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Publication of this paper sponsored by Committee on Environmental Factors Except Frost.

Desiccation of Soils Derived From Volcanic Ash

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Five volcanic-ash-derived soils from the island of Hawaii were studied to determine the relation of changing moisture content to engineering behavior. Two soils weathered on the leeward side of the island under relatively dry conditions; the other three developed on the windward side under high mean annual rainfalls. The dry soils show little change on desiccation whereas the desiccation of the wet soils is accompanied by an irreversible hardening that causes drastic changes in the index properties. Engineering behavior of the dry soils is similar to that of a sandy silt. The wet soils behave as plastic clays but, when they are dried out, their engineering characteristics change to those of a sand. Mercury porosimetry tests reveal that, in wet soils, volume changes between field moisture content and the oven-dry state are about 150 percent. The dry soils exhibit very small volumetric shrinkage. Drying tests under controlled relative humidity provide data on drying rates and critical moisture contents. The mineralogy of the soils was studied by using X-ray diffraction and fluorescence, differential thermal, and thermogravimetric analyses. The predominant minerals are gibbsite, iron oxides, and allophane. Mineralogical studies indicate that irreversible hardening is accompanied by an increase in gibbsite content. Mercury porosimetry results and mineralogical analysis indicate that a major portion of the shrinkage is due to contraction of the intermediate-size pores and that the extent of shrinkage is a function of allophane content.

The behavior of some soils derived from volcanic ash in very wet tropical areas has been of considerable interest to pedologists and soil engineers. Highway-construction experience with these soils in Hawaii has been discussed by Hirashima (7, 8), who pointed out problems associated with compaction at very high moisture contents. In general, ash soils are characterized by low density, high permeability, and high water-holding capacity (4, 7, 11, 15). Birrell (4), who worked with ash-derived soils from New Zealand, has reported that the preconsolidation pressure of the soils as determined in conventional consolidation tests is frequently greater than the overburden pressure but that once this preconsolidation pressure is exceeded the soils are highly compressible. Yamanouchi (16) has pointed out that the ash-derived soils of Japan are difficult to stabilize with conventional additives if the soils are high in organic content.

One of the most interesting properties of these soils is that they harden irreversibly when dried. This hardening is often accompanied by shrinkage. At field moisture contents the ash soils are plastic and claylike; if they are allowed to dry, however, sand- or silt-size aggregates form. Drying reduces liquid limits and decreases clay contents in these soils (3, 6, 7). If the soils are allowed to dry partially at relatively high moisture contents, they retain their plastic nature. No data were found to indicate the moisture content at which an ash-derived soil loses its plastic character. The component of ash soils that is responsible for irreversible hardening and for some other unique properties has been referred to variously as palagonite (7), amorphous clay (15), amorphous colloids (4), and allophane (6). Few quantitative data on the mineralogy of ash-derived soils are to be found in the literature. The confusion in terminology and the lack of quantitative data arise from the vague definition of the poorly crystalline components in these soils and from the resultant difficulties in making measurements.

The data presented in this paper may help to provide a better understanding of the desiccation process in ash soils and thus contribute to evaluating their potential for chemical stabilization, classifying them for engineering purposes, and predicting their behavior in the field.

SOILS STUDIED

Three ash-derived soils known to exhibit irreversible hardening when dried are the Kukaiau, Honokaa, and Hilo series from the windward side of the island of Hawaii. These soils were weathered from a volcanic ash known as the Pahala ash under very high mean annual rainfalls ranging from 178 to 457 cm. As a basis for comparison, two other soils were studied that weathered from the same parent material but do not exhibit irreversible hardening. These two soils, Waimea and Kilohana, developed under mean annual rainfalls ranging from 51 to

114 cm. Complete pedologic descriptions of the soil profiles can be found in the Hawaii soil survey report (10). A summary of the environmental conditions and the pedologic classifications of the five soils is given in Table 1.

Relatively undisturbed samples were collected from the B horizon of each soil series by means of thin-walled shelby tubes that were hydraulically pressed into the soil. The tubes were sealed to preserve field moisture contents and were air freighted to the mainland in specially constructed, rubber-foam-padded shipping crates.

TEST PROCEDURES AND RESULTS

Composite samples of each series were prepared by trimming about 100 g from every tube sample, mixing, and quartering. Some samples were air dried and passed through a 74-μm (No. 200) sieve prior to X-ray, thermogravimetric, and differential thermal analyses to determine mineral contents. Other samples in the field moisture state were also subjected to X-ray analysis.

Iron contents were determined by X-ray fluorescence. The method developed for this purpose was based on the comparison of X-ray fluorescent peak intensities of iron in the sample with intensities of iron peaks in specimens composed of the original sample plus known additional amounts of iron. The method and the derivation of equations can be found elsewhere (12). The fluorescent method is similar to the diffraction method described by Tuncer and others (13).

Gibbsite contents were determined by thermogravimetric analysis in which the weight loss corresponding to the most characteristic gibbsite thermal reaction of the soil sample is compared with that of a sample of pure gibbsite. The amount of gibbsite in the soil is calculated by simple proportioning (14).

Allophane is most difficult to determine quantitatively: It is amorphous to X-rays and isolating pure allophane for calibration of the thermogravimetric analysis is difficult. The allophane content in the test soils was estimated by selecting as the reference the Hilo soil, which contains the fewest mineral species, and assuming that the only minerals present were gibbsite, various iron oxides, and allophane. Once the iron oxides and gibbsite were measured, the allophane in the Hilo was calculated by simple subtraction. The allophane content in the other four soils was calculated by taking the weight loss for the allophane thermal reaction in Hilo and proportioning the weight loss in the other soils that corresponds to the same allophane reaction.

Organic carbon contents were measured by the dichromate method. The qualitative X-ray diffraction study reveals that the Kilohana soil has large amounts of plagioclase feldspar and some hydrated halloysite. The Waimea soil has even larger amounts of halloysite. No quantitative work was done on these minerals because these two soils do not exhibit irreversible hardening.

The chemical and mineral contents of the test soils are given in Table 2. Gibbsite is an important component of the soils that harden irreversibly (Kukaiau, Honokaa, and Hilo); allophane is present in all five soils but in greater amounts in the soils that harden. Iron oxide content increases from dry to wet soils, but organic carbon content does not show any systematic variations.

Mechanical analyses, Atterberg limit tests, and specific gravity tests were performed on composite samples of each of the soil series studied according to American Society for Testing and Materials (ASTM) procedures that require that the soils be air dried prior to testing. To evaluate the effect of irreversible hardening, additional gradation and Atterberg limit tests were conducted at field moisture contents (Tables 3 and 4). As expected there is little difference between the dry-state and moist-state index properties of the soils from the dry side of the island, but the soils that harden irreversibly show a marked decrease in clay and sand contents and a decrease in Atterberg limits after drying.

Densities and void ratios were determined by weighing the tube samples and measuring their bulk geometry. Eight to 10 tubes from each series were measured, and the data reported for each series (Table 5) are the averages. The soils that harden irreversibly exhibit extremely high void ratios and field moisture contents. The void ratios of the soils that do not harden irreversibly are somewhat lower.

The volume-change characteristics of the soils were investigated by shrinkage-limit tests and tests using mercury injection porosimetry. The shrinkage limit (Table 5) was determined for composite samples of each series according to ASTM procedures. Volumetric shrinkage was calculated by dividing the difference between the volumes of the soil at field moisture content and at the shrinkage limit by the volume of the soil at the shrinkage limit.

Mercury porosimetry tests were conducted on all five soils according to procedures described by Lohnes, Tuncer, and Demirel (9). Tests were run on air-dried samples as well as on samples that had been freeze dried at field moisture content. Freeze drying was done according to the method described by Erol, Lohnes, and Demirel (5). The change in pore volume from field moisture to oven-dry states was used to calculate the volumetric strain by dividing the change in pore volume by the pore volume at field moisture content. Shrinkage and hardening characteristics are given in Table 6.

To investigate the mode of volume change, the Hilo soil was subjected to controlled drying and samples from it were freeze dried at various moisture contents between field moisture content and the oven-dried state. The samples were then subjected to porosimetry tests. Pore-size-distribution curves at various stages in the drying history are shown in Figure 1. Figure 2 shows the variation in pores of various size ranges with changing moisture content. The greatest volume change occurs in the intermediate-size pores (10 to 0.01 μm), whereas the very large pores (>10 μm) and very small pores (<0.01 μm) are little affected by drying.

Undisturbed samples of each series were allowed to air dry in the laboratory at a relative humidity of 20 ± 3 percent. Moisture contents were taken periodically, and curves for moisture content versus time were plotted for all five series. The moisture content-time curves are shown in Figure 3. The initial linear portion of the drying curves is controlled by ambient conditions such as relative humidity and air velocity. During this constant-rate period of drying, the surface of the soil sample that is in contact with the air is completely wetted and the drying rate is independent of the characteristics of the solid and void space. The moisture content at which the curve deviates from linearity is the critical moisture content (Table 6) (2). The form of the drying curve at moisture contents below the critical moisture content depends on the structure and composition of the soil and the voids and on the mechanism by which the moisture moves within the soil (2). Drying curves for all soils are shown in Figure 3.

Slaking tests were performed at four stages in the drying history of the three soils that harden irreversibly. These tests were run in an attempt to define the moisture content at which the hardening would occur, i.e., the hardening limit of each soil. At moisture contents above this limit, the soils retain their plastic characteristics and slake when immersed. Below the hardening limit, the soils do not slake. Because the number of samples

Table 1. Pedologic classifications and environmental conditions of the soils studied.

Soil Series	7th Approximation Classification	Great Group	Range of Mean Annual Rainfall (cm)	Range of Slope Angles (%)
Kilohana	Mollic Vitrandept	Regosol	51 to 102	12 to 20
Waimea	Typic Eutrandept	Reddish Prairie	64 to 114	6 to 20
Kukaiau	Hydric Dystrandept	Humic Latosol	178 to 254	6 to 35
Honokaa	Typic Hydrandept	Hydrol Humic Latosol	254 to 381	10 to 35
Hilo	Typic Hydrandept	Hydrol Humic Latosol	305 to 457	0 to 35

Table 2. Chemical and mineral contents.

Soil Series	Allophane (% weight)	Gibbsite (% weight)	Iron Oxide (% weight)	Organic Carbon (% weight)	Relative Contents[a]		
					Quartz	Halloysite	Plagioclase
Kilohana	26	0	10	4.6	X	X	XX
Waimea	32	8	16.4	2.2	X	XX	0
Kukaiau	42	27	17.7	5.3	X	0	0
Honokaa	55	22	19.6	9.2	X	0	0
Hilo	42	32	26	4.2	X	0	0

[a] X indicates a small amount; XX indicates a large amount.

Table 3. Gradation data.

Soil Series	Sand (%)		Silt (%)		Clay (%)	
	Dry	Wet	Dry	Wet	Dry	Wet
Kilohana	69	68	24.8	28.8	6.2	3.2
Waimea	33	54	57.7	39	9.3	7
Kukaiau	89	59	10.4	32	0.6	9
Honokaa	89.5	42	9	33.5	1.5	24.5
Hilo	87.5	31	7.4	39.5	5.1	29.5

Table 4. Atterberg limits.

Soil Series	Liquid Limit (%)		Plastic Limit (%)		Plasticity Index (%)	
	Dry	Wet	Dry	Wet	Dry	Wet
Kilohana	NP	NP	NP	NP	NP	NP
Waimea	66.8	64	63	62.7	3.8	1.3
Kukaiau	93.3	164	88.6	162.4	4.7	1.6
Honokaa	NP	301	NP	279.9	NP	21.1
Hilo	61.4	206	NP	191.9	NP	14.1

Note: NP indicates nonplastic.

Table 5. Density data and shrinkage limits.

Soil Series	Field Moisture Content (%)	Void Ratio	Dry Density (g/cm^3)	Specific Gravity	Shrinkage Limit (%)
Kilohana	39.2	2.155	0.92	2.904	44.7
Waimea	45.79	2.802	0.81	3.084	35.0
Kukaiau	164.13	5.993	0.44	3.071	47.9
Honokaa	244.92	8.901	0.30	2.980	50.5
Hilo	234.90	7.130	0.35	2.842	56.3

was limited, it was not possible to monitor the behavior of the soils continuously throughout their drying history. Therefore, rather than precisely defining the hardening limit, the data given in Table 6 bracket the hardening limit between a higher moisture content at which the soil continues to slake and a lower moisture content at which the soil is observed to be irreversibly hardened. For the three soils that harden irreversibly, the upper and lower moisture contents that bracket the hardening limit also bracket the critical moisture content. These moisture contents also bracket the shrinkage limit (except in the case of the Honokaa soil where the shrinkage limit falls below the hardening limit).

DISCUSSION OF RESULTS

A comparison of the critical moisture contents in Table 6 with the shrinkage limits in Table 5 reveals that, although two of the three soils that harden have nearly equal shrinkage limits and critical moisture contents, the other three soils do not show this trend. A comparison of critical moisture content with the change in void ratio calculated from porosimetry data (Table 6) shows that there is a good correlation between the two parameters. Figure 4 shows a good correlation between the allophane content and the critical moisture content. These comparisons and correlations indicate that volumetric shrinkage is best predicted by the critical moisture content. Volume change as calculated by the shrinkage limit is based on tests on disturbed samples and is not representative of the shrinkage that can be expected from the desiccation of an undisturbed ash-derived soil. The correlations suggest that drying tests may be a valuable interpretive tool for a better understanding of soil structure and mineralogy.

The change in the pore-size distribution of the Hilo soil (Figure 2) that is caused by drying reveals that the major change occurs in pores between 10 and 0.01 μm in size, which covers the range of large, medium, and small pores defined earlier. A second observation is that, within this magnitude of pores, the 10 to 1-μm pores empty at the highest moisture range, i.e., 120 to 240 percent, and it is not until these pores empty that the pores in the 1 to 0.01-μm range begin to empty, as indicated in Figure 2. Although capillary tension is high in the very small pores (<0.01 μm), the structure of the soil around the pores is sufficiently strong that they do not collapse. The very large pores (>10 μm) do not show much change because the capillary tensions are lower in that size range. Thus the intermediate-size pores that combine the effects of a weak structure and moderately high capillary tensions are the pores most affected in the collapse. These observations result from the fact that the saturation pressure of the vapor, which is in equilibrium at the interface of the larger pores, must be reduced to the saturation pressure of the interface in the smaller pores before these pores can empty.

Previous researchers have indicated that allophane is responsible for the irreversible hardening and shrinkage of ash-derived soils. Figure 4 shows plots of the change in void ratio caused by drying versus allophane content and the initial void ratio versus allophane content,

which tend to support this idea that soils with higher initial void ratio and soils that exhibit greater shrinkage all have higher allophane contents. However, allophane content alone cannot be responsible for the hardening of ash-derived soils because the two soils that do not harden irreversibly contain fairly large amounts of allophane. Even though the quantitative estimates of allophane can be questioned as absolute amounts, their relative contents should be fairly accurate. The Hilo soil, which exhibits large shrinkage and hardening and was used as the standard, contains only 10 to 14 percent more allophane than the two soils that do not harden. Gibbsite, however, is present in large amounts in soils that harden but in small quantities or not at all in soils that do not harden. Data in Table 2 are based on thermogravimetric analyses; the soils were dry at the time their mineral contents were determined. To further evaluate the role of gibbsite in irreversible hardening, X-ray diffraction patterns (using $Cu_{K\alpha}$ radiation) were obtained on all three of the soils that harden at both the field

Table 6. Shrinkage and hardening characteristics.

Soil Series	Volumetric Shrinkage From Shrinkage Limit	Void Ratio Decrease From Porosimetry	Volumetric Strain From Porosimetry (%)	Critical Moisture Content (%)	Hardening Limit
Kilohana	0[a]	0.110	5.1	27	–
Waimea	9.03	0.539	19.2	30	–
Kukaiau	104.49	5.156	86	50	32.5 to 51.2
Honokaa	139.63	8.057	90.5	80	63.8 to 170.4
Hilo	166.66	6.109	85.7	56	34.0 to 122.0

[a] Field moisture content is lower than shrinkage limit.

Figure 1. Pore-size-distribution curves for Hilo soil at various stages of drying.

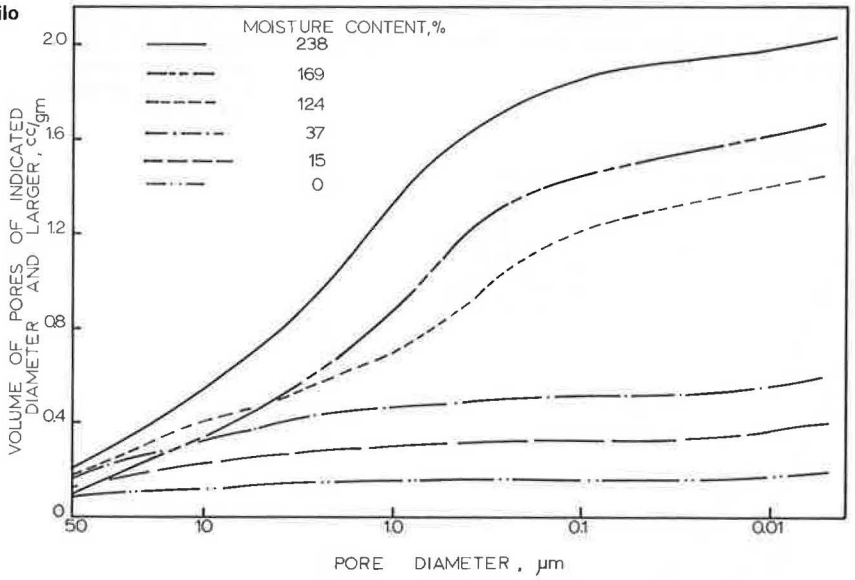
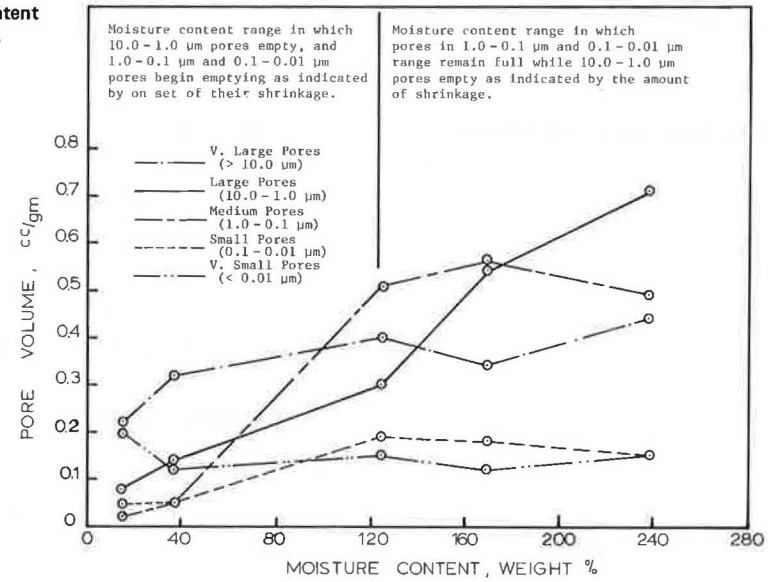


Figure 2. Pore volume versus moisture content for pores of various size ranges in Hilo soil.



moisture content and the oven-dry state. All three sets of X-ray diffraction tests gave results similar to those for the Hilo soil shown in Figure 5. The gibbsite peak is weak in all the soils at field moisture content but is more pronounced at oven dryness. The peak breadths are the same at both moisture contents as are the height and breadth of the quartz peaks. These observations lead to the conclusion that gibbsite is either synthesized or better crystallized in the drying process. No boehmite peaks nor other hydrated aluminum oxide peaks were observed in the diffractograms of the moist samples; therefore, if gibbsite is synthesized, the allophane must be the source material for it. Aomine (1) has suggested that allophane can be converted to gibbsite as part of the weathering process. It is possible therefore that allophane may be the source material in the drying process.

CONCLUSIONS

Based on data resulting from the study of Hawaiian volcanic-ash-derived soils, the following conclusions regarding the desiccation of soils may be drawn.

1. The drying process can more than double the sand content, reduce clay-size material as much as 12 times, and reduce the liquid limit as much as from over 300 percent to nonplastic behavior.
2. The moisture content at which the hardening process becomes irreversible is in the range of the shrinkage limit for two soils and in the range of the critical moisture content for all three soils that harden irreversibly.
3. The shrinkage of the soils is due mainly to the shrinkage of pores in the 10 to 0.01-μm-diameter range. Very large pores and very small pores do not enter into the shrinkage process because of low capillary tensions in the large pores and high structural strength around the small pores.
4. Although desiccation of allophane has been considered in the past to be the primary cause of hardening, in this study allophane was observed to occur in ash soils that do not harden. Gibbsite, on the other hand, is unique to ash soils that harden. X-ray evidence indicates that gibbsite is either synthesized or better crystallized in the hardening process.

ACKNOWLEDGMENTS

This research was supported by funds from the U.S. Army Research Office and the Engineering Research Institute

Figure 3. Drying curves for fine soil series.

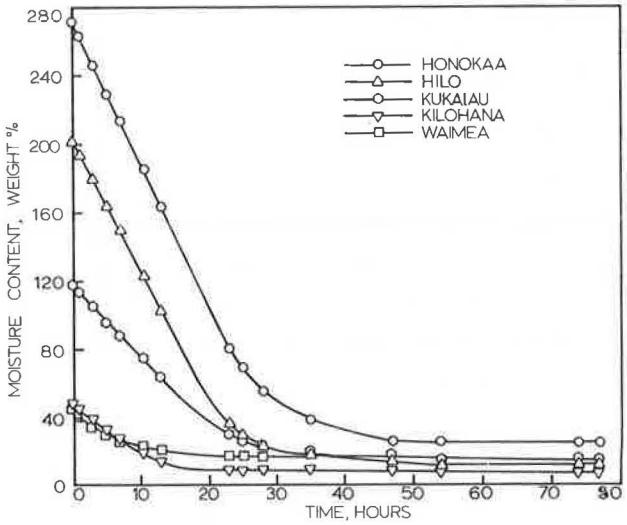


Figure 4. Allophane content versus void ratio, critical moisture content, and change in void ratio.

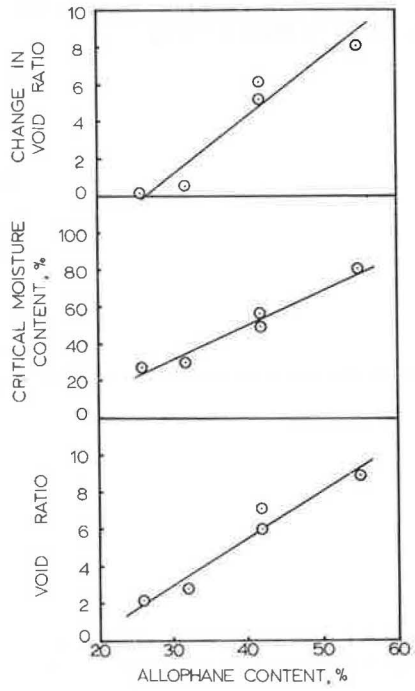
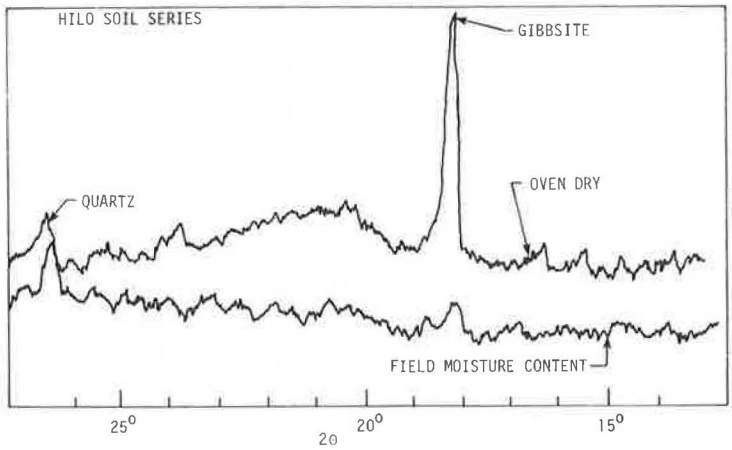


Figure 5. X-ray diffraction pattern of Hilo soil before and after oven drying.



of Iowa State University. We are also grateful to O. Bailey, state soil scientist of Hawaii, who selected soil series for study and helped with the field work, and to W. Mairaing and M. Lustig for their contribution to the laboratory study.

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Publication of this paper sponsored by Committee on Physicochemical Phenomena in Soils.

Clay Structure and Rate Process Theory

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An effort was made to incorporate structural variations into rate-process theory by defining a primitive or ideal clay that has a linear strain-time relation implicit in rate-process theory. The slope of the creep curve of the primitive clay is equal to the slope of the tertiary curve at its inflection point. The deviations of the tertiary curve from the straight line are a measure of the behavior of the real clay caused by the structural changes. The ratio of the strain of the real clay to the strain of the primitive clay can be calculated at any point in time. This ratio, defined as the mobilization ratio, is a measure of real-clay structure relative to primitive-clay structure, which remains constant during progressive creep deformations. The method of analysis proposed here reveals that equivalent mobilization ratios correspond to points of identical structure on creep curves. This hypothesis is supported by the experimental results. The analysis of undrained simple shear creep tests conducted on grundite-illite clay at various temperatures and shear stresses demonstrates that the rate process parameters—flow volume, activation enthalpy, and proportionality constant—are structure dependent. The structural changes that accompany creep deformations can be expressed in terms of variations in these parameters.

Although structure is accepted as one of the most important properties influencing the mechanistic behavior of soil, it is at best a descriptive concept manifest in terms such as single grained, massive, aggregated, dispersed, flocculent, and edge-to-face and face-to-face association. The following definitions taken from engineering and pedologic references briefly illustrate the current concepts of structure.

The U.S. Department of Agriculture (USDA) (10) defines soil structure as follows:

> Soil structure refers to the aggregation of primary soil particles into compound particles or clusters of primary particles, which are separated from adjoining aggregates by surfaces of weakness.

Although some researchers use the terms structure and fabric interchangeably, Mitchell (7) defines fabric as the arrangement of particles, particle groups, and pore spaces in a soil and states that "... structure is