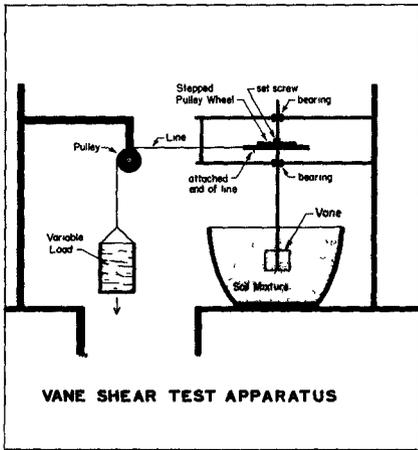


Fig. 1

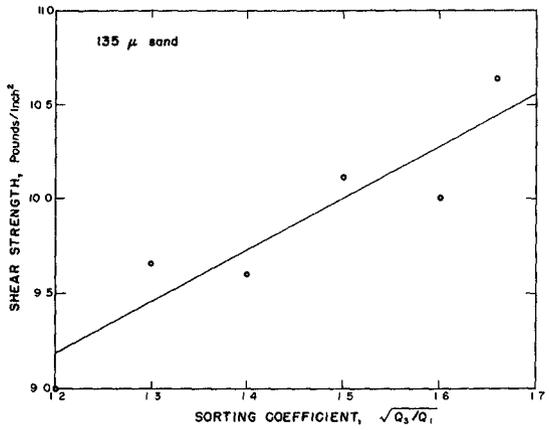


Fig. 2. Effect of sorting on shear strength of sand.

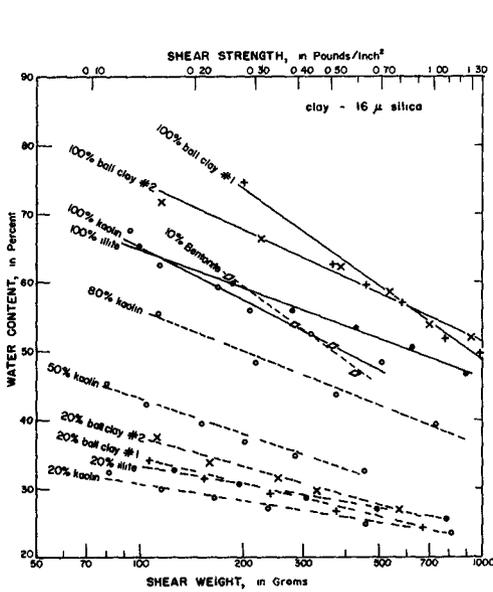


Fig. 3. Relation of clay type and clay concentration to shear strength and water content.

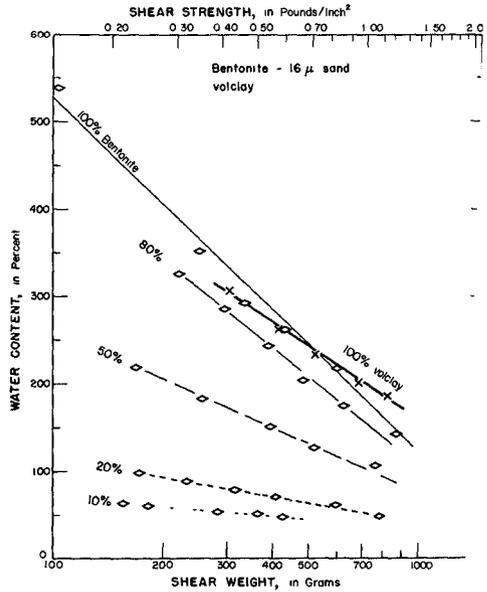


Fig. 4. Relation of Bentonite concentration to shear strength and water content.

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TABLE I

SEDIMENT PARAMETERS OF SAND USED IN STRENGTH STUDIES

M	Q ₁	Q ₃	D ₁₀	D ₉₀	So	Log SK
1.15	0.60	2.18	--	--	1.91	-.002
16.2	7.2	33.8	--	--	2.17	-.008
55	41.5 [?]	73	--	100	1.33 [?]	.001 [?]
80	52	110	37	135	1.45	-.048
136	87	175	42	224	1.42	-.043
180	168	190	150	200	1.06	-.003
350	295	425	250	500	1.20	.005
725	555	890	365	1000	1.27	-.016
945	700	1150	505	1310	1.28	-.023
1680	1460	1870	1050	2220	1.13	-.007

M - Median diameter

Q₁, Q₃ - First and third quartiles

D₁₀, D₉₀ - Ten and ninety percentiles

So--coefficient of sorting = $\sqrt{Q_3/Q_1}$

LogSK - logarithm of skewness to base 10 = $\log\sqrt{Q_1 \cdot Q_3/M^2}$

METHODS OF MEASURING STRENGTH

The strength of the other samples was measured in a mortar bowl about 8 inches in diameter with a shear vane and pulley apparatus shown in Fig. 1. Water is poured in the container at the end of the pulley system until the weight of the water causes the sediment to fail. The results are reported in the illustrations in this paper both in terms of grams of water added and the corresponding shear strength in pounds per square inch computed according to the formula of Capper and Cassie (1953, p. 112). This formula is

$$T = wr = C \pi \left(\frac{D^2 h}{2} + \frac{D^3}{6} \right)$$

where T is the torque, w the weight of water to cause failure of the sediment, r the radius of the pulley wheel, C the shear strength,

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D the diameter of the shear vane and h the height of the vane. In the present investigation the measurements generally were made for quantities of water ranging between 100 and 1000 grams. As the height and diameter of the vane and pulley radius of the torque wheel are the same in all tests, the weight in grams is directly proportional to the strength in pounds per square inch. The factor for converting grams to pounds per square inch is 1.37×10^{-3} . The height of the vane is 0.764 inch, the diameter 1.312 inch, and the radius of the pulley wheel 2.02 inches. The vane has 4 blades of equal size placed at right angles to one another.

In each experiment clay or a clay-sand mixture is mixed with a quantity of water close to the liquid limit of the soil, and the shear strength is measured with torque vane. A sample for determination of water content is taken immediately after the strength is measured. If the sample for water content is not removed immediately, water evaporates from the sediment, which causes anomalous results. After the shear strength is measured, additional material is added to the sample and thoroughly mixed into it. The shear strength is again recorded and the water content measured. More sediment is added until five or six determinations have been made. The results are then plotted on semilogarithmic paper with shear strength plotted logarithmically and the water content arithmetically. The experiments with given types of clays consistently give smooth curves as shown by Figs. 3 and 4. An effort was made to keep the sands saturated. The consistency of the results suggests that the samples were saturated. In preparing the samples, mixtures of desired proportions of clay and sand were made before adding water. In interpreting the effect of water content one should bear in mind that the water is measured according to the practice of engineers, which is the ratio of the weight of the water to the weight of the dried sediment expressed as percent. It is not the percent of water in the sediment as normally used by geologists.

When the investigation was first started water was added in successive increments to the samples, but this procedure proved less practicable than starting with dilute mixtures and increasing the concentration by adding sediment.

The sediments failed at fairly sharp end points. Measurements were made of strain before failure. As a rule the sediments failed before 5 grams had been added after first trace of noticeable movement. Thus the error in measurement is less than 5 percent and for most determinations is less than 3 percent. Satisfactory duplicates were readily obtained.

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LIQUID LIMIT DETERMINATIONS

A number of liquid limit determinations were made. As the liquid limit is a rough measure of strength it was thought desirable to measure the effects of (1) clay type, (2) clay-sand ratio and (3) grain size upon liquid limit (Figs. 9 and 10). The liquid limit was measured in the customary Atterberg hemispherical brass cup in which a pat of soil is molded into the hemisphere and a groove of given dimensions made in the sediment. The liquid limit is the water content at which 25 blows are required to cause the sediment on the two sides of the groove to flow together. Thus it is a rough measure of the strength of a sediment for a given water content. Experiments were made with different water contents for each of the given mixtures to determine the relationship between water content and the number of blows to cause flowage of the sample. Straight line relationships were found when blow count was plotted logarithmically and water content arithmetically (Fig. 9).

BASE EXCHANGE AND OTHER MEASUREMENTS

The effect of base exchange was measured on kaolin clay. In two experiments the clays were converted to hydrogen and to sodium clays by repeated washings with hydrochloric acid and sodium hydroxide solutions respectively until all the bases had been replaced by hydrogen and by sodium. Clay-water mixtures were then made with the hydrogen kaolin and with the sodium kaolin. The results are presented in Fig. 11.

The effect of temperature was also investigated by using water of different temperature to test the strength. Inasmuch as the strength is influenced by the water content, the strength had to be converted to the strength at a given water content in order to make the temperature results comparable. This water content for purposes of computation has been taken as 39 percent. The temperature measurements were made only on 100 percent kaolin.

The sediments tended to increase in strength with time of standing, that is, they showed a slight thixotropic effect. The strength of mixtures of illite with different amounts of water were measured after different intervals of time. As with the temperature studies, it was necessary to correct the strength for water content so that the results could be presented on a comparable basis. A water content of 50 percent was used. As the strength did not change greatly with time, errors due to thixotropic effects are believed to be relatively small.

The Land Locomotion Laboratory of the Ordnance Corps at the Detroit Arsenal has been experimenting with the strength of mixtures of

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glycerine and vol clay - a montmorillonite clay. Glycerine is used because it does not evaporate and gives a constant strength with respect to time, whereas water evaporates causing the strength to increase gradually with time. In order to make the results of the present investigation useful to the people at the Land Locomotion Laboratory, the strength of mixtures of vol clay with glycerine and with water has been determined with the shear vane devices illustrated in Fig. 1. The results are presented in Fig. 12.

RESULTS

COHESIONLESS SOILS

The results of this investigation are presented in two parts (1) cohesionless and (2) cohesive soils. Cohesionless soils tested with the shear vane device gave anomalous results owing to the effect of dilatancy, and after preliminary experimentation were not studied further. The effect of sorting upon shear strength was tested on a conventional direct shear device under 6 pounds per square inch normal load. The results as shown in Fig. 2 indicate that the shear strength increases with increasing poorness of sorting. All tests were made with artificially mixed sands of 135 microns median diameter. The shear strength increased regularly from 9.2 pounds per square inch for sediments having a coefficient of sorting of 1.2 to 10.6 pounds per square inch for a coefficient of sorting of 1.7. The data are not particularly consistent but they exhibit a general trend.

COHESIVE SOILS

Effect of clay type - The results of the studies of cohesive soils are shown in Figs. 3 to 12. In Figs. 3 and 4 the shear strength is plotted logarithmically and the water content arithmetically for mixtures of different clays with 16 micron sand. In these two figures the shear strength varies inversely with the water content. Samples of pure illite and kaolin have essentially the same shear strength, but kaolin shows a steeper relationship between water and shear strength than does illite. The two ball clays for given water content are slightly stronger than kaolin and illite. Wyoming bentonite is very much stronger. A sample of Wyoming bentonite with 500 percent water has essentially the same shear strength as a kaolin clay with 70 percent water. The vol clay shown in Fig. 12 has approximately the same shear strength with respect to water as the Wyoming bentonite as is indicated by Fig. 4. The differences in strength between kaolin, illite and ball clays is not great, whereas the difference between these

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clays and montmorillonite is large. Mixtures of 10 percent bentonite and 90 percent sand have about the same strength as pure clays of other types. Mixtures of 20 percent bentonite and sand are stronger than any of the other pure clays. To avoid crowding on Fig. 3, mixtures of 50 and 80 percent clay with sand are not shown for illite and the two ball clays. The strength data however were determined for these clays. They are similar to the data shown for kaolin of comparable sand content.

Effect of clay sand concentration - When water content is plotted arithmetically and shear strength logarithmically, an inverse straight-line relationship results (Figs. 3 and 4). The slope of this straight-line can be expressed mathematically:

$$M = \frac{\delta W}{\delta(\ln S)} = S \frac{\delta W}{\delta S}$$

where M is the slope of the line and is a dimensionless constant, W is water content in percent, and S is shear strength. When the clay content of a sand-clay mixture decreases the slope becomes progressively less, in a more or less regular fashion. On plotting these slopes M, against the corresponding clay content, C, a direct proportionality results, as illustrated by Table 2. The slope of this line, $\delta M/\delta C$ is a constant, and is characteristic of the clay type, at least in the water content range investigated. Viewed practically, M is a measure of the sensitivity of soil strength with respect to changes in water content and $\delta M/\delta C$ constitutes a measure of the change of this sensitivity as clay content is varied. The following table lists M and $\delta M/\delta C$ values for the clays investigated, in mixtures with 16 micron sand.

TABLE 2
RELATIONSHIP OF SLOPE OF WATER CONTENT -
SHEAR STRENGTH CURVES TO CLAY TYPES

Clay type	M values at different clay contents					$\frac{\delta M}{\delta C}$
	Percent clay					
	100	80	59	20	10	
Wyo Bentonite	-167	-145	-80	-32	-14	-1.700
Edgar ASP (kaolinite)	-11.5	-9.5	-5.8	-2.9	-	-0.118
Ky. Ball #1	-14.5	-	-8.9	-5.2	-	-0.116
Ky. Ball #2	-11.2	-	-7.5	-5.8	-	-0.068
Grundite (Illite)	-7.8	-7.4	-5.9	-4.0	-	-0.049

M = slope of water content-shear strength relationship.

$\frac{\delta M}{\delta C}$ = change in slope, M with respect to changing clay concentration C

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Effect of grain size - The relationship of grain size of sand in kaolin-sand mixtures is shown in Figs. 5 and 6. In Fig. 5 mixtures of different sands in proportions of 20 percent sand to 80 percent clay are shown. The sands range in median diameter from 1.2 to 350 microns. It is clear that for given water content the strength increases progressively as the grain size decreases. Sands with diameters ranging between 55 and 350 microns have relatively little effect upon strength but the finer sands show distinctive differences in strength effects. The slope of the water content-shear strength relationship for each mixture essentially constant. The shear strength of the 1.2 micron sand mixture is considerably greater than for the other sands.

Clay-sand mixtures of 20 percent kaolin and 80 percent sand for these same sand sizes were also studied. The 1.2 micron size could not be used owing to effects of dilatancy. Sands of 725, 945 and 1680 microns were also studied in this latter series of tests. The results are shown in Fig. 6. The relationship of shear strength to grain size for water contents of 17, 18 and 19 percent is indicated in this figure. Data for the 16 micron size are extrapolated from the slope of the water content-shear strength curve. In these tests, the lowest concentration of water used with the 16 micron sample is 23 percent. The data show that for grain sizes above 200 microns, the size has relatively little effect on shear strength but as the size decreases to 16 microns the shear strength increases progressively with increasing fineness of grain.

The sands used in this series of experiments have coefficients of sorting ranging from 1.06 for the 180 micron sand to 2.17 for the 16 micron sand (Table 1). Most of the sands of sand size had coefficients of sorting under 1.4, whereas the sands (clastic particles) of silt and clay size (16 and 1.2 microns) had coefficients of around 2.0, and thus were less well sorted. Hence though Fig. 6 purports to show the effect of median grain size on shear strength, it should be realized that each sand, because of the variation in size of constituent about the median as represented by the coefficient of sorting, contains significant quantities of constituents finer than the median. Hence these fine constituents may have a significant effect on strength. However, since Figure 6 shows increasing strength with increasing fineness of median diameter it would follow that the content of constituents finer than the median would increase more or less proportionally with increasing fineness of median diameter. Thus the graphs suggest that increasing content of fine particles increases strength.

This relationship is shown in another way by comparing Figs. 5 and 6. Extrapolation of the strength data in Fig. 5 to a water content 17 to 19 percent underwater materially greater shear strength for the water content in the 80 percent clay-20 percent sand mixture than in percent clay-80 percent sand mixture shown in Fig. 6. The content of

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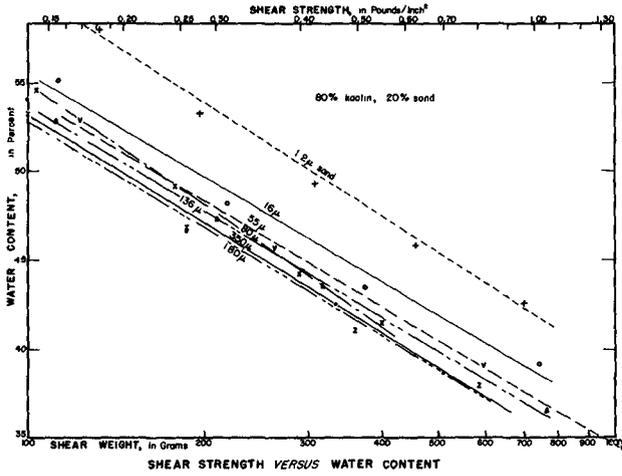


Fig. 5. Relation of median diameter of sand component to shear strength and water content.

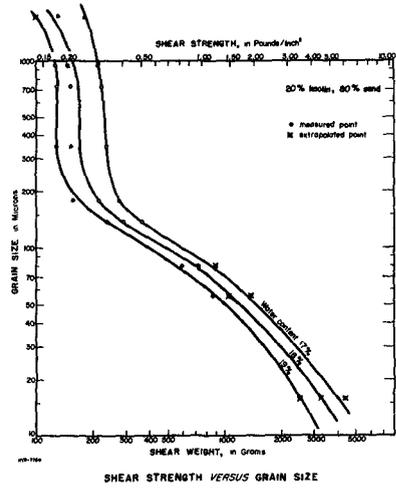


Fig. 6. Relation of water content to shear strength and median diameter of sand component.

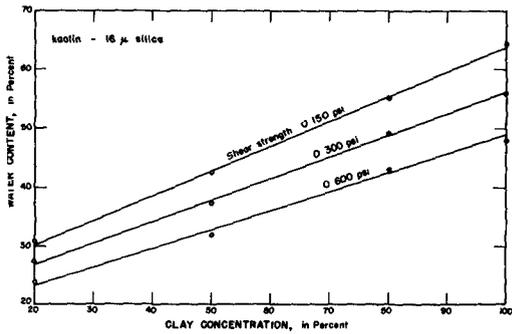


Fig. 7. Relation of shear strength to clay concentration and water content.

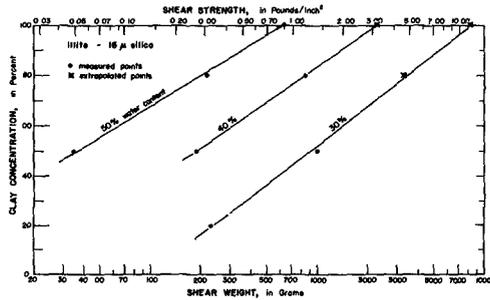


Fig. 8. Relation of water content to shear strength and clay concentration.

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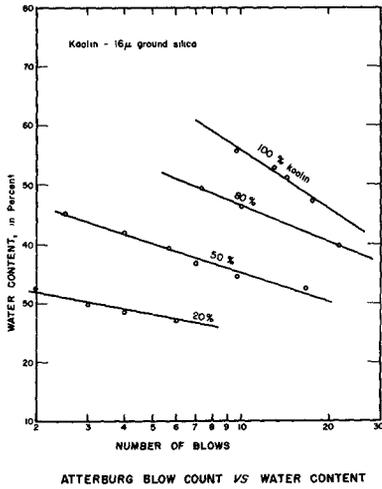


Fig. 9. Relation of clay concentration to Atterberg blow count and water content.

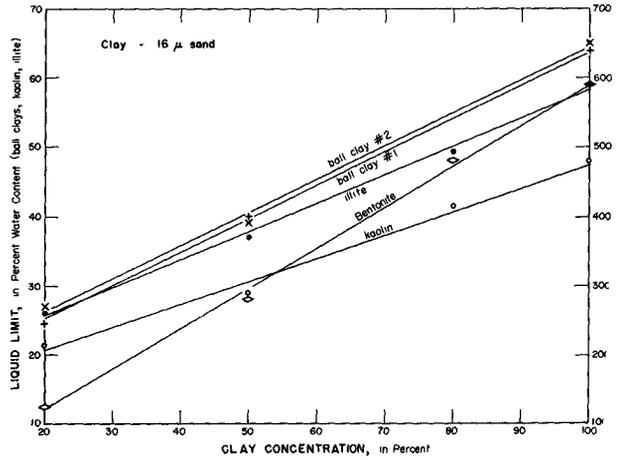


Fig. 10. Relation of clay type to clay concentration and liquid limit.

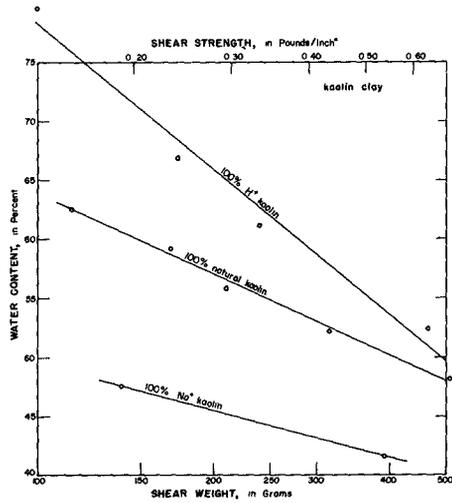


Fig. 11. Relation of exchangeable ion to shear strength and water content.

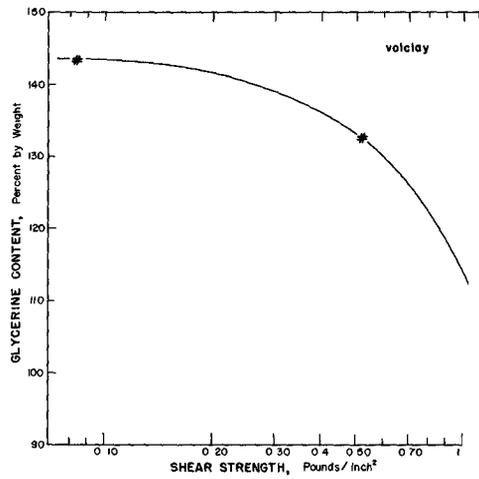


Fig. 12. Effect of glycerine content on shear strength.

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of fine particles is much greater in an 80 percent clay mixture than in a 20 percent clay mixture, since the average diameter of the clay particles is 1.2 microns compared with 16 microns or more in the sand fraction. The effect of course cannot be due entirely to grain size because a mixture of sand of 1.2 microns median diameter with bentonite in the proportion of 90 percent 1.2 micron sand and 10 percent bentonite has a shear strength of only 0.5 pound per square inch for a water content of 75 percent compared with a water content of 300 percent for 100 percent bentonite with the same shear strength of 0.5 pound per square inch. Thus as shown in Figs. 3 and 4, increasing content of clay increases the shear strength even for mixtures of sand of clay size as represented by the 1.2 micron sand. This greater strength for clay could be ascribed to the plastic nature of the clay compared with the clastic character of the sand. The effect of water content upon strength is shown in a different way in Figs. 7 and 8. Figure 7 shows relationships between water content and clay-sand concentration for mixtures of kaolin and 16 micron sand for constant shear strength. The water content increases in a regular manner as the clay concentration increases for each of the three shear strengths shown. Fig. 8 indicates how shear strength increases with increasing concentration of clay for three mixtures of constant water content in mixtures of 16 micron sand with illite. It is perfectly obvious from Figs. 7 and 8 that shear strength increases with concentration of clay in clay-sand mixtures.

Effect of clay content upon liquid limit - The liquid limit is a rough measure of the strength of clays. It represents the water content of a clay at the consistency at which 25 blows in the Atterberg testing device causes the clay to flow together in a groove of standard width. The liquid limit is thus a measure of the lower boundary of the plastic state of the soil. The plastic limit is a measure of the water content of the upper limit of the plastic state of the soils, and represents the water content at which thin threads of the clay begin to break when folded. In the present investigation only the liquid limit was investigated. The liquid limit of the several soils tested in the present investigation was determined by the standard means of measuring the water content. In making the test one mixes the soil in varying water concentrations and determines the blow count to cause closure of the groove. These blow counts plot on a straight line as shown in Fig. 9 which gives data for mixtures of kaolin and 16 micron silica. The liquid limit is taken where the 25 blow count ordinate intersects the water content-blow count curve. Fig. 9 shows that these water content-blow count curves plot as straight lines on semilogarithmic paper and that the water content for any given blow count increases progressively with increasing concentration of clay. The slopes of the curve likewise progressively steepen with increasing concentration of

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of clay, just as the slope of the water content-shear strength curves increase in the shear vane experiments illustrated in Figs. 3 and 4. As the strength varies directly with the number of blows required to cause flowage, this graph indicates increasing strength with increasing clay concentration.

The effect of clay concentration on the liquid limit of the clay type is shown in Fig. 10. Here the water content at 25 blows is plotted against the clay concentration for the different clays. The liquid limit increases with increasing clay concentration in a regular manner, and the liquid limits vary in the same manner with respect to clay type as do the water content-shear strength relationships shown in Figs. 3 and 4.

The effect of grain size upon the liquid limit and blow count was studied for one clay, the Wyoming bentonite. Mixtures of 20 percent bentonite and 80 percent of 1.2 micron and 16 micron sand, respectively, were made. The water content for given blow count was found to be approximately two times greater in the 1.2 micron mixture than in the 16 micron mixture. That is, decreasing the grain size of the clastic particles from 16 to 1.2 microns in montmorillonite-sand mixtures increases the water content 100 percent for given blow count. For blow count of 25, which represents the liquid limit, the mixture of 1.2 micron silica had a water content of 250 percent and of 16 micron silica, 125 percent.

Effect of base exchange - The effect of base exchange is shown in Fig. This figure presents data for shear strength and hydrogen and sodium bentonite and of raw bentonite as received from the manufacturer. Hydrogen clays are seen to be relatively strong, sodium clays are relatively weak and the raw bentonite is intermediate between hydrogen and sodium bentonite. Similar relationships have been reported by Sullivan and Gr (1940) for base exchange effects on other clays. The hydrogen clays for given water content are 5 to 8 times stronger than sodium clays. For example at 50 percent water the shear weight is 0.14 pounds per square inch for sodium compared with 0.75 pounds for hydrogen.

Effect of temperature - The strength increases slightly with falling temperature. In general the increase is less than one percent per decrease of one degree centigrade. In view of the fact that water becomes more viscous as the temperature drops, it could be presumed that the strength would increase with lowered temperature, because of the greater viscosity of the water.

Effect of time - The strength of pure illite was measured after different intervals of standing. The data were corrected to a constant water content. The strength is 0.70 per square inch after one minute

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standing, 0.79 after three minutes, and 0.93 pounds per square inch after 100 minutes. Most of the strength is thus attained in a short time, but additional strength is slowly gained with time, evidently owing to thixotropic effects.

Effect of glycerine - The strength of glycerine mixtures was measured on vel clay, a type of bentonite or montmorillonite. The results are shown in Fig. 12 which indicates that glycerine does not give the straight line effect of water mixtures. The strength increases from about 0.1 pound per square inch at 143 percent glycerine through 0.5 pounds per square inch for 132 percent glycerine to 1.3 pounds per square inch for 90 percent glycerine. The strength thus increases very rapidly as the glycerine content decreases below 100 percent. Mixture of water and vel clay as shown in Fig. 4 closely approximate the water-shear strength relation for Wyoming bentonite. As glycerine is non-polar, whereas water is polar, the forces that cause strength in glycerine mixtures evidently are different than those in water.

CONCLUSIONS

The strength of clays varies with clay type. For given water content illite is slightly stronger than kaolin. Ball clays, which are a mixture of kaolin, silica and organic matter are slightly stronger than illite. Montmorillonite is much stronger than any of the other clays. For given shear strength the water content increases progressively from kaolin through illite to montmorillonite. Montmorillonite, for given strength contains much more water than the other clays. It is interesting that the base exchange capacity of the clays varies in much the same manner as as the water content-strength relationships. The strength in some way is related to the inherent properties of the clay.

For given water content the strength increases with increasing clay-sand ratio and for given strength the water content likewise increases with increasing clay-sand ratio. Similarly with increasing fineness of grain of admixed sand particles, the strength and water content increase in the same way.

It is beyond the scope of this paper to explain the fundamental physical chemistry of the causes of strength in clay-water mixtures. For good discussions of this subject see Hauser, 1955, Norton, 1952 and Langston and Pask, 1956. In clay-water mixtures, the water occurs essentially in two ways; namely, bound and unbound water. Bound water is water associated with molecular and electrical forces surrounding

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clay particles and for given clay minerals has more or less similar dimensions. Unbound water is water between particles and is located outside the limits of bound water. For soils of given water content, when the content of clay increases in sand-clay mixtures and when the size of the particles diminishes, the size of the pores between particles diminishes with the result that the ratio of bound to unbound water increases, because the thickness of the bound water layer presumably does not change materially and the dimensions of the unbound water necessarily must diminish causing the bound-unbound water ratio to increase. Since the strength among other things is related to the forces that bind the water to the clay particles, the strength for given water content should likewise increase as the relative proportions of bound water increases.

With respect to increase in water content for clays of given strength, if the strength remains constant the ratio between bound and unbound water should likewise remain reasonably constant. If the surface areas of the particles increases or if the thickness of the bound layer increases, the content of unbound water must likewise increase if the ratio of bound to unbound water is to remain constant. Thus with increasing clay content in clay-sand mixtures, or with increasing fineness of grain with resulting increase in content of bound water, the total content of water both bound and unbound must increase for clays of constant strength.

With respect to liquid limit, since the liquid limit test is essentially a measure of the water content for constant strength conditions, the liquid limit should follow the same relationships as do the strength relationships described above. Even though the liquid limit may not be an exact measure of strength, it represents the energy required to close a furrow with 25 blows under standard conditions, and as such is a sort of measure of strength. The liquid limit thus can be expected to vary with (1) clay type, (2) clay-sand ratio and (3) grain size.

The effect of base exchange upon strength illustrated in Fig. 11 is similar to the findings of Sullivan and Graham. They found that for given water content hydrogen clays are considerably stronger than sodium clays. The effect of temperature upon strength is probably in part caused by increased viscosity of the water with lower temperature. Since the increase in strength with drop in temperature is very slight, temperature cannot be regarded as a major factor affecting strength.

The different relationship for glycerine compared with water, as indicated by Fig. 12, perhaps is caused by different molecular effects. Glycerine is non-polar, whereas water is polar, and according to Langston and Pask, 1956, polar effects are a partial cause of strength in clay water mixtures.

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