

THE INFLUENCE OF SESQUIOXIDES ON LATERITIC SOIL PROPERTIES

Frank C. Townsend, Soils Research Division, Waterways Experiment Station,
Vicksburg, Mississippi; and

Phillip G. Manke and James V. Parcher, School of Civil Engineering,
Oklahoma State University

The breakdown of the characteristic granular structure of lateritic soils by remolding is known to alter the plastic, textural, and engineering characteristics of these soils. This laboratory study was an investigation of some mineralogical, chemical, physical, and engineering properties of a lateritic soil in order to evaluate more fully the basic reasons for the effects of remolding. Results of X-ray diffraction and scanning electron microscopy studies showed that the hydrated iron and aluminum oxides (sesquioxides) coat the clayey constituents of the soil and bind them into coarser micro-aggregations. Analyses of grain size indicated that the remolding phenomenon disaggregates the micro-aggregations into finer clayey clusters because of the friable nature of the sesquioxidic cementing agents. DTA and chemical analyses revealed the presence of substantial quantities of amorphous material in the soil. Atterberg limits tests on sesquioxide-free soil indicated that the abnormally high moisture contents of this lateritic soil are a result of the high moisture-retention capabilities of the amorphous colloids and the porous micro-aggregations in the soil. Although remolding greatly altered the index properties, little change was observed in the strength characteristics of the various soil states. The magnitude of the angles of internal friction determined by triaxial compression tests reflect a greater amount of interlocking by the micro-aggregations than would be produced by a platy structure. Unconfined compression tests showed that lime was an effective stabilizer for this lateritic soil.

●LATERITE and "lateritic soils" are terms used to describe the red residual soils that occur abundantly throughout the tropical and subtropical regions of the world. Geomorphologically, laterization involves the leaching out or removal of the silica, alkali, and alkaline earths and the concentration of hydrated iron and aluminum oxides (hereafter referred to as "sesquioxides"). Generally, the resulting soil in situ possesses a granular structure due to these sesquioxides, which coat and knit the indigenous soil particles into tiny spherical aggregations (1).

Previous studies (16, 21, 23, 24) indicated that these micro-aggregations are quite friable and are readily disaggregated by remolding of the soil. Depending on the amount of remolding, this behavior produces considerable variations in the plasticity, grain size distribution, and engineering characteristics of these soils. As a result, there is no assurance that index tests can be used for predicting the engineering behavior of these soils, and such results reported in the literature may be unreliable. Consequently, the engineering classification of tropical-climate clays by systems oriented for temperate-climate clays has been questioned. Likewise, remolding has been shown to exert a considerable influence on the response of the soil to various stabilizing additives.

In a previous paper (23) the authors presented quantitative differences in the plasticity, textural characteristics, and stabilization responses of a relatively undisturbed or

unremolded (previously referred to as unworked) and remolded lateritic soil. These differences were attributed to a breakdown of the granular micro-aggregations in the soil. In that paper, it was postulated that a substantial portion of the clay particles had been coated with sesquioxide films and that working or remolding by mechanical agents caused a breakdown of the aggregations, partially abraded these films, and resulted in a more characteristic behavior of the clay particles.

Bennett (3) observed that the physical properties of clay colloids are influenced by their silica-sesquioxide ratio ($\text{SiO}_2/\text{R}_2\text{O}_3$). He concluded that on the basis of the $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio a differentiation might be made between friable nonplastic soils and nonfriable plastic soils. Such a differentiation would be a considerable asset to highway engineers in determining the quality and suitability of a doubtful clay soil in tropical areas for use as a road or airfield subgrade. Likewise, Winterkorn (24) commented that "the presence of iron in lateritic soils is one of the most important factors which influences their engineering properties." Based on these concepts and the authors' previous postulation, it appears that the sesquioxides and their relationship with the indigenous soil particles are key factors in understanding the usual behavioral characteristics of lateritic soils. The present investigation was directed toward studying the influences of the sesquioxides on the Atterberg limits, grain size distribution, and lime susceptibility of a Panamanian lateritic soil. These influences were evaluated by chemically extracting the sesquioxides, testing the sesquioxide-free soil, and comparing the test results with those of the previous study (23).

RELATIONSHIP BETWEEN CLAYS AND SESQUIOXIDES

Unusual soil behavior can frequently be explained in terms of composition (particularly the clay mineralogy) and soil structure. The clay minerals encountered in lateritic soils are principally 1:1 minerals, of which kaolinite is by far the most common. Halloysite occurs less frequently but is known to exist in lateritic soils. Montmorillonite and other 2:1 clay minerals generally are not associated with lateritic soils. The sesquioxides may exist in a variety of forms, of which goethite and hematite and gibbsite and boehmite respectively are the most common forms of these iron and aluminum oxides. Various amorphous forms of hydrated iron and aluminum oxides, or sesquioxidic allophane, are also known to exist in these soils (4, 10, 12).

Many investigators have shown that the sesquioxides are adsorbed on the surfaces of the clay minerals in lateritic soils. This adsorption occurs through the interaction of the positively charged sesquioxides and the negatively charged clay particles. However, the mechanisms governing the adsorption are quite complex and dependent on the surface characteristics of the iron and aluminum compounds, the charge characteristic of the clay minerals, and the pH of the surrounding medium (6). Mattson (13) demonstrated that the sesquioxides behave as electrical ampholytes, i. e., above a pH of 7.0 they are electronegative, whereas below this pH level they are electropositive. The adsorption of iron oxides on the surfaces of clay minerals must, therefore, occur at pH values below 7.0. Greenland and Oades (6), using electron microscopy, observed that at low pH values iron precipitates as a surface coating on kaolinite and that some of these surfaces are bound together by the iron hydroxide. Electron microscopy studies by Follett (5) indicated that colloidal iron hydroxide is adsorbed only on one basal surface of the kaolinite flakes. Apparently only the silica tetrahedral surfaces possess sufficient charge to fix the iron particles. The nature of the alignment of iron particles, according to Follett, suggested some neutralization of the charge on the colloidal iron that resulted in aggregation of the clays.

Petrographic studies (1, 7, 9, 18, 19, 20) reveal that lateritic soils often possess a porous granular structure consisting of iron-impregnated clayey material in minute spherical aggregations resembling popcorn balls. The strength of these aggregations is derived from the thin ferruginous films found within the microjoints of the elementary clay particles and as coatings over the particles (18). The role of the sesquioxides in the formation of these micro-aggregates is generally ascribed to one or all of the following: (a) cementation due to precipitation of a hydrated iron or aluminum gel and a subsequent irreversible dehydration of these materials, (b) the presence of iron in solution,

which prevents deflocculation, and (c) the formation of organic mineral compounds of humic acids with free sesquioxides (14).

INVESTIGATIVE PROCEDURES

Materials

Soil—The lateritic soil used in this investigation was obtained from a borrow pit located in Curundu, Panama Canal Zone. The geological profile of the borrow pit has been described elsewhere (23).

Lime—The lime used in this study is a quicklime (CaO) obtained from the St. Clair Lime Company, Sallisaw, Oklahoma. Because of the unstable behavior of quicklime upon exposure to the atmosphere, fresh lime samples were used to avoid carbonated fractions.

Sample Preparation

Sesquioxide Removal—The free iron and aluminum oxides in the soil were extracted by the sodium dithionite-citrate-bicarbonate treatment of Mehra and Jackson (15).

Remolding—Remolding of the soil to simulate the effects of heavy construction equipment was accomplished by mixing the soil in a Hobart mixer at a water content above the liquid limit for 2 hours. Unremolded soil was obtained by gently hand sieving the material at low moisture contents. Further details have been presented elsewhere (23).

Compaction—All test specimens were impact-compacted in a Harvard miniature compaction apparatus. For an objective comparison of the strength values of various soil-lime mixtures, it is essential that all specimens be compacted to the same density and possess relatively the same particle orientation. These criteria were developed in previous studies (23).

Methods and Equipment

X-Ray Diffraction—The mineralogical composition of the soil fractions was analyzed by X-ray examination of the oriented specimens (10). The procedure that was used involved separation, sesquioxide removal, and ion saturation. The silt and clay fractions were separated by gravity sedimentation. The coarse and fine clay fractions were subdivided by using a Sharples Supercentrifuge. Potassium or calcium saturations were accomplished by three washings with 1 N KCl or 1 N CaCl₂ respectively. The X-ray diffraction patterns were obtained by using a General Electric XRD 6 and a SPG 2 spectrogoniometer with a Ni filtered Cu K α radiation generated at 40 KV and 20 ma. The slits used were 1 deg MR beam and HR soller and 0.2 deg detector slit. The settings were T.C. of 2.0, CPS range of 1,000, and amplitude gains of 16 for coarse and 88 for fine.

Differential Thermal Analysis—The soil material analyzed consisted of unremolded, remolded, and "sesquioxide-free" soil samples that passed the No. 80 U.S. Standard sieve. These samples were allowed to equilibrate for 4 days in a sealed chamber over a saturated solution of magnesium nitrate, Mg(NO₃)₂ · 6H₂O. This pretreatment assured an exposure of the samples to a standard of 56 percent relative humidity, which permitted valid comparisons of the low-temperature peak system of clay thermograms (11). The DTA curves were obtained by using a Fisher Differential Thermal Analyzer Model 260 connected to a 1-mv strip chart recorder. Operating procedures involved heating the sample from ambient temperature to 1,200 C at a rate of 10 deg per minute.

Grain Size Distribution—The hydrometer method of analysis was used to obtain the grain size distribution curves of the portion passing the No. 100 U.S. Standard sieve. The unremolded soil was dispersed by gentle rotation of the graduated cylinder, while the remolded soil was dispersed in an electric mixing cup according to the usual procedure. Subsequently, the sesquioxides were extracted from the soil samples used for the unremolded and remolded analyses, and the grain size distributions of the sesquioxide-free soils were determined. Two milliliters of a 4 percent solution of Calgon were used as the deflocculating agent for all hydrometer tests.

Scanning Electron Microscopy—The scanning electron micrographs of the remolded, remolded plus lime, and sesquioxide-free soils were taken with a JEOLCO JSM-2

scanning electron microscope. Prior to scanning, the samples were coated by vaporizing a gold-palladium alloy metal wire in a JEOLCO JEE-4C vacuum evaporator.

DISCUSSION OF RESULTS

Mineralogical Analysis

The X-ray diffraction patterns of the coarse clay fractions of sesquioxide-free and remolded soil samples shown in Figure 1 reveal that the clay mineral of this soil is a 1:1 poorly crystallized kaolinite. The existence of iron coatings on the soil particles is indicated in this figure by the occurrence of a previously absent quartz peak (3.35 Å) after removal of the sesquioxides. The increased sharpness of the kaolin peaks (7.24 Å and 3.47 Å) upon treatment of the soil for sesquioxide removal also substantiates the presence of iron coatings. Additional X-ray diffraction studies of the silt fractions of the same samples shown in Figure 2 reveal that the soil has been extremely weathered with only some resistant quartz grains, a poorly crystallized kaolin clay, and magnetite remaining as the identifiable minerals. The presence of some secondary silica as cristobalite and some amorphous material is also suspected. The iron coatings inferred from comparisons of these diffraction patterns must exist as microcrystals or in amorphous forms that are undetectable by X-ray. No peaks were observed for goethite (4.15 Å, 2.69 Å, and 2.44 Å) or hematite (2.69 Å, 2.57 Å, and 1.69 Å), which are the most common forms of iron oxide coatings in soils. These findings are consistent with those of other investigators (8) who identified quartz, "intermediate kaolinite" (poorly crystallized kaolinite), and cristobalite as the mineral constituents of Panamanian lateritic soils.

The DTA thermograms of the unremolded, remolded, and sesquioxide-free samples are shown in Figure 3. These patterns indicate the presence of an amorphous material that is undetectable by X-ray diffraction. The large endothermic peak at 100 C is an important feature of thermograms for halloysite and allophane because kaolinite only exhibits a relatively small peak (10, 11). Allophane, an amorphous hydrous aluminosilicate, often occurs as a co-precipitate of iron oxides in highly weathered latosols and is believed to be a weathering relic (10) or precursor (1, 8) of halloysite or kaolinite. The marked decrease of this 100 C temperature endotherm in the iron-free sample

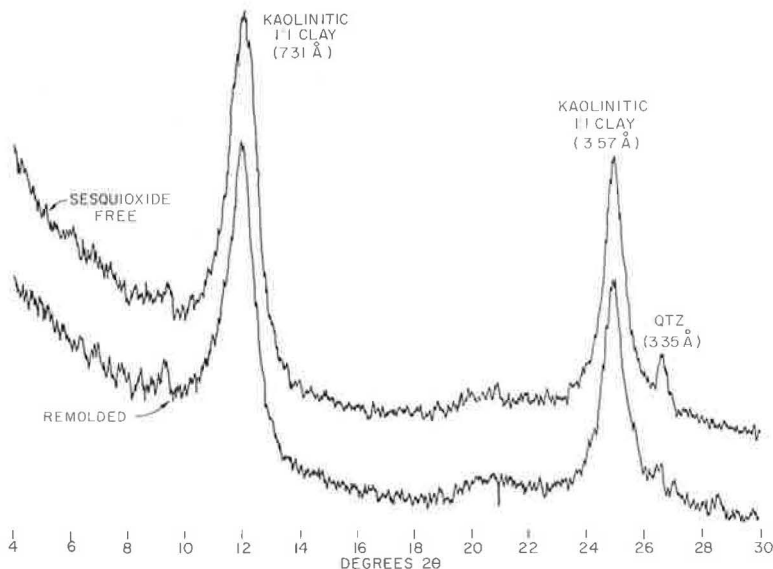


Figure 1. X-ray diffraction patterns of the coarse clay fraction (K-saturated).

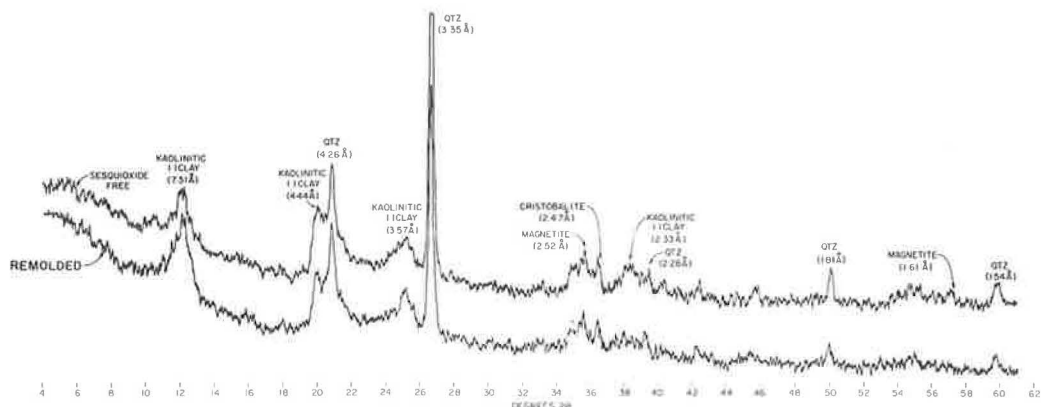


Figure 2. X-ray diffraction patterns of the silt fractions (Ca-saturated).

indicates the presence of an allophanic material. If this endotherm had been attributed solely to halloysite, it would still exist at an appreciable magnitude after the iron-removal treatment.

A large endotherm at 500 to 600 C is characteristic of 1:1 kaolin minerals, although highly crystallized kaolinite generally exhibits an endothermic peak at 600 C. However, a poorly crystallized kaolinite will dehydroxylate at slightly lower temperatures. The symmetry of this peak discredits the presence of halloysite. Thus, the main endotherm at 560 C confirms the X-ray diagnosis that the kaolinite is poorly crystallized.

The small exotherm at 880 C is suggestive of a mixture of poorly crystallized 1:1 kaolin minerals. The exothermic peak for highly crystallized kaolinite generally occurs in the neighborhood of 950 to 980 C. However, if the kaolinite is poorly crystallized or if allophane is present, this exotherm will be lower (10, 11).

The presence of a considerable quantity of amorphous material in the soil, perhaps as sesquioxidic allophane, was confirmed by a chemical analysis for allophane (10). The analysis revealed that approximately 20 percent free SiO_2 , 4 percent free Al_2O_3 , and 6 percent Fe_2O_3 exists in the minus No. 40 U.S. Standard sieve fraction. Generally, lateritic soils are considered to be low in free silica and relatively inactive. However, amorphous aluminosilicates have been reported in Panamanian soils (4) and in soils derived by the weathering of andesite (8), one of the parent rocks for this particular lateritic soil. The presence of these amorphous colloids undoubtedly contributes greatly to the behavior of this soil, as high water-retention capabilities and large specific surfaces are characteristic of amorphous colloids.

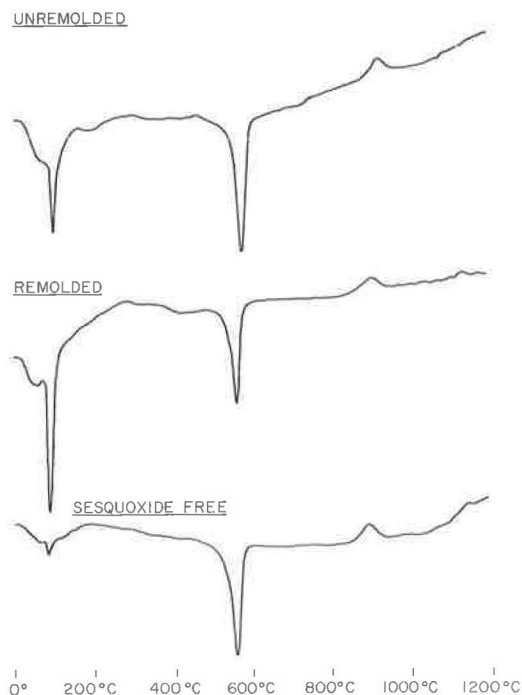


Figure 3. DTA thermograms of unremolded, remolded, and sesquioxide-free lateritic soil.

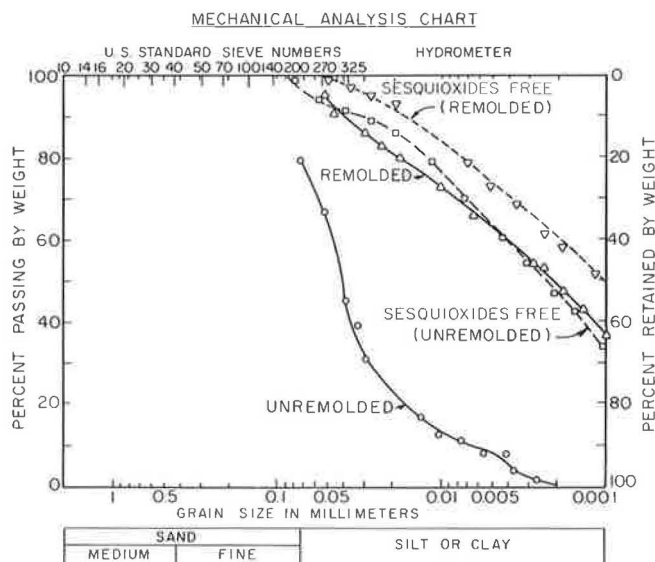


Figure 4. Effect of sesquioxide removal on the grain size of lateritic soil.

Physical Properties

Grain Size Analysis—Grain size distribution curves in Figure 4 show that remolded soil has a greater percentage of fine particles than does unremolded soil. This greater percentage of fines indicates that remolding by mechanical agents causes disaggregation of the friable granular soil aggregates. A comparison between the grain size curves for the unremolded soil in the natural and sesquioxide-free conditions shows a considerable increase in finer sizes after removal of the sesquioxides. This increase confirms that the soil in its natural state consists of clay-sized particles bonded into micro-aggregates by sesquioxide cementing agents. Similar results have been reported by Winterkorn (24) and Pearing (17), who showed increases in clay-size fractions and corresponding decreases in sand- and silt-size fractions after removal of the sesquioxides from various lateritic soils.

A comparison of the grain size curves for remolded soil in the natural and sesquioxide-free conditions reveals that removal of the sesquioxides further increases the amount of fines in the soil. This increase suggests that the iron and aluminum oxides continue to coat and to bond the soil particles. Thus, the remolding phenomenon merely produces smaller micro-aggregates of iron-impregnated clays.

TABLE 1
PHYSICAL PROPERTIES OF UNREMOLDED, REMOLDED,
AND SESQUIOXIDE-FREE LATERITIC SOIL

Property	Unremolded	Remolded	Sesquioxide-Free
Atterberg limits			
Liquid limit (percent)	57.8	69.0	51.3
Plastic limit (percent)	39.5	40.1	32.1
Plasticity index (percent)	18.3	28.9	19.2
Specific gravity	2.80	2.80	2.67
Proctor density (pcf)	84.5	83.0	88.0
Optimum moisture content (percent)	35.0	34.5	29.5

Atterberg Limits—The results of the Atterberg limits tests given in Table 1 show that remolding increased the liquid limit of the soil, whereas the plastic limit remained essentially the same. This increase in plasticity has been attributed to the breakdown of the granular structure, which increases the amount of fines and exposes more surface area for the adsorption of moisture (16, 23, 24).

Removal of the iron and aluminum oxides would be expected to increase the plasticity of the soil because of (a) increased amounts of fine particles released from the previously cemented clay clusters and (b) removal of the plasticity-suppressing sesquioxide coatings from the surfaces of the clay minerals. Newill (16) obtained an increase in liquid limit from 77 percent to 93 percent after removal of the iron oxides from his lateritic soil sample. However, the results given in Table 1 show that removal of the sesquioxides caused a significant decrease in the liquid limit and plastic limit values of the soil. Apparently, removal of the sesquioxides alters the water-retention capabilities of the soil. This alteration was also shown by the drastic reduction in peak intensity of the 100 C peak of the DTA curves in Figure 3. One of the characteristics of amorphous colloids is a high water-retention capability due to their large specific surfaces. Therefore, the decrease in plasticity of the remolded soil from 28.9 to 19.2 percent after removal of the sesquioxides can be partially attributed to the removal of these amorphous sesquioxides of the soil. Concurrently, removal of sesquioxidic cementing agents destroys the porous micro-aggregates, thereby eliminating the micro-voids and clayey clusters that Terzaghi (21) described as the cause for the high Atterberg limits associated with lateritic soils.

Engineering Properties

Proctor Density—Density values were determined from miniature samples compacted with an energy per unit volume equal to that used in the standard Proctor compaction test. These values are given in Table 1. Usually, rather high compacted densities would be anticipated for lateritic soils because of the high specific gravity of the abundant iron oxides (2). However, compaction studies revealed very low densities and very high optimum moisture contents in comparison with temperate-zone clays with similar index values. The low density of this soil, 84.5 pcf, is attributed to its granular nature. The micro-aggregates in the soil impart a high void ratio and corresponding low density. The relatively high optimum moisture content results from water held within the porous micro-aggregations and from that associated with the amorphous constituents of the soil. This moisture is trapped and unable to contribute substantially to the "lubrication" of the soil particles during compaction.

Contrary to normal expectations, removal of the heavy sesquioxides resulted in an increase in density (84.5 to 88.0 pcf) and a decrease in optimum moisture content (35.0 to 29 percent). This apparently contradictory behavior is attributed to the breakdown of the granular structure by removal of the sesquioxidic cementing agents. This breakdown allows a closer packing of the clayey particles and a lower void ratio. The decrease in optimum moisture content is due to an alteration of the amorphous colloids and porous micro-aggregates. The effects are analogous to those resulting in the reduction in plasticity.

Shear Strength Parameters—The results of various triaxial compression tests for compacted soil in the saturated and unsaturated conditions are given in Table 2. The undrained test (Q) was used to evaluate ϕ and c values of unsaturated soil, whereas the "effective stress" parameter, ϕ' , was measured by consolidated-undrained tests with pore pressure measurements (\bar{R}). These results indicate that, despite its low density

and high plasticity, this soil possesses satisfactory strength characteristics in a compacted state. The magnitude of the ϕ' values reflects the inherent granular nature of the soil.

Apparently, remolding has little effect on the shear strength parameters of the compacted soil. However, remolding decreased the angle of internal friction and increased the cohesion. This reduction in ϕ and ϕ' is attributed to a reduced interlocking of the disaggregated soil grains, whereas the increase in cohesion is due

TABLE 2
SHEAR STRENGTH PARAMETERS FOR A LATERITIC SOIL

Test Conditions	Unremolded	Remolded	Sesquioxide-Free
Undrained test (Q)			
ϕ (deg)	26.0	24.0	11
c (kg/cm ²)	0.42	0.56	0.91
Consolidated-undrained (\bar{R})			
ϕ' (deg)	38	37	32

to a more characteristic behavior of the disaggregated clays. Nevertheless it must be concluded that, although remolding greatly influences the index properties, little change is observed in the strength characteristics of the various soil states.

Lime Stabilization—The results of lime stabilization are shown in Figure 5. For these tests 5 percent lime was selected as the comparison percentage. Comparisons of the various curves shown in Figure 5 reveal some interesting aspects. The unremolded, remolded, and sesquioxide-free soils all exhibit strength increases with time. These strength increases indicate that pozzolanic reactions are occurring. However, the variations in the magnitude and the speed of the strength gains suggests that the susceptibility of the soil to stabilization is influenced by mechanical working and chemical alteration.

Because most or all of the free silica has been removed from lateritic soils during the genesis of the soil, the primary source of silica available for pozzolanic reactions would be in the inherent clay minerals. However, the presence of sesquioxidic coatings on the surfaces of these clays inhibits the calcium and clay (silica) reactions. Thus, the retarded and poor response of the lime-stabilized unremolded soil in producing significant strength increases is attributed to the nonavailability of the clay minerals for reaction with the lime. The exhibited strength gains of the unremolded soil are probably limited to the reaction of the lime with small amounts of amorphous silica.

Although the clay surfaces probably remain coated by the sesquioxides after mechanical remolding, evidently the lime susceptibility of the soil is enhanced. Apparently the increased amount of finer particles produced by remolding supplies greater surface areas for soil-lime reactions. Therefore, the primary difference between the responses of the unremolded and remolded soil to lime treatments is attributed to particle size.

Generally, it would be expected that removal of the sesquioxides would produce greater strength gains than those obtained for the natural soil in the unremolded and remolded conditions. These greater strengths would result from (a) increased amount of fines due to the chemical breakdown of the clay aggregations and (b) removal of the protective sesquioxidic coatings from the surfaces of the indigenous clay particles. Thompson (22) evaluated this concept using natural and iron-free non-lateritic soils that were treated with 5 percent lime. His results showed that strength increases were greater for the soil in the iron-free state than for the corresponding natural condition. However, Figure 5 shows that removal of the sesquioxides from the Panamanian lateritic

soil produced strengths higher than those of the unremolded soil but lower than those of the remolded soil. Thus, the concept that the free iron and aluminum oxides retard the lime susceptibility of the soil is only partially substantiated.

Comparisons of the strengths of remolded soil with those of sesquioxide-free soil indicate that extraction of the sesquioxides reduces the lime reactivity of the soil. Because both the remolded and sesquioxide-free samples possess similar grain size distributions (Fig. 4), it appears that the sesquioxide extraction process removed something that contributed to the stabilizing reactions. Previously it was indicated that the extraction procedure greatly alters the characteristics of the amorphous materials in the soil. Therefore, it is apparent that the major contributors to the stabilizing reactions in this soil are the amorphous alumina and silica because these amorphous colloids can readily enter into pozzolanic reactions because of their high specific surfaces and reactivity. It appears reasonable to conclude that lime

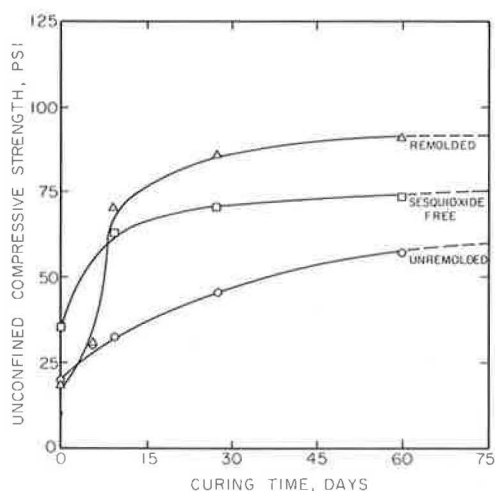


Figure 5. Effect of curing age on unconfined compressive strength of a lateritic soil plus 5 percent lime.

would be an ineffective stabilizer for lateritic soils unless a substantial quantity of amorphous allophanic colloids are available in the soil for pozzolanic reactions.

The scanning electron micrographs shown in Figures 6 through 9 were obtained using samples from sealed lime-treated, remolded specimens that had cured for more than 18 months in a moist room at 20 C. The micrographs were made to observe the various types of soil-lime reaction products and to determine at what lime concentration they were formed. Generally, these reaction products have been identified as hydrated forms of calcium silicate (CSH) that resemble the tobermorite minerals and/or calcium aluminate (CAH).

Photomicrographs of remolded and sesquioxide-free specimens to which no lime has been added are shown in Figures 6 and 7 respectively. The granular, fluffy, micro-aggregated clays of the remolded soil are easily seen in Figure 6. Contrasting with this aggregated structure is the platey structure of the sesquioxide-free soil shown in Figure 7. Jointly, these two photomicrographs strikingly show the agglomerating effect of the sesquioxides.

A photomicrograph of a specimen to which 10 percent lime has been added to the remolded soil is shown in Figure 8. The formation of new crystals is quite evident in this figure. The irregular platelets whose edges appear as laths are tentatively identified as CSH. The cubic crystals (grape-like bunches) shown in Figures 8 and 9 are thought to be lime, CaO , that has not entered into any pozzolanic reactions. However, CAH also possesses a cubic structure, and these cubes may be some form of this compound.

A photomicrograph of a specimen to which 20 percent lime has been added to the remolded soil is shown in Figure 9. The rolled-up tubular sheet is tentatively identified as a pseudo-tobermorite mineral (CSH).



Figure 6. Scanning electron photomicrograph of remolded lateritic soil (3,000X).

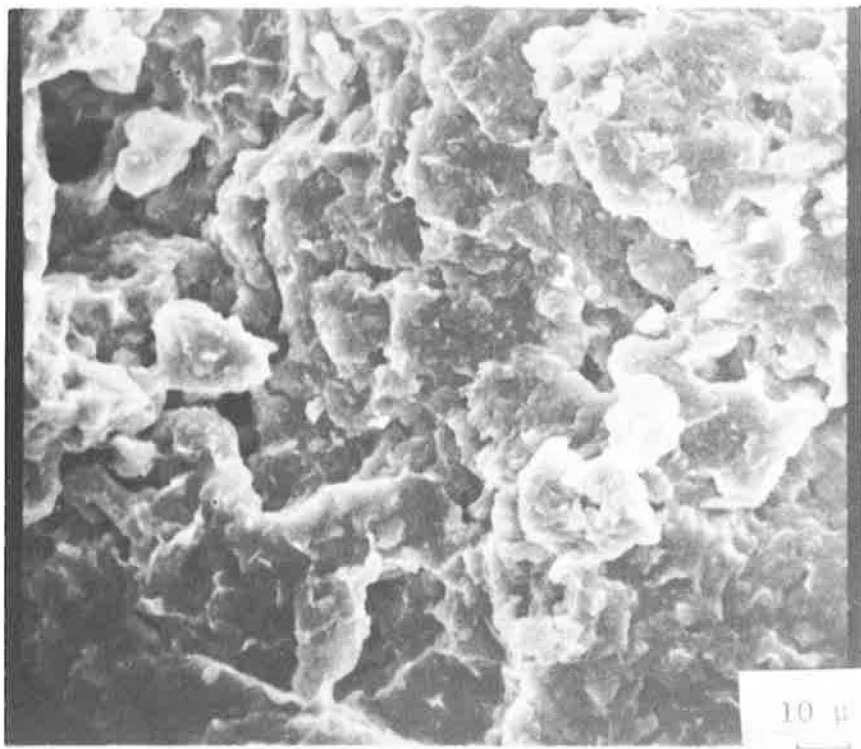


Figure 7. Scanning electron photomicrograph of sesquioxide-free lateritic soil (600X).

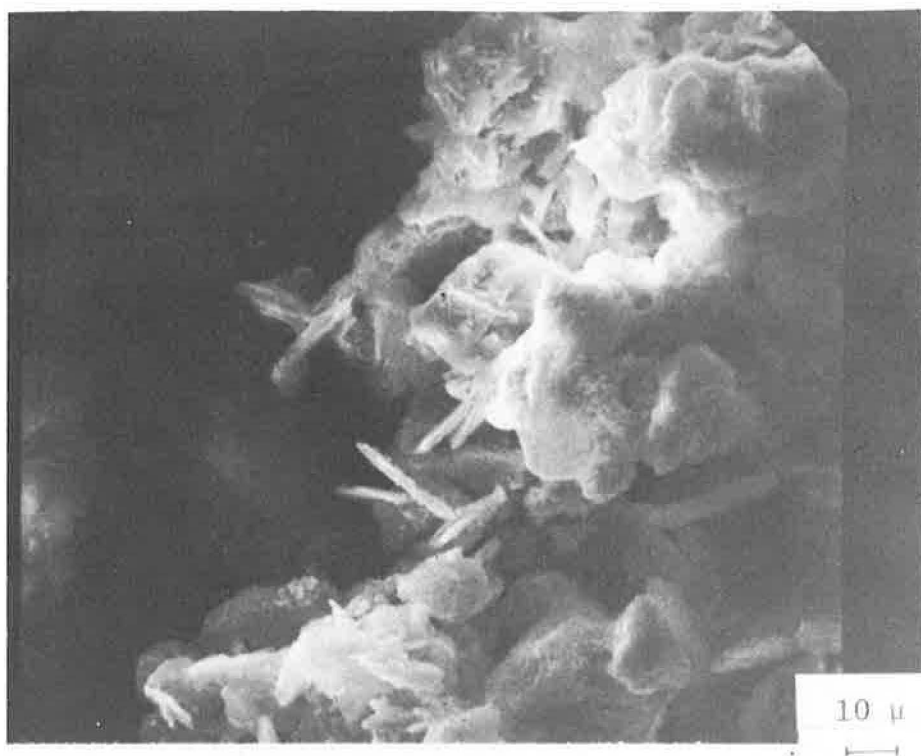


Figure 8. Scanning electron photomicrograph of remolded lateritic soil plus 10 percent lime (600X).

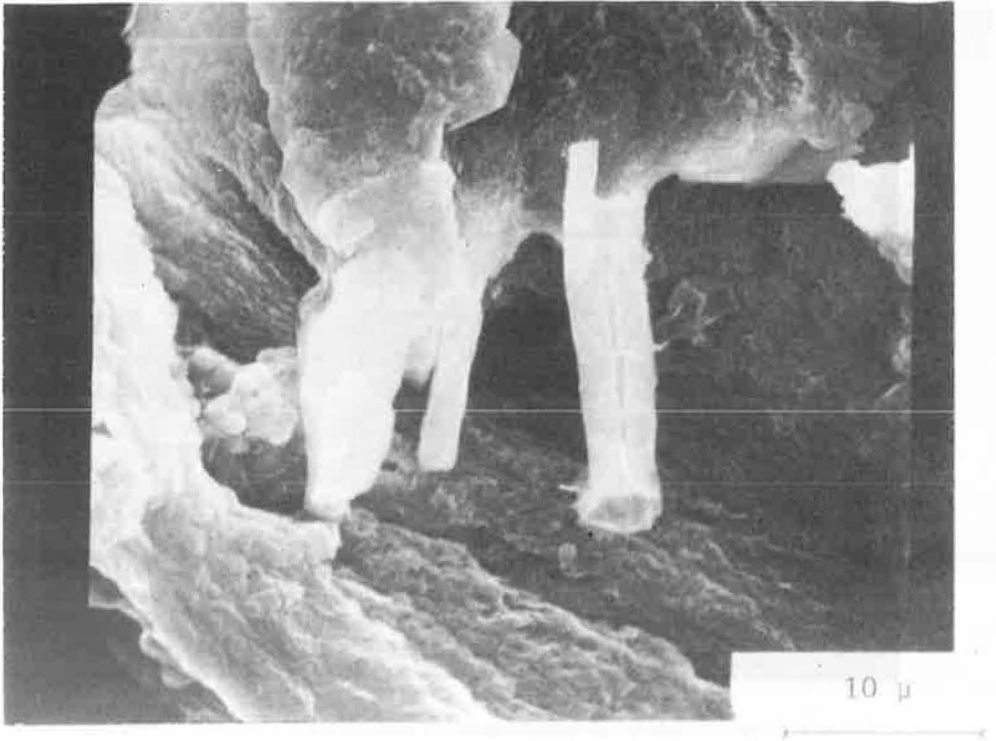


Figure 9. Scanning electron photomicrograph of remolded lateritic soil plus 20 percent lime (2,400X).

Figures 8 and 9 show that lime reaction crystals are formed in the lateritic soil-lime mixtures. However, these crystals were only observed in photomicrographs of soil-lime mixtures containing more than 5 percent lime.

CONCLUSIONS

The results of this investigation revealed that the sesquioxides of iron and aluminum strongly influence the engineering behavior of this lateritic soil. The following conclusions can be made for this type of soil and the testing procedures employed:

1. Mineralogically, the soil is composed primarily of remnant quartz grains and a 1:1 poorly crystallized kaolinite. Secondary silica, such as cristobalite and chalcedony, and magnetite exist in the soil in lesser amounts. In addition to these minerals, considerable quantities of free amorphous iron, aluminum, and silica are present in the soil.
2. The sesquioxides of iron and aluminum influence the behavior of this soil by coating the clayey constituents of the soil and binding them into coarser aggregations. These sesquioxides coatings on the indigenous clay minerals suppress their normal behavioral characteristics, and the aggregations impart a granular structure to the soil.
3. The amorphous allophanic constituents are largely responsible for the exhibited physicochemical behavior of the soil because of the large specific surfaces and high moisture-retention capabilities characteristic of these materials. Undoubtedly the index properties and chemical stabilization susceptibility of the soil would be affected by the presence of these colloids.
4. Remolding of the soil greatly influences the textural characteristics and plasticity. The granular structure is quite friable and readily breaks down to increase the percentage of finer particles. The increased amounts of fines cause an increase in the plas-

ticity of the soil. The high moisture-retention capabilities of the amorphous constituents provide abnormally high moisture contents for this soil. Because these index properties are affected by remolding and the presence of amorphous colloids, new or revised laboratory tests should be developed to evaluate the properties of lateritic soils. The $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio provides a possible means of predicting the engineering characteristics of lateritic soils.

5. The inherent granular structure of the soil influences the engineering characteristics. Despite the presence of heavy sesquioxides in the soil, the granular aggregations produce a soil that has a low density and high void ratio. The high angles of internal friction reflect a greater amount of interlocking than is normally found in soils having such a high proportion of platy minerals. Disruption of the granular structure by remolding has little effect on the shear strength parameters of the compacted soil.

6. Lime is an effective stabilizer for this lateritic soil. Its effectiveness is primarily attributed to the availability of amorphous silica, rather than to the sesquioxide-coated clay minerals, for strength-producing pozzolanic reactions.

7. Because of the apparent relationship between amorphous constituents and lime susceptibility of this soil, it may be possible to predict the lime stabilization capability of lateritic as well as other types of soil through determination of the amorphous allophanic colloid content.

REFERENCES

1. Alexander, L. T., and Cady, J. C. Genesis and Hardening of Laterite. USDA Tech. Bull. 1282.
2. Bawa, K. S. Laterite Soils and Their Engineering Characteristics. Jour. Soil Mech. and Found. Div., ASCE, Vol. 83, Nov. 1957.
3. Bennett, H. H. Some Comparisons of the Properties of Humid Tropical and Humid-Temperate American Soils, With Special Reference to Indicated Relations Between Chemical Composition and Physical Properties. Soil Science, Vol. 21, 1926, p. 349.
4. Brown, J. W., and Wolfschoon, T. A. Some Chemical and Physical Properties of Representative Soils of the Republic of Panama. 7th Internat. Conf. on Soil Science, Vol. 4, 1960, p. 271.
5. Follett, A. E. C. The Retention of Amorphous Colloidal "Ferric Hydroxide" by Kaolinite. Jour. Soil Science, Vol. 16, 1965, p. 334.
6. Greenland, D. J., and Oades, J. M. Iron Hydroxides and Clay Surfaces. 9th Internat. Conf. on Soil Science, Vol. 1, 1968, p. 657.
7. Hamilton, R. Microscope Studies of Laterite Formation. In Soil Micromorphology, Elsevier Pub. Co., Amsterdam, 1964, p. 269.
8. Hendricks, D. M., and Whitlig, L. D. Andesite Weathering: I. Mineralogical Transformations From Andesite to Saprolite. Jour. Soil Science, Vol. 19, 1968, p. 135.
9. Humbert, R. P. The Genesis of Laterite. Soil Science, Vol. 65, 1948, p. 281.
10. Jackson, M. L. Soil Chemical Analysis. Univ. of Wisc. Press, Madison, 1956.
11. Mackenzie, R. C. The Differential Thermal Investigation of Clays. Mineralogical Society, London, 1957.
12. Maignien, R. Review of Research on Laterites. Nat. Res. Research IV, UNESCO, Paris, 1966.
13. Mattson, S. Anionic and Cationic Adsorption by Soil Colloidal Materials of Varying $\text{SiO}_2/\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ Ratio. Proc. First Internat. Cong. of Soil Science, Vol. 2, 1927, p. 199.
14. McIntyre, D. S. Effect of Free Ferric Oxide on Soil Structure. Jour. Soil Science, Vol. 7, 1956, p. 302.
15. Mehra, P. O., and Jackson, M. L. Iron Oxide Removal From Soils and Clays by a Dithionite-Citrate System With Sodium Bicarbonate Buffer. Proc. 7th Conf. on Clays and Clay Minerals, Pergamon Press, N.Y., 1960, p. 317.
16. Newill, D. A Laboratory Investigation of Two Red Clays From Kenya. Geotechnique, Vol. 11, 1961, p. 302.

17. Pearring, J. R. A Study of Basic Mineralogical Index Properties of Lateritic Soils, Physical-Chemical and Mineralogical. Tech. Rept. No. AFWL-TR-69-21, USAF Weapons Lab., Kirtland AFB, New Mexico, 1969.
18. Ramashkevich, A. I. Micromorphological Indications of the Processes Associated With the Formation of the Krasnozems (Red-Earths) and the Red-Colored Crust of Weathering in the Transcaucasus. In *Soil Micromorphology*, Elsevier Pub. Co., Amsterdam, 1964, p. 261.
19. Schmidt-Lorenz, R. Zur Mikromorphologie der Eisen und Aluminiumoxydranreicherung Beim Tonmineralablauf in Lateriten Kerolas und Ceylons. In *Soil Micromorphology*, Elsevier Pub. Co., Amsterdam, 1964, p. 297.
20. Sirarajasingham, S., Alexander, L. T., Cady, G., and Cline, M. G. Laterite. *Adv. in Agron.*, Vol. 14, 1962, p. 1.
21. Terzaghi, K. Design and Performance of Sasamua Dam. *Proc. Inst. of Civil Eng.* Vol. 9, April 1958, p. 369.
22. Thompson, M. R. Lime Reactivity of Illinois Soils. *Jour. Soil Mech. and Found. Eng.*, ASCE, Vol. 92, Sept. 1966.
23. Townsend, F. C., Manke, P. G., and Parcher, J. V. Effects of Remolding on the Properties of a Lateritic Soil. *Highway Research Record* 284, 1969, pp. 76-84.
24. Winterkorn, H. F., and Chandrasekharan, E. C. Lateritic Soils and Their Stabilization. *HRB Bull.* 44, 1951, p. 10.
25. Wissa, A. E. Z., and Rurik, H. Chemical Stabilization of Selected Tropical Soils From Panama and Canal Zone. *Waterways Experiment Station, WES Rept. No. 3-63*, Vicksburg, Miss., 1963.