research is explained on the basis of its applicability to subsoil stabilization and surfacing problems.

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SENISTIVITY OF CLAY TO REMOLDING AND ITS POSSIBLE CAUSES

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SYNOPSIS

The sensitivity of clays to remolding is correlated with the general problem of soil structure. The soil-physical facts and theories of structure are presented in a simplified manner. Fragmental and granular soil structures are revealed to be consequences of the law of minimal areas with modification as a result of chemical and (or) mineralogical inhomogeneity of soil composition. The importance of physico-chemical and (or) chemical cementation as a factor in water resistant massive or granular soil structure is emphasized. Experiments performed on five soil samples (two from Mississippi, and three varved clays from Albany, N. Y.) indicate that the great susceptibility of the varved clays to remolding derives from their cementation.

Tests on undisturbed cohesive soils at moisture contents within the plastic range have shown that remolding may result in:

1. Decrease of unconfined compressive strength $(3, 8)^{1}$

2. No effect on compressive strength, or

3. Increase of compressive strength (4, 8, 2).

The response of a soil to remolding is of great importance in foundation engineering. Direct determination of this response by unconfined compression test is at least as simple as any other test which can be performed on a soil. Consequently there appears to exist little practical reason for ascertaining the possible cause of the sensitivity of clay to remolding.

As a matter of fact, the effect of disturbance of a cohesive soil on its strength properties is of importance not only for individual foundation

¹ Italicized figures in parentheses refer to list of references at the end of the paper. designs but also, and to a much greater extent, because of its bearing on the central problem of stability and strength properties of cohesive soils. It is for this reason that the present study was undertaken.

Most common building materials owe their specific strength properties not only to their composition but also to their structure. A good example of this importance of structure is furnished by the carbon steels in which the chemical composition indicates potential strength properties while the actual properties are determined by the structural arrangement established through heat and mechanical treatment.

Similarly, as in the case in steel, the actual mechanical properties of soils are dependent not only upon their composition but also on the structural arrangement of the component particles, and the forces which hold these particles together. What is Soil Structure?—The term soil structure comprises the macroscopic and microscopic visual pattern and also the permanency of this pattern, which involves the resistance towards mechanical and slaking forces.

Historically, the first classification of soil structure was in accordance with the macroscopic visual structure which ranges from a single grain, massive type to a structure composed almost entirely of secondary particles. Intermediate between these two extremes are structures composed of both primary and secondary particles. can be expected in accordance with the law of minimal areas or the law of the triple corner (?). This basic structure will be influenced by directional properties of the constituent particles (9) and also by chemical inhomogeneity of the solid, plastic, or liquid phases of the system. Thus it has been found that varnish dissolved in dry acetone gives a regular hexagonal pattern, while, in the case of a small water content of the acetone, the pattern approaches cubical or spherical arrangement (?). These phenomena are illustrated in Figures 1 and 2.



Figure. 1. Cracks in Drying Mud-(after R. H. Wodehouse (7))

According to most investigators establishment of a secondary structure involves periodic desiccation; also, the degree to which a secondary structure is developed depends upon the amount of clay particles present in the soil. For these reasons it appears permissible to assume that at the basis of secondary soil structure lies the fundamental phenomenon of shrinkage cracks as observed in drying mud and also in drying films of asphalt, varnish, and other materials which exhibit volume change upon drying.

If the drying material possesses isotropic character, either as a result of isotropic character of the constituent particles or as a result of random arrangement, a hexagonal structure A typical soil structure classification based upon normal visual inspection is that of Baver (1) given in Figure 3. It is significant that in this classification the different geometric soil structures are related to the great pedological soil groups, a fact which points to underlying physical and physico-chemical causes.

The structural pattern of a soil may be considered as a permanent inherent soil property; however, the individual soil structural units may be ephemeral, lasting only until the next rain, or may be possessed of a considerable slaking resistance. The water-resistance of secondary soil particles is usually determined by wet sieving, elutriation, and sedimentation. Extensive investigations on formation of water resistant aggregations in soils have permitted correlation with climatic soil-forming factors (1). These relationships are shown in

nents. A non-swelling soil will tend to possess a monolithic structure.

2. The water-resistance of fragmented or granular secondary soil particles is a function



Figure 2. Cellular Patterns in Varnish (7) (a) dissolved in dry acetone (b) dissolved in acetone containing a little water

Figures 4 and 5. These figures illustrate the

following important facts: 1. When soil was formed in the presence of plentiful moisture, the percentage of stable aggregates varied from approximately 25 for podsolic soils (low temperatures) to approximately 95 for lateritic soils (high temperature).

2. For temperate climates, the percentage of aggregation decreases with increasing amount of precipitation; however the aggregation of desert soils appears to be of a different (flocculent) character than that of soils developed at intermediate and high moisture conditions (dipole linkage as indicated in Figure 6).

3. In semi-arid (chernozem) soils the percentage of stable aggregates decreases with increasing temperature, which is accompanied by decreasing content in organic matter. It should be noted that the organic matter in semi-arid soils is of different chemical character than that in podsolic (moist, cold) soils.

This general pedologic evidence points to the following more specific physico-chemical conclusions:

1. Whether a dry cohesive soil possesses a monolithic structure or a granular (or fragmented) structure depends on the swelling and shrinkage properties of its mineral compo-





Figure 3. Classification of Soil Structure According to Baver (1)

of the water repellancy of organic matter concentrated on the outside of the granules, and of the water-resistance of cohesion inducing soil components.

3. The internal cohesion of soil granules, may be:

(a) ephemeral if due only to surface tension of moisture films;

(b) reversible if due to reversible hydrophilic clays and colloids;

(c) practically irreversible if due to dehydrated irreversible hydrous iron and aluminum oxides. Irreversible cohesion, such as due to (c) can properly be called cementation.

4. If the term cohesive soil is employed in the general engineering sense, rather than in the restricted, pedologic sense, we can include among the more or less irreversible cementing agents, hydrous silica, carbonate of lime, and powdered igneous rock, reduced in size either by glacial action or by volcanic activity. The latter materials possess hydraulic cementing properties to a greater or lesser extent.



Figure 5. Aggregation of Soil as Affected by Temperature (1)

Mass cementation can be expected to occur especially in marine and lacustrine clays which often are intermediate in character between typical pedologic soils and cemented sedimentary rock.

The problem of more or less permanent soil structure, in which alone we are interested, reduces itself on one hand to water-proofing action of organic matter, and, on the other hand, to cementation. There appears to be little doubt that knowledge concerning the ways of nature in achieving these phenomena can be of great importance in the further development, theoretical as well as practical, of soil stabilization by means of waterproofing and (or) cementation. In line with this objective the microscopic structure of soil as revealed by the work of Kubiena should be of great importance. For this reason the classification of microscopic structure by Kubiena is given in Table 1. A schematic presentation

TABLE 1 KUBIENA CLASSIFICATION OF SOIL MICRO-STRUCTURE (MICROPEDOLOGY, COLLEGIATE PRESS, AMES, IOWA)

Coating of Mineral Grains	Arrangement of the ''Fabric''	Occurrence			
Grains not coated	 Grains em- bedded loosely in a dense ground mass. Grains united by intergranular braces Intergranular spaces, contain- ing loose de- posits of floc- culent material. 	Lateritic soils Chernozem, brown- earths, lateritic soils Sandy prairy soils			
Grains coated	 Grains ce- mented in a dense ground mass Grains united by intergranular braces Intergranular spaces empty 	Desert crusts podsol B-hori- zons B-horizons podso- lized brown forest soils			



Figure 6. Molecular Mechanism of Clay Aggregation According to Russel (6)

of the molecular mechanism of clay aggregation is found in Figure 6(6).

In this paper, soil structure is treated primarily from the point of view of soil physics. This should not be taken as an implication that the importance of soil structure has been overlooked in soil mechanics. The contrary is evidenced by the time and effort which has been spent in soil mechanics in the development of methods for obtaining undisturbed--i.e. structurally intact- test specimens. However, contrasted with the large number of different types of soil structure observed and investigated by the soil physicist, only a few structural models have been proposed in soil mechanics Of the latter, that by Casagrande (3) is probably the most widely known. Concerning these soil mechanical models, it appears justified to state that they are in the main schematic expressions of observed effects of structure, rather than pictures of the actually observable microscopic and submicroscopic structure.

Returning to the original problem of the sensitivity of clay to remolding we must conclude that this sensitivity is to a great extent a function of the soil structure. In order to account for a large decrease in non-confined compressive strength due to remolding, masstype cementation, such as occurs in a loess soil or in a sandstone, must be made responsible. Establishment of this type of structure is connected either with relatively slow recrystallization processes or with formation of cementing materials from inorganic substances of low solubility. Of course, the actual time required depends upon the physico-chemical reactions involved and upon environmental conditions; in some cases even geologic times may be required.

Soils which are unaffected by remolding appear to owe their cohesive properties mainly to the cohesive action of oriented water films of internal-air-liquid surfaces, and of reversible inorganic colloids. Because of the relatively small viscosity of water, re-establishment of this water-type cohesion can be expected to occur within a relatively short time.

The explanation of increase of compressive strength as a result of remolding is somewhat more complicated. Theoretically such increase in strength may be due to:

1. The breaking down of secondary aggregates exposing more mineral surfaces which can absorb the available water with great avidity, changing it from free to more viscous or plastic film water;

2. The movement of particles into positions of greater average attraction—a possibility which seems to exist, especially in the case of certain flocculated sedimentary clays; 3. The breaking up of planes of weakness and lubrication, similar to grain refinement in metal working. (There exists also a possibility of mechanisms akin to slip interference which is better known in the cold drawing of metals and the mercerizing of cotton.); or

4. The closing of fissures and consequent elimination of planes of weakness, the role of which has been demonstrated by Oscar Faber with respect to the undisturbed and remolded strength properties of London fissured clay (4).

EXPERIMENTAL PART

It appeared of interest to check, at least in part, on specific soil samples, the general conclusions which have been derived above, from the large but more or less qualitative information available. Five soil specimens were chosen for this purpose-two of these were varved clays from Albany, N. Y., and the remaining three were clays from Greenville. Miss. All clay-soils were greenish-blue in color indicating anerobic conditions prevailing in situ. The clavs from Albany were of a more blueish tint, those from Mississippi were more green in color. Also the clays from Albany appeared to be stiff and hard, cleaving easily at the interstratification due to the varved nature of the clays.

The clays from Mississippi were of softer consistency and had a higher water content. The properties of these soils are given in Table 2.

The compressive strength of these soils was determined on undisturbed samples as well as on remolded samples. The ratio of the strength of the undisturbed sample at failure to the remolded strength, at a strain corresponding to the strain at failure of the former. was designated as sensitivity ratio. The strength of the samples was determined by unconfined controlled-stress compression tests. The data in Table 2 show that the Albany clays possessed a high sensitivity ratio ranging from about 24 to 49 while one sample from Mississippi had a sensitivity ratio of one, the other of 0.7. A sensitivity ratio smaller than one indicates, of course, that the strength of the sample was improved by remolding.

Soil cohesion residing mainly in its smallest size (clay and colloidal) fractions, it was decided to separate these fractions from the soil samples and to analyse them for their mineral constituents, by the differential thermal

SOILS

BINERGIII AND CONSISTENCI DAIN OF THE SOLID TEDIDD											
Sample No.	Unconfined Compressive Strengths			Sensi-	Consistency Limits						
	Undisturbed		Remolded		tivity Ratio.	W_					
	Stress	Strain as Percent- age of Height	Stress	Strain as Percent- age of Height	of effect of re- molding)	Natural Water Content	W ₁ (LL) Liquid Limit	W _p (PL) Plastic Limit	Ip (PI) Plastic Index	Liquid- ity Index	
	T. per sq. ft.	%	T per sq.∫t.	%		%	%	%	%	%	
Mississippi (1-1)-2 Mississippi (2-4)-2 Albany 4-9 Albany 9-8 Albany 7-5	$\begin{array}{c} 0.99 \\ 0.33 \\ 1.63 \\ 2.43 \\ 1.19 \end{array}$	13.1 12.5 4.6 5.0 3.7	0.99 0.46 0.16 0.19 0.15	19.9 11.8 20.0 20.0 20.0	1.0 0.7 29.6 48.6 23.8	85 50 40 33 30	57 66 46 40 31	19 24 27 24 22	38 42 19 16 9	42 63 68 57 89	

TABLE 2 STRENGTH AND CONSISTENCY DATA OF THE SOILS TESTED



Figure 7. Thermal Curves of Minus 2-Micron Fraction of the Five Soil Samples Investigated

method. This method is described in detail in the mineralogical and ceramic literature (δ) , and need not be presented here.

The fundamental principle employed in this method is based on the fact that solid materials rearrange their internal structures at characteristic temperatures; this reorientation resulting either in an absorption or a release of heat energy. Upon heating of such a solid with a thermically inert companion sample,



Figure 8. Thermal Curves for Minus 2-Micron Fraction of Mississippi Soil:

(a) untreated

- (b) treated with hydrogen peroxide
- (c) treated to remove iron oxides

differences in temperature between these samples at the critical temperatures may be observed. These temperature differences may be converted into electrical potential differences, and registered, using thermocouples, mirror galvanometers, and a photosensitive Kymograph arrangement. Simultaneously, with the temperature differences between the two samples, the oven temperature is registered by means of an independent thermocouple. This method goes back to the work of Le Chatelier (1887) and the concept of critical temperatures is, of course, familiar to every materials engineer from the Iron-Carbon phase diagram.

The differential thermal analysis gives a curve which is characteristic for the material

under test. The obtained curve is compared with curves obtained for known clay or other minerals or mineral mixtures, and the material under test is visually identified. Where such identification is not possible because of a hitherto uninvestigated mineral or mineral mixture, one possesses at least a permanent record of the thermal characteristics of the material, which is available for future interpretation. Samples of the soils under investigation were dispersed in water and the minus 2-micron fraction separated by decanting.



Figure 9. Thermal Curves for Minus 2-Micron Fraction of Albany Soil:

- (a) untreated
- (b) treated with hydrogen peroxide

(c) treated to remove iron oxides

The Mississippi soils could be dispersed by means of distilled water alone. Two of the Albany soils could be dispersed by means of ammonia, while one required the use of aerosol. The difficulties encountered in securing dispersion of the Albany clays, as well as the low PI of these clays indicated rock flour rather than clay-mineral properties.

Thermal tests were performed on the five original minus 2-micron fractions. In addition the minus 2-micron material of one of the Mississippi soils, and of one of the Albany soils, were treated with hydrogen peroxide to remove possible organic matter, and by means of a special process to remove superficially adsorbed iron oxides, and thermal tests were made on the treated materials. Before testing, all samples were permitted to come to adsorption equilibrium over a saturated solution of calcium chloride.

RESULTS OF THE THERMAL TESTS

The results of the differential thermal analyses are given in Figures 7 to 9. Figure 7 shows the striking difference in pattern of the Mississippi clays on one hand, and the Albany clays on the other. The Mississippi clays produced typical clay-mineral patterns, while the Albany fractions produced patterns which do not correspond to those of known clay minerals, and which indicate the rock-flour nature of the investigated fractions.

Figure 8 gives the thermal curves for untreated, oxydized, and iron-oxide free fractions, respectively, of one of the Mississippi soils. The respective treatments resulted in a clearer definition of the clay minerals involved.

Figure 9 gives the thermal curves for untreated, oxydized, and iron-oxide free fractions, respectively, of one of the Albany soils. The changes in pattern caused by these treatments is impressive. These treatments, especially that for iron-oxide removal, apparently attacked the rock-flour, and, significantly, the trend of the pattern especially at the higher temperatures is toward that of a clay mineral. This is not surprising since the physico-chemical treatment employed is in some ways akin to natural rock weathering which produces clay minerals.

CONCLUSIONS FROM THE EXPERIMENTAL EVIDENCE

The experimental evidence indicates that the great sensitivity of the Albany samples to remolding is due to destruction of cementation bonds which have been developed over a long period of time between the individual rock powder particles.

The non-sensitivity of one of the Mississippi samples can be related to the reversible claywater-type of cohesion. The increase in compressive strength of the other Mississippi sample may be due to any of the factors previously mentioned; unfortunately, the experimental evidence is too limited to permit a more definite statement concerning this phenomenon. The results of the experimental investigation appear to be in close accord with the general theory of soil structure as outlined in the first half of this paper.

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