A STUDY OF LATERITIC SOILS

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SYNOPSIS

The paper deals with the problem of testing and evaluating engineering properties of red tropical soils referred to in the literature as "lateritic soils." Before World War II, these soils had been studied almost exclusively from the standpoint of agronomy. The warfare in the tropical regions and the expanded war program in the southern United States, revealed the peculiar behavior of certain red soils employed as subsoil material which differs from that of ordinary mainland soils.

Recognizing that lateritic soils belong to the groups of soils whose accurate evaluation is difficult, a study was undertaken to determine the relationship of physical characteristics of selected representative soils from Hawaii to those of similar origin and appearance in the mainland.

The report describes the origin and alterations of the laterites, touches on the available data pertaining to the research and analyses of the tropical soils and their suitability as identification criteria in the existing classification systems. Some properties peculiar to the Hawaiian lateritic soils as revealed in laboratory tests and confirmed by the field experience in the Pacific area are discussed. A similar comparison study was performed on some mainland red soils whose field performance departs from the predicted behavior based on standard laboratory routine tests. The friable structure characteristic of the lateritic soils makes the effect of remolding a factor of foremost importance in their subsequent behavior. Certain of the routine laboratory tests had to be modified to attain an initial state of soil putty permitting successful performance of tests. The length of time of wetting and remolding proved to be the determining factor influencing the obtained results, and tentative test procedure is indicated which may remedy existing discrepancy in soil evaluation.

The question has often been raised as to what extent the behavior and performance of tropical soils, serving as foundation materials in engineering construction, can be forecast from knowledge of similar soils from the continental United States. The purpose of this study was to determine pertinent physical characteristics of a few representative tropical soils from Maui, Territory of Hawaii, to compare them with soils of similar type or appearance occurring on the Mainland. How well Hawaiian soils are representative of all tropical soils would have yet to be determined by systematic research, thus far not undertaken.

Unfortunately until World War II, research on tropical soils was confined almost entirely to problems in the field of agriculture. Laboratory investigations in the United States and other countries have produced a considerable volume of data, among the important contributors being Edward Carl Julius Mohr (*1*)[2] of the Dutch East Indies and F. Hardy of Trinidad. So far, agricultural experiments and research have identified various types of laterites, determined their chemical composition, and capacities for base exchange, and have discovered the significance of high organic content to the moisture-holding capacity. On the other hand, the research of geologists has produced a feasible theory on the origin of laterites and the process of their formation down to the various species now found in the world.

Several years of wartime construction work in the tropical regions, even under emergency conditions with poor testing equipment and insufficient skilled personnel, have doubtless been able to throw more light on the behavior of lateritic soils from the practical engineering point of view. However, no report has been made public on this subject by a government agency. The chief difficulty in a direct approach to the problem lies in the fact that most of the accepted soil consistency limits are not adapted to the undisturbed natural state of these soils and do not reveal their relative value

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[2] Italicized figures in parentheses refer to list of references at the end of the paper.

in engineering structures or give positive indication as to their bearing or drainage value in the subgrade or as backfill for engineering purposes. The granular or so-called friable structure of certain Hawaiian lateritic soils is responsible for their favorable engineering characteristics such as free internal drainage, high bearing capacity or subgrade value. Remolding and wetting transforms them ultimately into silty or clay-like soil of inferior quality. Clay content determined by wet analyses depends upon unpredictable factors and the different nature of clay prevents correlation with normal alluvial soils. Tests on a few Hawaiian and mainland red soils reveal that their behavior as compared with normal inorganic soils is substantially different.

The usual techniques of chemical analysis of soils does not serve the purpose of explaining peculiarities within physical characteristics; the components are first broken down and quantitatively determined as oxides, thus obscuring whether or not the actual original combination of elements was in the form of oxides, hydrates, or hydrated silicates. Almost all the chemical analyses for which results are available have been obtained by the method of concentrated hydrochloric acid digestion. The insoluble residue may contain, besides insoluble silica, some manganese, titanium, phosphoric acid, as well as a little iron and alumina which all pass by unidentified.

ORIGIN AND ALTERATIONS OF LATERITES IN HAWAIIAN ISLANDS

It is the prevailing opinion among geologists that laterites or "red earths" are products of disintegration of igneous rock, although perhaps not exclusively from those of volcanic origin. By their appearance, physical character, chemical composition, and engineering properties, these soils are distinctly different from other products of weathering. From the chemical standpoint, when still in compact state, they can be described as red or brick-like rock, being composed chiefly of silicate of alumina and iron oxide. Blandford in his "Geology of India" refers to "high level" laterite as "non-detrital or iron clay." Often in literature reference is made to "ochres" regardless of the continent where they occur.

The conspicuous red, brown, or yellow-red color has been attributed to the effect of weathering in the atmosphere or to being "burnt into red brick by the overflowing lavas" according to Charles Lyell. The lack of products resulting from the action of carbonic and sulphuric acid in the laterites would tend to disprove the theory that sulphuric and carbonic acid contained in vapors caused disintegration of the original rock. Nevertheless, numerous authors concur in the opinion that chemical reactions on a large scale were instrumental in the formation of laterites through the process of primary disintegration.

The color of soils has its origin in the oxidation and hydration of iron oxide present in the lava rocks. In the process of disintegration, the iron oxide passes over into ferric oxide and if sufficient moisture is constantly maintained, as in humid regions of great rainfall, the iron oxide changes into hydrous ferric oxide. The color of soils with the hydrous iron compounds is yellow or brown while the soils with ferric oxide formed in an arid climate are characteristically dark red.

The overall alteration of original rocks is accomplished by the process of simple weathering which consists of variations in atmospheric heat and moisture. While all the earth surface is subject to weathering effects, only some limited areas have been acted upon by chemical agents. Thus there are lavas which have undergone the process of weathering only, the final product being soils of a certain composition. Great extremes in temperature cause rapid disintegration of surface rocks provided moisture is present. In tropical regions the continuous high temperatures and large rainfalls produce similar results, especially with the assistance of the abundant growth of tropical vegetation.

For the sake of simplicity only the residual soils of Hawaii are treated in the discussion that follows; the alluvial soils, products of the separation process and water transportation, are omitted.

In general the soils of Hawaii are products of complicated disintegration and weathering processes under varying rainfall conditions, with local accumulation of organic matter. As a result of these agencies the color of the soils is rusty brown, combining the yellow and dark red shades to a variable degree. Where the decay of vegetation took place a dark brown color prevails in the top soil horizons, and locally in upper lands the soil is almost black in appearance. It is significant that the color of soil is controlled by the chemical form of the iron constituent and not by its amount.

According to rainfall conditions, two distinct regions are recognized in the Hawaiian Islands: the "windward side," where the rainfall is great, resulting in a high moisture content in the air, and the "leeward side," where rainfall is very light, making the air dry and the heat effect uninterrupted and more intense. The weathering is influenced by the humidity in such a manner that in leeward parts of the islands the lava is subject to the process of dry oxidation which produces rich cocoa-brown or bright red colors of soils owing to the presence of nonhydrous iron oxide. In the humid, windward parts of the islands the lava rocks of the same origin undergo hydrous oxidation and the final product is soil of yellow or light brown color because of the development of iron hydroxide.

TABLE 1

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
	%	%	%	%	%	%	%
Hawaiian Lavas	47.9	18.2	13.4	9.0	6.0	2.2	1.5
Hawaiian Soils .	29.8	27.2	34.3	0.9	1.4	1.6	0.9

In the process of weathering the action of water and air has brought about the removal of silica and alkalis; consequently the proportion of ferruginous residue has risen in variable amounts.

Walter Maxwell (*2*) compiled a comparison table, indicating the mineral composition of the original Hawaiian lava rocks and that of the derived soils in percentages as shown in Table 1. These values demonstrate the transformation in the original chemical composition of lava through the process of disintegration. Some 38 percent of the original silica and 90 percent of lime was removed while the concentration of the iron and aluminum compounds increased by 150 and 50 percent respectively. Apparently the water, and to some extent the air, have been the agents responsible for the leaching of the soluble constituents from the basaltic lavas and together with the heat have acted as catalysts in the oxidation and hydration processes of ferruginous compounds. It was found by observation and measuring that the sun radiation alone may bring about temperatures on the surface of the earth which are twice as high as the temperature of the air. In Hawaii, while the air temperature was 85 F, the lava surface displayed 160 F.

The effect of cropping is noticeable by its capacity to remove as much as 40 percent of the original content of the lime from the soil, up to 17 percent of the potash, and up to 2 percent of the phosphoric acid; however, the experiments proved that the same limiting amounts can be leached out by water alone.

Charles Richter (*3*) made a general comparison of the chemical composition of Mainland and Hawaiian soils based on his research. According to him, an average Mainland soil contains three times as much silica as the average Hawaiian soil. The iron and alumina components constitute approximately 52 percent of the total weight, and that amounts to more than three times the iron and alumina content in Mainland soils. However, it is not clear whether the reference is made to Mainland red soils, or more likely, to the average common soils. The average content of organic matter in Hawaiian soils was determined to be two or three times as high as in Mainland soils. The radical discrepancy in chemical composition of Hawaiian and Mainland soils is a warning not to use indiscriminately the same criterion while comparing their mechanical properties. In a soil substance of dissimilar chemical composition a special meaning must be assigned to certain routine physical tests which serve to determine soil characteristics, such as plasticity limits, clay content, specific gravity, and CBR, arbitrarily used in engineering evaluation of soils.

GENERAL DISCUSSION OF ENGINEERING CHARACTERISTICS

Soil testing was done by the writer, who used the conventional equipment and laboratory methods in the soil mechanics laboratory at the Engineering School of Columbia University. In testing representative samples of friable Hawaiian soils, the standard soil testing methods were followed as nearly as possible, in order to obtain a comparative evaluation with respect to the other soils. Certain procedures had to be modified individually in order to achieve equivalent initial conditions of tested specimens in the course of wetting, remolding, powderizing, and dispersing of fine particles.

Almost all the publications on Hawaiian

soils treat the subject from the standpoint of agronomy and lay emphasis on chemical composition, base exchange capacities and moisture retaining properties. As a rule, mechanical analysis serves as a means of classification according to texture (*4*). In no publication, however, can the physical properties indicative of the engineering value of soils be found except for the tabulation of the results of physical tests made by the Public Roads Administration on a number of Cuban soils. In elaborating on the results, Dr. Karl Terzaghi (*5*) discussed in 1926 the significance of various tests in the evaluation of soils for engineering purposes. He suggested representing the results of tests by reference to the liquid limit, which has the advantage of the greatest sensitivity, ranging in magnitude from 15 to 120 percent or more. The significance of Atterberg's test is duly emphasized and the values of plastic limit, liquid limit, and plastic index have been considered indispensable in classifying soils from different regions according to their plastic properties which reflect best upon the performance of soils as subgrade material. The opinion is expressed that the moisture equivalent serves merely as an index of the drainage properties of friable soils only, with no particular meaning in plastic or semi-plastic soils.

The shrinkage limit is indicative of the compressibility of the soil and the maximum capillary pressure. The results of this test in conjunction with the plastic limit indicate the behavior and volumetric changes of subgrade soil under varying moisture content. The soils from Maui, however, having been dehydrated, were not tested for shrinkage limit as the results would not have been reliable.

Grain size curves, developed through mechanical analysis of friable, lateritic soils, have an academic value only. The quantitative clay content does not permit a reliable appraisal of the engineering characteristics of soil and their behavior in construction projects. It is the inherent quality of clay which determines the behavior of the soil.

The specific gravity determination was necessary for the interpretation of the hydrometer analyses and furnished information on the relative amount of iron and alumina concentration in soils. This indicated indirectly peculiarities in their chemical composition, since a chemical analysis was out of the scope of this investigation.

Many laterites when analyzed in the laboratory on clay content (particles smaller than 0.005 mm according to the CAA classification) and on Atterberg's limits, would fall into clay soils, ranging from low to high compressibility (*4*). Construction experience in the field has been to the contrary. Most of such soils behaved satisfactorily as subgrade material and their generally porous profile is responsible for well-drained sites, unlike ordinary clayey soils. The friable and porous structure developed during the weathering process which embodies disintegration and chemical decomposition, the iron and alumina concentration and the removal of the silica were the main factors involved in the formation of red or brown lateritic soils. Essentially they are now a mixture of ferric and aluminum hydroxide with some free silica.

The routine identification soil tests currently used in evaluating engineering properties of soils have so far constituted satisfactory criteria of ordinary soils. The best systems of soil classification have been based on the Atterberg's limits and their representation by the Public Roads Administration as later modified and perfected by Professor Arthur Casagrande. The use of plastic and liquid limits is one of a great number of methods for measuring the plasticity of clays, and most of them were developed in the ceramics field. The main advantage of Atterberg's method is that two of his constants define the plastic property of clay and its consistency can be determined beyond the plastic range (shrinkage limit). The difference between the liquid and the plastic limit, expressed numerically as the plastic index, has been adapted as a basis for classification. This mechanical device for the determination of the liquid limit has eliminated the personal influence of the operator, and the plastic limit test gives results of sufficient accuracy. The term "toughness" has been given to the shearing resistance at the plastic limit.

The greatest, and perhaps the only objectionable handicap of the Atterberg's limits as criteria of the engineering properties of soils is that numerical values are obtained on remolded specimens of soil and thus the effect of internal, undisturbed structure can be judged only indirectly, since the aggregation of particles derived from internal structure superimposes new characteristics on soil. This fact is being recognized, especially in certain groups of soils. Other significant features too have influenced the arbitrary values determined from tests. Drying produces an irreversible change in the organic content of a soil. As a result, oven-drying brings about a considerable drop in the Atterberg's limits of organic soils. Even inorganic soils are affected by air and oven drying with respect to their liquid limits and plastic limits, which may be either raised or lowered according to the individual properties of the soil. The hand or mechanical mixing influences the limits to a degree, and the addition of defloculating agents of sodium base causes a great increase in the limits. The plastic limit is affected less, but in the same direction as the liquid limit. Other less important factors enter into action and to some extent may help to obscure the true nature of soil being tested.

The Hawaiian soils had been subjected to a process of air-drying while in storage, and the change which their physical characteristics have undergone cannot be adequately appraised. Judging from discrepancy in color as described at the time of sampling and their recent appearance, the soils have undergone some process of dehydration which, perhaps, became more pronounced in soils of higher organic content.

Unfortunately, inadequate quantities of the soil samples prevented running the California bearing ratio test. As an empirical method of testing, this one gives satisfactory results in estimating engineering properties of soil, although some difficulties have been experienced in the way of correlating the CBR values obtained on remolded and compacted soils in the laboratory with the results of the latest field in-place CBR apparatus. During the investigation at the U. S. Waterways Experiment Station, Vicksburg, Mississippi, good correlation was obtained between field in-place CBR tests and laboratory tests on undisturbed samples of clays, silt, and plastic gravel-sand-clay mixtures (*6*). Less satisfactory agreement was observed in experiments with cohesionless or granular soils.

PECULIAR PROPERTIES OF HAWAIIAN SOILS

In their book, "The Soils of Cuba," (*7*) Bennett and Allison, in tabulating characteristics, make no distinct line between the red soils of friable structure and other clayey soils of definitely alluvial origin. An attempt to correlate physical constants of these two different types can bring only their comparative evaluation in remolded state, which have little relation to their original properties when undisturbed. In this instance, the arbitrary soil tests fall short of estimating the engineering properties and of predicting the true field performance of tropical soils.

The problem of friable lateritic soils from Hawaii lies in the transformation of naturally granular soil which results from mechanical agents (powderizing, remolding by traffic or wheel action especially under moist conditions) into highly plastic soil having most of the undesirable characteristics associated with this class of soil, such as low bearing capacity and poor drainage. Samples of friable soil from Honokawaii, Maui, were soaked in water during the laboratory investigation for from two to seven days, but did not change their granular structure until considerable force was applied to individual nodules in breaking them down by means of a spatula or fingers. The clay-size particles contained in the samples did not display the water-absorbing and swelling property, but rather behaved as a water inert substance. In another experiment when the voids of dry granular soil in a dish were filled with water, the soil as a whole behaved like moist sand of considerable shearing resistance and offered a fairly solid supporting surface. When this material, without the addition of water, was remolded with a great deal of effort it became a liquid mass and its water content was far above the Atterberg's liquid limit. It is apparent that if such friable soil in undisturbed state in nature is carefully treated it may be a very good subgrade, of ample supporting and draining capacity. On the other hand, if heavy construction equipment is allowed to destroy the granular structure, breaking down the grain agglomerations into dust and sticky paste, the medium-to-high plasticity of this product at the soil surface impedes drainage and is instrumental in a drastic decrease of the CBR value and of the supporting capacity when used as a subgrade. Favorable weather and hand labor help to preserve the natural granular structure of the lateritic soil until the base course and impermeable surface course are in place.

Rational use of constructional equipment may greatly improve the quality of engineering projects such as roads and runways. In fact, it has been reported that the Japanese through manual labor produced relatively good roads and airfields in the Southwest Pacific even though they lacked almost all the modern construction equipment which our forces had.

The implication of these experiments is that evaluation of tropical friable soils, based on customary standard tests on soils in remolded state, does not do justice to their natural engineering characteristics. In essense, the resistance to shear deformation is the criterion of the engineering value of earthy materials. A friable lateritic soil has a wide variation in magnitude of shearing resistance, ranging from a high value when in undisturbed granular structure to a very low value when completely remolded. Laboratory tests have clearly confirmed the experience in the field. In other words, the intensity of mechanical remolding bears permanently upon the consistency of soil, in the way of decreasing its shearing resistance to displacement and the bearing capacity in general.

It is noteworthy that farmland lateritic soil of a friable structure can be plowed under any weather conditions. Such soils are not baked hard in dry weather nor do they get soaked and plastic when it is raining so that the farming equipment bogs down.

Previous laboratory research has discovered and verified that although lateritic soils have an extremely high clay content when analyzed in natural wet condition, upon drying they display a greatly decreased amount of clayey particles (*8*). In the writer's opinion, the determined percentage of fine particles depends also on the mechanical effort and the chemical agency used to defloculate soil.

Figure 1 shows grain size distribution curves plotted from the results of the hydrometer analysis.

Figure 2 contains the plasticity chart developed by Professor Arthur Casagrande for the classification and engineering evaluation of soils commonly encountered in engineering work in northeastern United States. The plasticity constants are the main criteria, together with the proportion of coarse-grained particles and organic content. The inclined line divides the plotted soils into two great groups, the inorganic above the line and the organic below. The tested soils are plotted in symbols to make apparent any possible correlation with each other and with ordinary soils.

Upon studying the plasticity chart on which the characteristics of the lateritic soils from the Mainland and Maui, Hawaii, are plotted, it becomes apparent that no feasible comparison of both can be made because their plastic properties are so far apart. The sample of Greenville soil is in the area of low com-

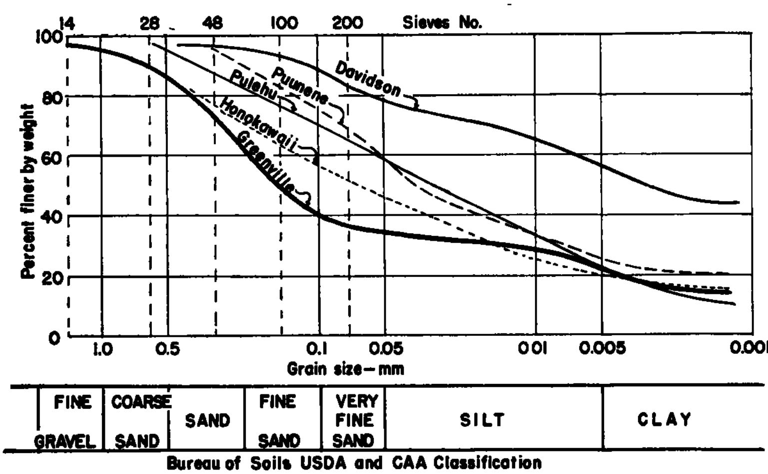

Figure 1. Gradation of Lateritic Soils

pressibility and the Davidson soil is far out in the region of highly compressible and rather organic soils. The locations of the plotted plasticity characteristics of Maui soils are close together, two of them (Puunene and Pulehu) fell almost at one point in the zone of inorganic clays, while the plasticity of the Honokowaii soil falls on the other side of the arbitrary line among organic soils.

Whereas this plasticity chart serves as a criterion of the engineering classification of soils and their behavior, besides the results of several other tests such as the shrinkage limit tration), and CAA (Civil Aeronautics Administration). Ordinarily, non-lateritic soils thus would be definitely evaluated and the design of construction requirements could be determined by means of other diagrams based on corresponding values of the California bearing ratio test. On the other hand, the lateritic soils of friable structure show characteristics different under field performance from those obtained in the laboratory test of ordinary soils having analogous physical characteristics; consequently classification efforts are only of relative value.

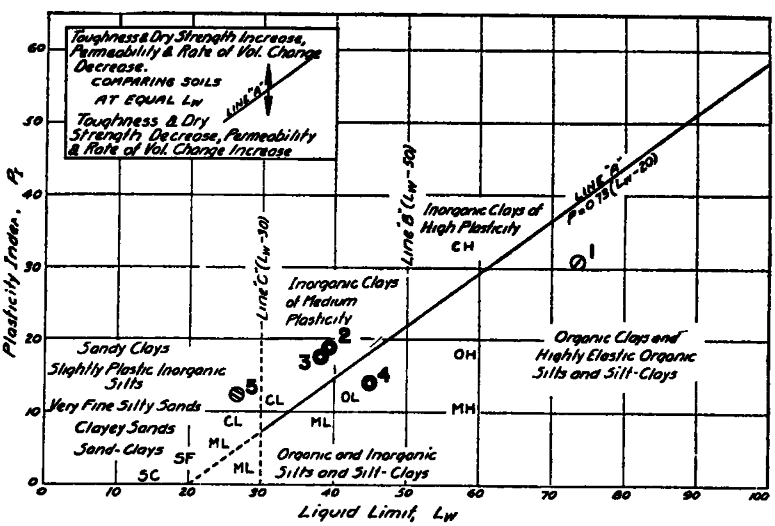

Figure 2. Plasticity Chart (A. Casagiande)

Number	Source
1	**Davidson**
2	**Puunene**
3	**Pulehu**
4	**Honokawaii**
5	**Greenville**

and CBR, it seems obvious that the widely scattered points indicate soils of entirely different characteristics.

The determining characteristics of the tested soils are incorporated in Table 2 listing all of the available information regarding the origin, depth of samples, elevation above sea level, annual rainfall, color when examined, and the obtained physical constants. According to their constants each soil has been tentatively given an individual group symbol in the three classification systems: USED (Corps of Engineers, War Department), PRA (Public Roads Adminis-

Figure 3 shows the interrelationship of the three soil classification systems as compiled by W. R. Macatee, and their respective advantages. It indicates the practical, wide ranges of the individual PRA groups and depicts the comparatively narrow ranges of the CAA soil classes, especially in the realm of plastic soils.

Taking into consideration all the factors such as grain size, plastic limit, volume change, capillary rise, CBR, permeability, and frost susceptibility, upon which each classification or grouping is based, it becomes evident that the advantage of a narrow range in magnitude of constants of plastic soils as specified in the CAA system tends to become a disadvantage when evaluating friable lateritic soils. The experimental values of the CBR seem to be better suited to determining the bearing value of soil, especially if the field in-place test is possible. Unfortunately, without such tests prediction of the carrying capacity of natural soils is problematical, because soil constants may have misleading significance.

The tested soils can be briefly characterized as follows:

The Greenville soil from Albany, Georgia, falls in the realm of ordinary (non-lateritic) plasticity quickly increases with mechanical remolding. Nevertheless, from the engineering standpoint Davidson soil is superior to non-lateritic, alluvial clays which would display similar plastic characteristics because of some degree of dehydration which has taken place in the past. The specific gravity, 2.83, is still within the range of ordinary inorganic clays and does not suggest any excessive concentration of iron or alumina compounds as would the red-brown color alone.

The tested Maui soils are very similar in appearance and in the magnitudes of their physical characteristics. All have about the

TABLE 2
SOIL CHARACTERISTICS

Soil Origin	Depth	Elevation—*ft* Annual Rainfall—*in* Color	Sp. Gr	Soil Class USED PRA CAA	Particles Smaller than 0.005 mm	Plastic Limit	Liquid Limit	Plastic Index	Note
	in.				%				
Greenville Series (Clark Mt.), Albany, Ba.	8–42	+600 47 Light Brown	2.70	CL A-4 E-4	23	15.0	27.0	12	
Davidson Series, Rapidan, Va	0–24	184 50 Red-Brown	2.83	OH A-7, A-8 E-10	55	41.9	73 0	31.1	Unusual plastic properties
Honokawii, Maui, T.H.	0–14	1200 53 Brown	3.10	OL A-6 E-6	20	30.4	44.6	14.2	
Puunene, Maui, T.H	14–24	73 21.4 Dark Reddish Cocoa Brown	3.03	CL A-7 E-6	25	20.7	39.5	18.8	
Pulehu, Maui, T.H.	0–25	560 14 Dark Gray-Brown	2.84	CL A-6 E-6	22	20.4	38 6	18.2	Thread-like roots, vegation remnants
Pauwela, Maui, T.H.	34–48	300 24 Ochre	3.10	granular					Over-dehydrated for satisfactory testing

Mainland sandy soils of low plasticity and compressibility. Their performance in engineering can be safely predicted on an established basis.

The soil of the Davidson Series from Rapidan, Virginia, has in many respects abnormal characteristics which place this soil outside the group of ordinary clays. It has a very high liquid limit, high plastic limit, and behaves to some extent like friable tropical soils considering the difficulty experienced with its remolding, kneading, or dispersing when dry specimens are tested. However, the beneficial property of friable laterites is not inherent to the full extent in this type of soil, inasmuch as in the presence of water its

same relative clay content ranging from 20 to 25 percent of particles smaller than 0.005 mm. The liquid limit and the plastic index of the Honokowaii soil places it into the zone of organic or inorganic silt and silt clays, while the Puunene and Pulehu series fall into the zone of inorganic clays of medium plasticity according to the Casagrande classification. Both the zones are separated by the arbitrary line $P_1 = 0.73\ (L_1 - 20)$. In the field, however, all of these soils under certain conditions will have considerably better ratings as subgrade or sub-base materials than their classifications would imply. The Honokowaii and Pauwela soils had the highest specific gravity, 3.10; Puunene, 3.03; and

INTERRELATIONSHIPS OF SOIL CLASSIFICATIONS (1)

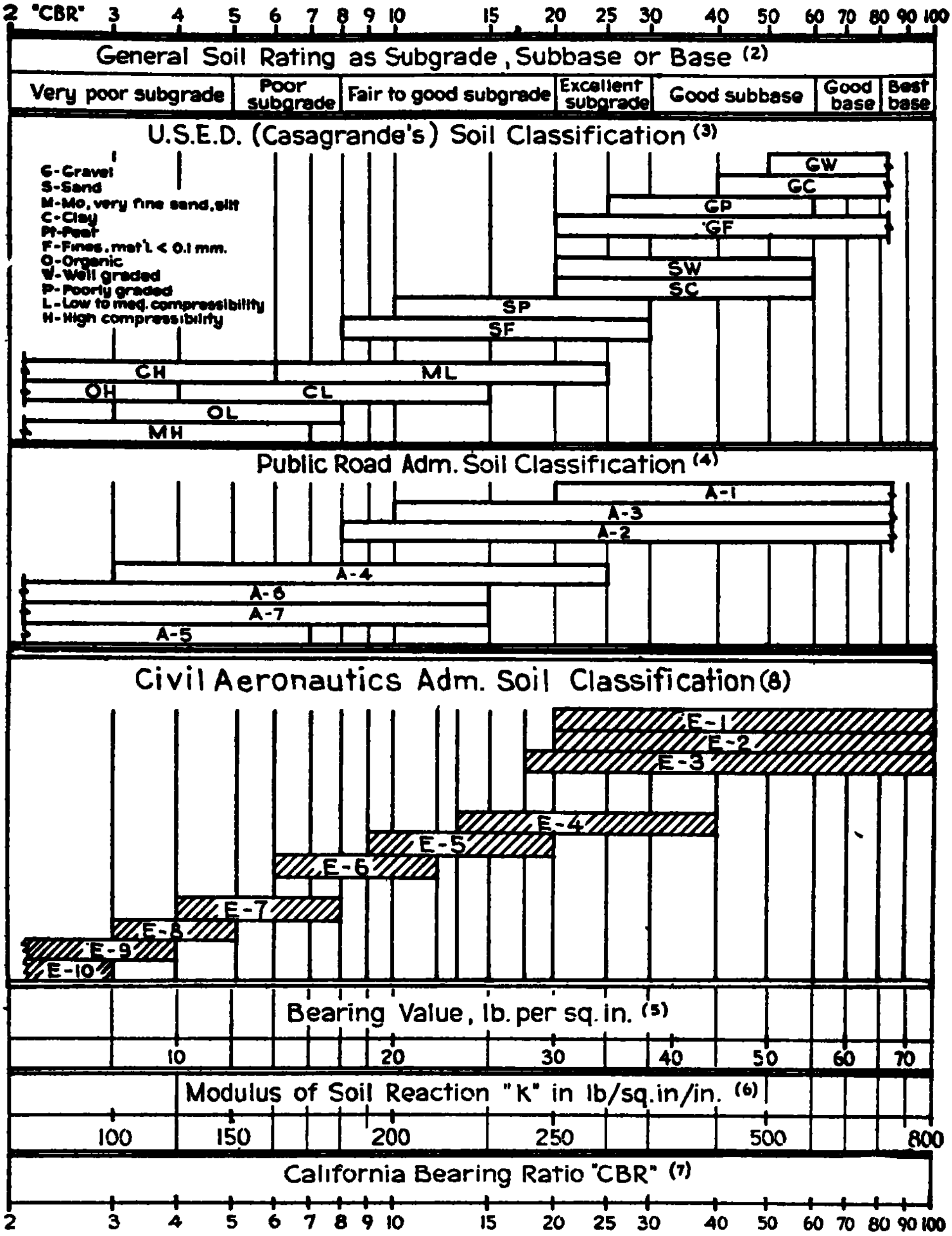

Figure 3

(1) All interrelationships are very approximate. Actual field and laboratory tests are required to determine "k," "CBR," and bearing values.
(2) See "Foundations for Flexible Pavement" by O. J. Porter, 22nd An. Mtg. Highway Research Board, 1942, for basic idea.
(3) See Engineering Manual, Chapter XX, March 1943, War Dept., Office of the Chief of Engineers. See also, "Soil Tests for Design Runway Pavements," by Middlebrooks & Bertran, 22nd An. Mtg. Highway Research Boad, 1942.
(4) See item (3), A-6 and A-7 soils cut off at CBR = 15, rather than 25 as indicated in Chapter XX CBR for A-5 soils of volcanic origin etc., may range above 7 and go as high as +80.
(5) See second reference of item (3), page 184. Bearing values measured at 0.1-in. deflection. Bearing plate area not given.
(6) See item (3), "k" is factor used in Westergaard's Analysis for thickness of portland cement concrete.
(7) See items (2) and (3).
(8) Prepared by W. R. Macatee from information furnished by CAA-Staff and CAA-Publication, "Design Manual for Airport Pavements," March 1, 1944.

Pulehu, 2.84 (apparently because its organic content is higher than that of the others). The high values of specific gravity are an indication of high iron and alumina concentration and perhaps of some accumulation of titaniferrous minerals.

CONCLUSION

Notwithstanding the urgent need for broad comprehensive research on the nature of lateritic soils from the engineering standpoint, the writer is of the opinion that a new supplementary soil test ought to be devised to depict and evaluate many of the tangible features of friable soils in conjunction with present standard routine tests. Just as the varying water content in ordinary clayey soils may affect their plasticity, shearing resistance, and bearing capacity, the effect and degree of mechanical remolding will influence the same characteristics in friable lateritic soils. The approach to the solution of the problem can be found, perhaps, in varying the consistency of soil at certain arbitrary water content in order to evaluate the effect of remolding in engineering properties of soil. For example, tri-axial tests can be performed on a specimen of soil containing a given amount of water in a closed system after no, partial, and complete remolding; thus far results are encouraging.

At present engineering soil mechanics is seeking an adequate interpretation and classification of major soil groups on the basis of certain standard routine tests. In the case of lateritic soils the accuracy of results does not satisfy the requirements which the soil mechanic has been accustomed to receiving.

Any arbitrary classification of tropical soils can be used only with extreme caution, inasmuch as the reported investigation disproved the possibility of classifying them on the same basis as other non-lateritic soils with respect to their value in engineering. Many examples have proven that misleading data about soils, based on unwarranted assumptions or analogies and lacking experimental justification, have led to unusual construction difficulties, delays in schedules, increased expenditures, or an inferior final product.

This study tends to show the considerable difference in character of the ordinary mainland soils and the tropical lateritic soil on one hand, and that of some Mainland red soils and Hawaiian lateritic soils on the other.

ACKNOWLEDGMENT

The Geologic Branch of the Geological Survey approved and encouraged the work on this project. Acknowledgment is made to Dean J. K. Finch of the Engineering School, Columbia University, and to Professor Donald M. Burmister for providing the laboratory facilities of the school. The writer wishes to thank Professor Burmister for helpful hints and suggestions during the performance of the tests.

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APPENDIX

The colors of soils determined on the basis of comparison with the agricultural color standards and names[3] are listed below. The colors were matched as closely as the standard scale allowed.

Greenville series.	Light Brown
Davidson series.	Moderate Reddish Brown
Honokawaii	Moderate to Strong Brown
Puunene	Weak Reddish Brown
Pulehu	Moderate Brown
Pauwela	Light to Strong Yellowish Brown

DISCUSSION

MR. EDWARD A. WILLIS, *Public Roads Administration:* Mr. Fruhauf's paper presents very interesting information on the properties of certain soils from the Territory of Hawaii.

The Public Roads Administration has recently had occasion to test two samples of soil from the Papaikou-Pepeekeo section of the Hawaii Belt Road on the island of Hawaii. These soils possessed very unusual characteristics. The results of tests are presented here as a matter of general interest.

Mr. B. F. Rush, Territorial Highway Engineer, stated in his letter of transmittal that the characteristics of the soils represented by these samples appeared to improve if the soils were allowed to dry out from their natural moisture content. A natural drying process is rather difficult of accomplishment in this section of Hawaii where the annual rainfall is between 150 and 200 in.

Owing to the unusual nature of the soils, special test procedures were employed as described below. The samples were boiled in water prior to shipment from Hawaii in order to pass Federal quarantine inspection and were shipped in sealed containers to prevent the samples from drying out during shipment. The following tests were made: mechanical analysis, determination of soil constants, chemical analysis, compaction tests, and triaxial shear tests.

The results of the mechanical analyses and the plasticity, moisture equivalent, and shrinkage tests are shown in Table A. Three methods were used in preparing sample No. 71730 for test: air drying, partial air drying with subsequent wet separation on the No. 40 sieve, and washing the sample as received on the No. 40 sieve. The results of tests on material prepared in the three different manners are identified in Table A as dry, moist, and wet, respectively. Sample No. 71731 was prepared by washing the material as received on the No. 40 sieve.

TABLE A
RESULTS OF TESTS ON TWO SAMPLES OF SOIL FROM HAWAII

Preparation	Sample No			
	71730 dry	71730 moist	71730 wet	71731 wet
Sand				
2 to 0 25 mm—%	52	20	19	23
0.25 to 0 05 mm—%	34	22	11	11
Silt—%	11	17	34	10
Clay—%	3	41	36	56
Colloids—%		25	17	33
Liquid Limit	NP	217	245	230
Plastic Index	NP	71	110	95
Field Moisture Equivalent	72	204		248
Centrifuge Moisture Equivalent	31	170		206
Shrinkage Limit		44	44	46
Shrinkage Ratio		1.17	1.17	1.19
Specific Gravity	2.84			2.80

The fraction passing the No. 40 sieve in the "moist" and "wet" preparations was recovered from the wash water by filtering through a Buchner funnel equipped with a filter paper. Application of a vacuum materially hastened the filtering process. After filtering, the soil cake was removed from the funnel, the filter paper was stripped off and the sample thoroughly mixed. The sample was then stored in a humidifier until the tests were run.

The tests on sample No. 71730, dry, were run in the usual manner and, except for unusually high field and centrifuge moisture equivalents, the results obtained were characteristic of a nonplastic sand. The field moisture equivalent of 72 and the centrifuge moisture equivalent of 31 for the air-dried sample indicate a high degree of porosity in the material in this state.

A sample of the air-dried material was

[3] "Preliminary Color Standards and Color Names", U. S. Department of Agriculture Miscellaneous Publication 425.

soaked in water to determine whether it would regain its plasticity. After soaking for one week, the material retained its granular characteristics.

Samples Nos. 71730 moist, 71730 wet, and 71731 wet, flocculated in the hydrometer test when sodium silicate, as called for in the standard AASHO procedure, was used as a deflocculating agent. The mechanical analyses shown in Table A for all samples, except No. 71730 dry, were determined with about 2 grams of Calgon deflocculating agent per liter of suspension. Even with this agent, the determination of the silt, clay, and colloids cannot be considered too reliable.

The physical constants of the material passing the No. 40 sieve on the moist and wet samples were determined by allowing the moisture to evaporate from the material reclaimed by the filtration process until the end point indicated by standard test procedure was reached. In the case of the centrifuge moisture equivalent, a lump of wet soil weighing approximately 5 g was pressed into the prepared crucibles by hand. The crucibles were then set in a pan of water until free water appeared on the surface of soil. Thereafter the test was run in the usual manner.

The degree of aeration and drying to which the soil was subjected prior to testing influenced the physical constants to a marked degree, as shown in Table A. It is believed that almost any values between the limits shown could have been obtained by varying the method of preparation. In the condition in which the samples were received in the laboratory, the material was very sticky and plastic having liquid limits of 245 and 230 and plastic indexes of 110 and 95, respectively, for samples Nos. 71730 and 71731. Yet when the material was air-dried it was nonplastic and no amount of soaking or manipulation could restore the plasticity.

Results of chemical analysis were:

	%
Ignition loss	20.20
SiO_2	5.70
R_2O_3	65.52
CaO	0.23
MgO	0.98
Na_2O	4.86
K_2O	2.47
Total	99.96

Compaction tests were run on a composite of the two samples submitted. The material was removed from the containers and thoroughly mixed. As soon as the moisture content had been reduced sufficiently to permit compaction, testing was started. The standard AASHO equipment and procedure were used except that successive points were obtained by allowing the moisture to evaporate for 24 to 48 hr. After the soil had become so dry and dusty that it was difficult to com; pact, additional points were obtained by adding increments of water in the usual manner. Under this procedure free water was forced from the soil in the compaction mold at a moisture content of about 40 percent, although no difficulty had been experienced in compacting the soil originally at a moisture content of about 185 percent.

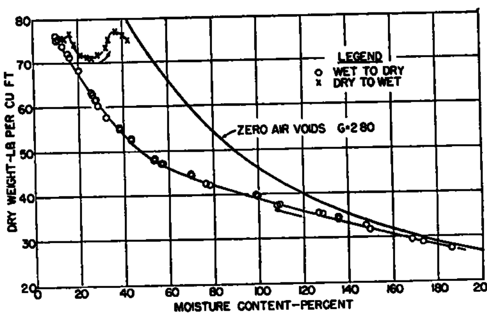

Figure A. Compaction Test Results Composite Sample No. 71730, 71731, Hawaii Proj. 14-B.

The moisture-density curve obtained from the compaction tests is shown in Figure A. It is evident that changes in the character of the soil occurred continuously as the material dried out. Lack of sufficient sample precluded the possibility of reversing the direction of the moisture content change at more than one location.

Cores 2 in. in diameter were cut from the compacted sample at several points during the compaction test. These cores were tested in the triaxial shear device and values of the cohesion c and the angle of internal friction ϕ were determined. As shown in Table B, values of cohesion range from 0.4 to 2.4 kips per sq ft and values of the angle of internal friction range from 4 to 49 deg, depending on the moisture content and density at which the tests were made.

Values for computed bearing value will vary widely depending on which set of test values are used in the computations. Similarly, calculations of pavement thickness will yield a wide range of results for the various conditions under which the soil was tested. The formula published on page 114, *Proceedings* of the Highway Research Board, Vol. 23 (1943) may be used to illustrate this variation.

TABLE B

VALUES OF COHESION, COEFFICIENT OF FRICTION, AND ANGLE OF INTERNAL FRICTION OBTAINED ON A COMPOSITE SAMPLE OF TWO SOILS FROM HAWAII AT THE MOISTURE CONTENTS AND DENSITIES INDICATED

Moisture Content	Dry Density	Cohesion	Coefficient of Friction	Angle of Internal Friction
%	*lb per cu ft*	*kips per sq ft*		*deg min*
171	29	1.1	0.07	4
149	31	1.2	0.19	10 45
135	34	2.0	0.13	7 24
100	39	2.4	0.42	22 47
77	42	2.2	0.57	29 41
13	73	0.4	1.15	49

The formula is as follows:

$$T = \left[\sqrt{\frac{(3P)^2}{(2\pi CS)} - a^2}\right]\left[\sqrt[3]{\frac{C}{C_p}}\right]$$

in which

T = Total combined thickness of sub-base, base course, and surface course, in in.

P = Wheel load in lb.

C_p = Modulus of deformation of pavement in lb per sq in.

C = Modulus of deformation of subgrade in lb per sq in.

S = Assumed allowable deformation of pavement in in.

a = Radius of assumed area of tire contact in in.

The following assumptions are made:

P = 10,000 lb.

C_p = 10,000 lb per sq in.

S = 0.1 in.

a^2 = 31.8 sq in. corresponding to an inflation pressure of 100 lb per sq in.

Then for a modulus of deformation for the subgrade of 600 lb per sq in. corresponding to a moisture content of 171 percent and a dry density of 29 lb per cu ft, the required thickness as computed from the formula would be about 31 in.

For the same assumed conditions and for a subgrade modulus of 2,500 lb per sq in. corresponding to a moisture content of 13 percent and a dry density of 73 lb per cu ft, the same formula indicates that a thickness of only about $11\frac{1}{2}$ in. would be required.

The above discussion should be considered as illustrative only since the soil was not tested in its natural conditions nor were any tests made on sub-base or base course material which might be used in construction.

The unusual nature of the material represented by the samples submitted is manifested by the change in properties which takes place as the material dries out. The behavior of the soil as a subgrade will be dependent largely upon the treatment during construction. Aeration and drying are definitely beneficial, both from the standpoint of reducing the plasticity and increasing the supporting power of the soil.

BEDRICH FRUHAUF, *Closure*—Mr. Willis's discussion is a valuable contribution to the present limited knowledge of engineering characteristics of lateritic soils.

The tests were performed on soil from the "Big Island" of Hawaii, geologically the youngest and also the largest of all the central Pacific islands. The samples which originated from a location near the eastern coast 4 to 7 mi north of Hilo belong to the Hamakua volcanic series, probably of tertiary age. The writer recalls his trip to Hawaii and the red appearance of this fertile strip of land on the windward side of the island. The underlying rock consists of basaltic lava flows and is capped with Pahala volcanic ash. In deeply dissected valleys high organic content darkened originally brown-red soils into a black-brown color. Most probably the tested samples belong to the residual lateritic soils.

The results of the tests performed in the laboratories of the Public Roads Administration reveal utterly unusual soil characteristics. Aside from the fact that during a drying process soils acquired properties of cohesionless material in confirmation with the writer's findings, the most interesting feature of the results is that soils tested in fairly natural, undried state display plastic characteristics in magnitude exceeding by far those of any known ordinary or lateritic soils. Because only two samples were obtained from one locality, it is not possible to assume that such soils occur over a wide area; nevertheless such condition is not remote.

To summarize available data on soils from the Territory of Hawaii, a previous work in another engineering laboratory is briefly mentioned. Besides the writer's tests on soils from the second largest Hawaiian Island of Maui reported on in this paper, a series of tests on soils from Oahu (the third largest Hawaiian Island) and their engineering characteristics were reported on by Professor Carl B. Andrews (*8*). His results showed that residual and apparently lateritic soils had liquid limits ranging from 75.6 to 107.5 percent, plastic limits from 48 to 72.7 percent, and loss on ignition varied from 14.1 to 23.9 percent.

It is a well known fact that high organic content in ordinary soils radically changes their plastic properties; both the liquid and the plastic limits grow higher though generally the liquid limit increases by greater percentage than the plastic limit. The chemical substance of the "organic content" is seldom determined, yet it is generally accepted that the chemical nature of any ingredient may greatly affect the results of the routine soil tests. In ordinary organic silts and clays loss on ignition of 6 to 7% may be considered as an indication of a high organic content; in tropical lateritic soils a loss on ignition three times as large is quite normal. In the writer's data on the soil characteristics the values of ignition loss were as follows:

Type of Soil	*Ignition Loss* %
Greenville Series, Albany, Ga.	2.73
Davidson Series, Rapidan, Va. .	3.6
Honokawii, Maui, T.H.	20.5
Puunene, Maui, T.H. .	10.8
Pulehu, Maui, T.H.	11.9
Pauwela, Maui, T.H. .	. . 20

The first two soils from the United States ("lateritic" in the agricultural classification) have low organic content in spite of visible numerous tiny root remnants in the Greenville soil. High organic content in Honokawii soil corroborates well with the plastic properties as the plotting falls into the zone of organic soils in the Casagrande's plasticity chart; otherwise anomalies must be anticipated because tropical soils are chemically of quite a different composition as had been noted in the body of the report. Besides, soil samples reported on by Mr. Willis seem to have an unusually small proportion of silicon dioxide thus deviating still more from ordinary soils.

Although not specifically mentioned in Mr. Willis's discussion the air dried soil sample apparently was passed through the No. 40 sieve without any further attempt to break or powderize agglomerations of grains. It was the writer's experience that soaking alone of the soil did not materially affect the granual (friable) structure of the dried soil. Only a considerable effort through mechanical remolding in both the dry and wet state restored, though only partially, the plastic properties of the dried lateritic soil.

The loss on ignition alone in the order of magnitude of 20 percent as reported by Mr. Willis, however, does not substantiate extremely high values of the liquid and plastic limits; their plotting would fall way beyond the margin of the sheet on which the plasticity chart is drawn.

Nevertheless, in the writer's mind there is another possible explanation for this phenomenon. The origin of the samples suggests that volcanic ash of ultra microscopic grain size constitutes a considerable portion of the material. Volcanic ash is the major ingredient of our Mainland bentonites; most of the deep deposits of highly plastic colloidal clays in the basin of Mexico City originated from volcanic ash settled in water. The writer visited Mexico City in 1936. Subsequently he carried out research on Mexican clay of the montmorillonite type at Harvard University Graduate School of Engineering in Dr. Casagrande's laboratory. The tested clay had a natural water content ranging from 365 to 422 percent (by weight) and still under strain possessed a stiffness until it was remolded; then it became soft to soupy, sticky putty. The process of air drying and oven drying yielded specimens which displayed plastic characteristics analogical to some extent to those from the Papaikou-Pepeekeo locality in Hawaii reported by Mr. Willis. For this reason it may be appropriate to include here a table of the pertinent characteristics of the volcanic clay from Mexico City (Table A). It should be stated that dried material had to be remolded while being soaked and dispersed in water with considerable mechanical effort and over a period of many days as indicated in the tabulation.

An X-ray diagram of the soil from Hawaii might furnish the Public Roads Administration with the answer to its true nature and indicate whether it has bentonite minerals, namely those of montmorillonite series (Montmorillonite, Beidellite, Nontromite). The complicated crystalline structure of these clay minerals combined of layers of alluminates, silicates, and semi-solid water causes the anomalous plastic behavior.

It is difficult to conduct extensive research on soils from the tropics for two reasons: (1) Before the shipment the samples are always sterilized by the Department of Agriculture to pass the federal quarantine inspection, which process impresses certain irreversible changes on natural soils; (2) Shipping distance explains limited quantities of specimens and thus usually prevents running of all the necessary engineering tests or their repetition often required for reliable results and their confirmation. Returning from the Pacific area the writer was bringing about 70 lb of specimens on a Liberty ship. Unfortunately, the ship never made the US port and the writer landed in San Francisco after a rescue, minus soils and belongings. Running out of limited quantity of newly acquired specimens prevented the writer from concluding his study as he had originally planned. Therefore it is most gratifying that the Public Roads Administration, through its soil research program, helped to throw more light on this intriguing problem while in its early stage of exploration.

TABLE A
CHARACTERISTICS OF VOLCANIC CLAY FROM MEXICO CITY

Origin of Sample	Treatment of Material	Liquid Limit	Plastic Limit	Plastic Index I	Flow Index F	Toughness $T = \frac{I}{F}$	Linear Shrinkage	Note
							%	
National Theatre, Depth 30 ft., A-1	Remolded nat'l material, 10 days of remolding in dispersion above liquid limit and then partially air dried	516	168	368	86	4.28	52 55	
B-1	Remolded fresh nat'l sample, 2 days of remolding in dispersion, then partially air dried	444	120	324	85	3.81		Not so perfectly remolded as the former sample
A-2	Air dried material, 5 days of remolding in dispersion, then partially air dried	133	74	59	33	1.79		
A-3	Oven dried material, 7 days of remolding in dispersion, then partially air dried	100	67	33	14	2.36		Material had an appearance of a silt and a low plasticity.