Effects of Remolding on the Properties of a Lateritic Soil

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This laboratory study of a Panamanian lateritic soil shows that remolding or working by mechanical agents alters the soil's physical properties and strength parameters. Results of grain size analysis and Atterberg limits tests indicated that working causes a breakdown of its granular structure and an increase in its plasticity. The efficacy of various stabilizing additives using both worked and unworked soil samples was investigated. Results indicated that stabilization is influenced to a considerable extent by the amount of mechanical working. Portland cement was the most effective of the three additives tested and yielded higher unconfined compressive strengths with the unworked soil. Lime was also an effective stabilizer, but reacted more favorably with the soil in the worked condition. The primary benefit derived from asphaltic stabilization was waterproofing rather than substantial strength gains.

An evaluation of the test results led to the postulation that a substantial portion of the clay particles has been coated with iron and aluminum oxide (sesquioxide) films, and that working by mechanical agents causes a breakdown of this coating allowing the clay particles to behave in a more characteristic fashion. New or revised laboratory testing techniques are needed for this type of soil.

•LATERITES are residual soils found primarily in tropical areas of Africa, Central and South America, and Southeast Asia. The soil is formed by the intensive weathering of almost any rock: basalt, granite, gneiss, breccia and conglomerates (1). The weathering process, laterization, involves the complete leaching out or removal of the silica, alkali, and alkaline earths, and the concentration of iron and aluminum oxides in the hydrated form.

The engineering characteristics of laterite vary with geographic location in accordance with the soil form that develops. Generally, in situ laterite and lateritic soils possess a granular structure due to the abundance of iron and aluminum oxides (sesquioxides) that coat the pore walls, fill the voids, and bind the soil particles into agglomerated nodules of various sizes. Winterkorn (2) stated that the presence of iron in laterite soils was one of the most important factors influencing their engineering properties. The granular structure is responsible for the desirable engineering properties displayed by unworked laterite and lateritic soils. However, the high bearing strength, low plasticity, and high permeability associated with unworked laterites are lost upon working the soil, i.e., mixing, compacting, or employing any type of extensive mechanical manipulation in the presence of water. When worked, the granular structure is apparently broken down, and the material becomes highly plastic with low bearing capacity and poor drainage.

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As Winterkorn (2) stated, "the task is to search for and adopt suitable mixing and compaction methods that would not destroy the granular structure and yet yield sufficient density." The use of stabilizing admixtures, e.g., lime, portland cement, asphalt, or chemicals, would appear to be a possible solution. However, it is possible that admixtures could produce different stabilization characteristics depending on the intensity and duration of the mixing process. Knowledge in this area should assist in explaining the peculiar behavior of lateritic soils and quite possibly would be of assistance to construction and soils engineers working in tropical areas.

In the case of laterite soils, it appears that excessive manipulation transforms a desirable construction material into an undesirable one. This investigation was directed primarily toward the determination of quantitative differences in the plastic properties, grain size distribution, and compaction characteristics of worked and unworked laterite soil. The influence of these changes on the unconfined compressive strengths has also been investigated, both in relation to the natural soil and to soil in which stabilizing additives have been mixed. The investigation was limited to soil from a single source, and to the stabilizing additives, lime, portland cement, and MC-3 asphaltic cutback.

ENGINEERING CHARACTERISTICS OF LATERITIC SOILS

Structure and Physicochemical Properties

The success of any stabilizing additive depends to a large extent on the physicochemical properties of the soil. The intense weathering processes which produce lateritic soils are quite complex and have been emphasized in the studies of several soil scientists (3, 4, 5, 6). The presence of the sesquioxides and their relationship to the clay minerals are probably the most influential factors affecting the engineering behavior of lateritic soils. In the natural condition, the soil appears granular and possesses characteristics comparable to coarse-grained rather than clayey soils. These characteristics are due to the aggregation of the clay particles into clusters by the sesquioxides.

Based on petrographic studies, several authors (5, 6, 7) report that lateritic soils appear as tiny spherical aggregates or clusters of clayey materials. The formation of these clusters is partially due to the opposing electromagnetic charges possessed by the clay and iron. In tropical areas, the clays appear to develop an extra amount of negative charge due to the neutral or slightly alkaline rainwaters. This is caused by the dissociation of the Si-OH groups into SiO-H+ (8). Because of its electropositive charge, the iron vigorously attaches itself to the clay (4). Continued movement and dehydration increase the crystallinity and continuity of the iron (goethite) films, which cause clustering of the clay particles.

Atterberg Limits

The Atterberg limits have been used extensively and quite successfully to classify cohesive soils in temperate areas and, in a general way, to predict their behavior on the basis of these index properties. However, correlation of this kind in connection with lateritic soils has often led to erroneous conclusions. It has been shown that the Atterberg limits of lateritic soils depend to a large extent on the amount of remolding or working of the sample during the test and treatment of the sample prior to testing (9). A liquid limit deviation of ±15 percent, depending upon treatment of the sample prior to testing, was reported for a lateritic clay near Nairobi, Kenya (7).

Winterkorn and Chandarshekharan (2) observed a change in liquid limit from 46 to 53 percent, depending upon the amount of remolding of the soil, with no observed change in plastic limit. Terzaghi (7), explaining the anomalous behavior of lateritic soils as contrasted with normal soils having similar Atterberg limits, attributed the differences to the presence of microaggregate clusters of clay and goethite (hydrated iron oxide). He stated the soil had the plasticity index and engineering properties of a relatively coarse-grained soil. Yet, the liquid limit was equal to that of a normal soil of high plasticity, because the quantity of water which evaporated during the process of drying a sample was equal to the sum of the quantity of water located between the clusters and that contained in the voids of the porous microaggregates.

Grain Size

The friable nature of some laterites allows a ready breakdown of the granular components into finer particles. Therefore, the treatment prior to or during testing can greatly alter the results. Because the particle size depends upon the amount of disaggregation prior to testing, it is difficult to obtain reliable grain size data for these residual soils (10).

Compaction

Experience has shown that the optimum moisture content is commonly close to or slightly below the plastic limit. Since, during the wet season, the natural moisture content of lateritic soils may be slightly above the plastic limit, it is often necessary to dry the soil prior to compaction (7). Compaction of the soil at moisture contents higher than the plastic limit is accompanied by remolding and a subsequent increase in plasticity. This results in lower densities and may create problems in the efficient and economical utilization of equipment.

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 is described as follows (11):

> 0-4 ft—Clay OH 3-4. Medium hard to hard, moderate strength, moderate to high plasticity, high dry strength, moderate water content, silt content increases with depth; consists of a residual saprolitic clay derived from agglomerate by normal weathering processes. Color: mottled bright reds and buff.
>
> 4-17.5 ft—Silt OH 3-4. Medium hard to hard, moderate strength, low plasticity, moderate to low dry strength, moderate water content, very clayey at top becoming sandy at base; consists of residual saprolitic clayey, sandy silt derived from agglomerate by normal weathering processes. Color: mottled bright red and buff at top grading to mottled greys and browns at base.
>
> 17.8-18.5 ft—Top of sound rock Agglomerate RH 3. Hard, strong, massive jointing and bedding; consists of andesitic and basaltic pebbles ranging from 1/4 in. to 3.0 ft in diameter in a fine-grained sandy matrix of similar composition. Color: mottled reds, browns, blue-grey in a blue-grey matrix; oxidizes rapidly to dark grey and brown on exposure to air.

A narrow grey mottled zone mentioned by several authors (3, 12), as characteristic of lateritic soils, was observed approximately 2 to 4 ft below the natural ground surface. During laboratory testing, numerous small angular pebbles of chalcedony, quartz, and probable parent rock were encountered in the soil. The quartz and chalcedony are secondary products of laterization which were formed by chemical precipitation of the leached silica.

The results of a chemical analysis on the soil showed the $SiO_2{:}R_2O_3$ ratio was 1.22. Using the classification criterion of Martin and Doyne (13), the soil would be classed as a "laterite"; however, because there is no hard indurated crust in the natural formation, the term "lateritic soil" is preferred.

Stabilizing Additives—Many different materials have been used as stabilizers with varying degrees of success. Quicklime (CaO) was the primary stabilizing additive used in this investigation. A comparison series of specimens utilizing either 5 percent Type I portland cement or 6 percent MC-3 asphaltic cutback were also tested. No attempt was made to determine the optimum quantity of the respective stabilizers to be used with this particular soil.

Sample and Specimen Preparation

Mechanical manipulation to simulate the effects of heavy construction equipment was accomplished by mixing the soil, at a water content above the liquid limit, in a Hobart mixer for various periods of time. Worked soil used for standard index property tests was mechanically mixed for 2 hr and the worked material utilized for unconfined compression test specimens was mixed for a ½-hr period. After mixing, the worked slurry was air dried and ground to pass the No. 10 U.S. Standard sieve. Unworked material was obtained by gently hand sieving the soil through a No. 10 sieve.

Sample Mixing—A major problem in all phases of study was to prevent or minimize working the unworked material used in the various tests and the compacted test specimens. In some cases this could not effectively be done, e.g., in determining the Atterberg limits, in performing hydrometer analyses, and in compacting test specimens. This points out the need for the development of new or modified laboratory testing procedures, as mentioned by Winterkorn (2), when testing a friable soil such as laterite.

Moisture was added to the unworked samples of the soil prior to compaction or addition of the stabilizer by placing the sample in tare pans, sprinkling it with the desired amount of water, then sealing the pan and contents in a plastic bag and allowing them to sit undisturbed for at least 24 hr to assure a uniform distribution of the added moisture. For the worked samples, the soil, additive, and required amount of water were mixed in a Hobart mechanical mixer. To achieve thorough mixing of the soil and MC-3, the soil was moistened to the optimum moisture content prior to the addition of the cutback. The moisture in the soil serves as a carrier for the cutback and permits uniform distribution of the asphalt during the mixing operation.

Compaction of Test Specimens—For a valid comparison of the strengths of various soil-stabilizer mixtures, it is necessary that all specimens be compacted to the same density and possess about the same particle orientation. Prior to compacting the test specimens, Proctor compaction tests were made on the respective mixtures using varying compactive efforts (Table 1).

The compactive efforts used were 15, 25, and 35 blows per layer on three layers per test specimen. These tests were conducted using the same compaction mold that was used to mold the unconfined compression test specimens. This method allowed the approximate determination of the number of blows per layer required to achieve a density of 82.5 pcf and the optimum moisture content for this number of blows.

All specimens were compacted in a Harvard miniature compaction apparatus. Approximately 110 gm of soil-stabilizer mixture were compacted in three layers to a density of 82.5 pcf.

TABLE 1

COMPACTION DATA OF SOIL MIXTURES

Mixture	d	w_{opt} (%)	No. Blows per Layer
Unworked—no additives	82.5	35	18
Worked—no additives	82.5	35	30
Unworked + 5% lime	82.5	34	42
Worked + 5% lime	82.5	33.5	32-33
Unworked + 5% PC	82.5	33	20-25
Worked + 5% PC	82.5	32	25-28
Unworked + 6% MC-3	82.5	35[a]	25-27
Worked + 6% MC-3	82.5	33[a]	15

[a]Based on liquid content (volatiles plus water).

Curing Test Specimens—After compaction, the soil-lime and soil-cement specimens were wrapped in Saran Wrap, waxed, and stored in a moist room for a specified curing period. Three curing periods (12, 28, and 60 days) were used for the soil-cement mixtures. The soil-lime mixtures were cured for 5, 12, 28, and 60 days before testing. The soil-asphalt mixtures were dried in an oven at 150 F until a major portion of the volatile constituents in the cutback and most of the mixing water were removed. After drying to an estimated "optimum liquid content" the soil-asphalt mixture was removed from the oven and compacted into test specimens.

Testing Procedures

Atterberg Limits—Atterberg limits were determined for the soil in the unworked and worked conditions. New material was used for the determination of each point on the flow curve of the unworked soil in order to minimize spatula manipulations. The used unworked soil was then worked for 2 hr, air dried, and ground to pass the No. 40 U.S. Standard sieve. Limit determinations on the worked soil were carried out with no modification of the standard methods. Four flow curves were plotted for both the unworked and worked soil and a least square regression analysis was used to combine the curves into one average curve for each of the soils.

Grain Size Analysis—Grain size determinations utilized slightly modified mechanical and hydrometer methods of analysis. Before conducting the analysis, the soil samples were soaked in distilled water to which a deflocculant, Calgon, had been added. The soaked samples were washed through a set of U.S. Standard sieves and, after drying, the percentages retained on the various sieves were calculated. The material passing the No. 100 and retained on the No. 200 sieve was recombined with the material passing the No. 200 and used for the hydrometer analysis. By this procedure, an overlap point (a point determined by both sieve and hydrometer analysis) was obtained. The unworked samples were not beaten in an electric mixer as suggested by normal procedures. Flocculation was avoided by using only 2 ml of 4 percent Calgon.

Unconfined Compression Tests—After the specified curing time, the compacted specimens were stripped of their wax coatings, and their unconfined compressive strength determined. The tests were conducted at a constant deformation rate of 0.05 in./min. The reported results are the average of at least four tests. The peak stress was chosen to represent failure. Moisture contents of the broken specimens were determined to insure that no appreciable moisture changes had occurred during storage.

RESULTS AND DISCUSSION

Test results reported in the literature (1, 2, 7, 9) and those obtained in this study indicate that working causes a breakdown of the lateritic soil particles and an increase in plasticity. During the laterization process, kaolinite, a clay, is one of the early primary minerals formed by weathering. Further weathering leaches the silica and alkaline earths leaving an abundance of iron and aluminum oxides in hydrated form. These sesquioxides coat and impregnate the clay particles, satisfying their electromagnetic charges and altering some characteristics of the clay, e.g., its plasticity. It is postulated that when these coated clay particles are worked by mechanical agents in the presence of water, the iron oxide coating is partially or totally abraded from the clay, allowing the clay characteristics to become more prevalent. Therefore, the integrity of the iron coatings, which provide the granular structure, largely determines the engineering properties and behavior of lateritic soils.

However, it might also be argued that the change in plasticity of the soil by mechanical working results solely from the increased amounts of fine particles created by the breakdown of the microaggregates. The results of the tests performed in this study do not offer sufficient evidence to verify or refute either concept.

Atterberg Limits

The test results (Table 2) show that working increased the liquid limit of the soil from 57.8 to 69.0 percent and that the plastic limit remained about the same. Similar increases in the liquid limit of lateritic soils have been reported by Winterkorn (2) and Newill (9). The increase in plasticity is probably due to both an increased number of fines and a partial removal of the sesquioxide coatings as a result of the breakdown of the granular structure.

TABLE 2

PHYSICAL PROPERTIES OF UNWORKED AND WORKED LATERITIC SOIL

Property	Worked	Unworked
Atterberg limits:		
Liquid limit, %	69.0	57.8
Plastic limit, %	40.1	39.5
Plasticity index, %	28.9	18.3
Specific gravity	2.80	2.80

The one-point liquid limit determination offered a means of evaluating the liquid limit for the unworked soil without excessively manipulating the sample. Pilch et al (14) proposed the following equation:

$$LL = Wn(N/25)^{\tan \beta}$$

where

LL = liquid limit of the soil;
Wn = moisture content at N blows;
N = number of blows; and
$\tan \beta$ = slope of flow curve on a log-log plot of N vs W.

The average value of $\tan \beta$, determined by experiments, was 0.121, and this value was adopted in ASTM Test D 423-59. If there is a substantial difference in the value of $\tan \beta$ for the worked and unworked soil, it might be expected that the one-point determination would be unreliable. It was found from a least square regression analysis that $\tan \beta$ for the unworked soil was 0.05, while $\tan \beta$ for the worked soil was 0.16. Such differences in $\tan \beta$ would appear to prohibit the use of this method. However, the error induced by using $\tan \beta$ = 0.121 is 1.55 percent for unworked soil and 1.16 percent for worked soil at 20 or 30 blows. These errors do not exceed those associated with standard liquid limit determinations. Thus, the one-point determination appears practicable for this type of soil.

Grain Size Analysis

The grain size distribution curves (Fig. 1) show that the worked soil has a larger percentage of fine particles than does the unworked soil. This indicates that mechanical working does cause a disaggregation of the soil structure into fine particles. The curves show that both the unworked and worked soils were fairly well graded.

Proctor Compaction

The data in Table 3 show that the density of the soil is very low in comparison to temperate zone clays having similar Atterberg limits. For example, Permian red clay

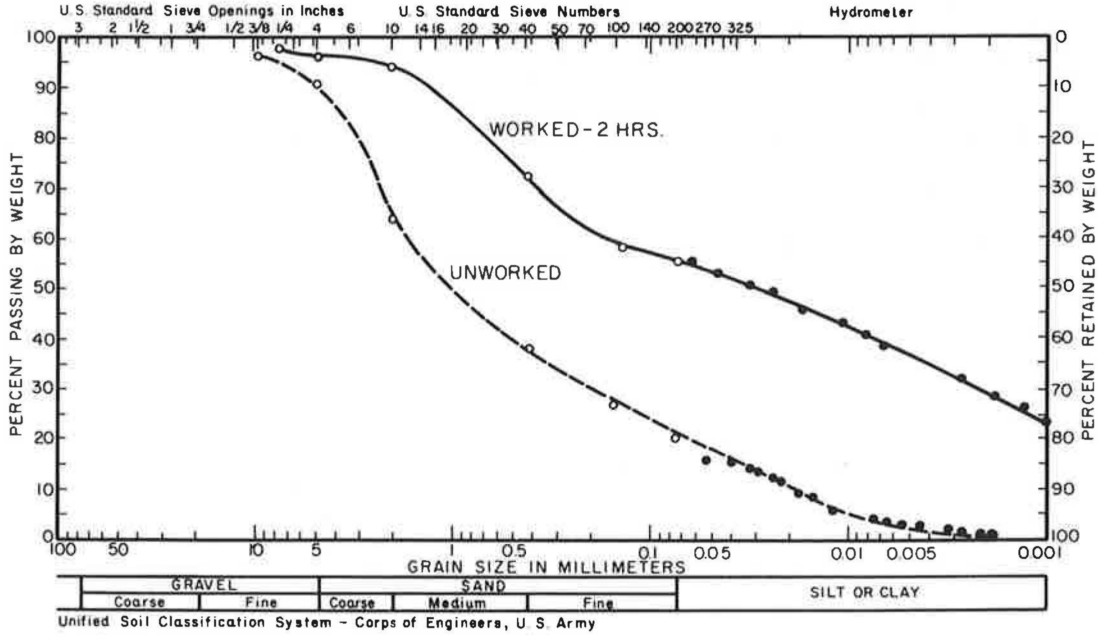

Figure 1. Grain size analyses of worked and unworked lateritic soil.

TABLE 3

STANDARD PROCTOR COMPACTION CHARACTERISTICS OF STABILIZED LATERITIC SOIL

Stabilizer	Worked		Unworked	
	Density (pcf)	Opt. Moisture Content (%)	Density (pcf)	Opt. Moisture Content (%)
Natural soil	83.0	34.5	84.5	35
Lime	82.0	34	80.5	35
Portland cement	84.6	32	85.5	32

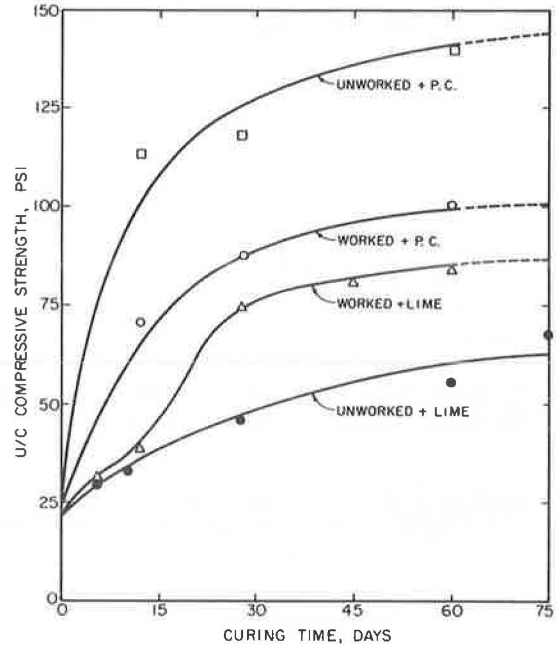

Figure 2. Effect of curing on unconfined compressive strength of laterite + 5 percent lime and 5 percent portland cement.

from Stillwater, Oklahoma, with a specific gravity of 2.7, has a plasticity index of 22 percent and standard Proctor density of 106 pcf. Working caused only a slight decrease (1.5 pcf) in maximum density of the raw lateritic soil, and little change in the optimum moisture content.

Effects of Stabilizers

The results of unconfined compression tests of the various stabilized soil mixtures are shown in Figure 2. Each plotted value is an average of the results of not less than four tests.

Lime—It is well established that the plasticity of many clay soils is reduced by the addition of lime and that substantial increases in strength occur under proper conditions of curing. The fundamental causes for these effects are not fully understood, but it appears that both base exchange (replacement of sodium or hydrogen ions with calcium) and pozzolanic reactions are operative (15). Under certain conditions, carbonation may also contribute to the stabilization processes. Base exchange reactions occur rapidly, whereas pozzolanic reactions and carbonation proceed much more slowly.

The curves in Figure 2 show that the unconfined compressive strength of both worked and unworked soil is increased by the addition of lime. Both the worked and unworked soil-lime mixtures gain in strength as the curing time increases, with the worked soil showing more rapid and greater strength gains. The rapid initial strength gains for the 5-day tests are attributed in part to increased intergranular friction caused by aggregation of the soil particles from base exchange reactions.

Since most of the free silica has been leached from lateritic soils, the silica available for pozzolanic reaction with lime should be found predominantly in the clay particles. Thus, the more rapid and greater strength gains of the worked soil reflect a higher effective clay content. It appears that pozzolanic action proceeds more slowly in unworked soil than in worked soil, as there is evidence of only a minor strength gain in the former during the first two weeks of curing. Joffe (16) stated that sesquioxides may serve as protective coatings for soil minerals and that in the case of clays, these coatings reduce the plasticity of the mass. If the silica sources in the soil are limited to the clay particles and these particles are protected by coatings, the soil-lime reaction would be retarded (17).

Strength gains from pozzolanic action in unworked soil are probably limited to the reaction of the lime with small amounts of unleached silica and with the "exposed" clay particles present in the soil. In worked soil, the soil-lime reactions are enhanced by two factors: (a) the sesquioxide coatings have been partially broken down by abrasive action; and (b) the amount of finer particles has been increased. The removal of the sesquioxide coatings would supply more silica and the smaller-sized silica particles present greater surface areas for reaction. These factors would increase the supply of silica for a more rapid and efficient pozzolanic reaction.

With the addition of lime, the standard Proctor density of the unworked soil decreased 4.0 pcf, while only a 1.0 pcf decrease occurred in the worked soil (Table 3). Since the unworked soil possessed a lower effective clay content, aggregation caused by flocculation of the clay was apparently more significant than in worked soil. The worked soil with a higher effective clay content apparently possessed a more dispersed structure which would require more lime to achieve the same degree of aggregation as for unworked soil.

Portland Cement—The test specimens stabilized with portland cement had higher strengths for both the worked and unworked soil than those stabilized with lime or MC-3 (Fig. 2). The hydration of the cement is relatively unaffected by the chemical composition of the soil particles. This is indicated by the rapid gains in strength of both the worked and unworked specimens during the first few days of curing. However, these specimens, in contrast with the lime-stabilized specimens, show higher strengths for the unworked soil. The lower strength of the worked soil probably results from the increased quantity of fine particles present. In general, fine-textured soils require more cement to achieve a given strength than do coarse soils.

MC-3 Asphaltic Cutback—Successful stabilization of fine-grained plastic soils with asphalt has been somewhat limited because of the difficulty of properly mixing the two materials. If it were possible to waterproof the particles of a lateritic soil, the water used in compacting the soil would be much less influential in promoting disaggregation of the particles. During preparation of the soil-asphalt specimens, it was found that a soil-asphalt mixture, completely cured in an oven, could not be mixed with water. If such a mixture could be properly compacted, even with relatively low percentages of asphalt, the resulting material would be quite waterproof and considerably more stable. The test results and experience of this study indicate that aeration or curing of lateritic soil-asphalt mixtures is quite critical if good results are to be achieved with this type of stabilizer.

Test results indicated that the addition of MC-3 cutback slightly reduced the strength of both worked and unworked soil. Thus, the primary benefit derived from using an asphalt cutback would be related to waterproofing of the soil rather than directly increasing its strength.

Testing Procedures

The test results indicate that there is a significant difference in the physical properties and in the behavior of worked and unworked lateritic soil. Laboratory test results are influenced by the working or remolding required by the test procedures. For example, the spatula working during a liquid limit test and the use of impact compaction will break down the soil structure to some extent. Newill (9) also reported that the method of treatment prior to testing will affect the results.

It appears that the standard laboratory testing procedures should be modified to prevent or minimize working of lateritic type soils. Some such modifications were used in this study, but more detailed investigations are needed to define precisely the modifications that should be incorporated in test procedures. One-point liquid limit determinations utilizing a minimal amount of spatula working and limited to a range of 20 to 30 blows give excellent results and could be used to replace the standard test when lateritic soils are investigated. Compaction techniques designed to minimize disturbance of the soil are another possibility. A comparative study of impact versus static compaction procedures on this particular soil is presently being conducted.

In any event, the technique of testing lateritic soils in both the worked and unworked conditions would seem desirable and could furnish some insight as to field behavior of the soil in regard to the use of stabilizing admixtures and compaction procedures.

SUMMARY AND CONCLUSIONS

In this investigation, the engineering characteristics of a Panamanian lateritic soil were studied and the suitability of various stabilizing additives was investigated. For the type of soil and testing procedures employed, the following conclusions can be made:

1. Mechanical working causes a breakdown of the soil particles and increases the percentage of fine particles.
2. Mechanical working of the soil apparently increases its "effective" clay content. The breakdown or stripping away of the sesquioxide coatings allows the indigeneous clay particles to behave in a more characteristic fashion.
3. Mechanical working causes an increase in the plasticity of the soil. Because of this increase, the one-point liquid limit determination should be used for a more reliable evaluation of the Atterberg limits.
4. Stabilization of the soil by various additives is influenced to a considerable extent by mechanical working. The type and quantity of stabilizer necessary in field application will depend to a large extent on the construction equipment and techniques employed. From the standpoint of strength, portland cement is the most effective of the three stabilizing additives used, and better results can be achieved with the soil in the unworked condition. Lime is an effective stabilizer for this type of soil and reacts more favorably, i.e., develops higher strengths, with the soil in the worked condition. The primary benefit from asphaltic stabilization will be waterproofing of the soil rather than substantial strength gains.
5. New or revised laboratory techniques should be developed for reliable evaluation of the properties of laterites and lateritic soils, and such soils should be tested in both the worked and unworked conditions.

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