THE EFFECT OF SAMPLE PREPARATION AND TESTING PROCEDURE ON THE GEOTECHNICAL PROPERTIES OF TROPICALLY WEATHERED RESIDUAL LATERITE SOILS OF ETHIOPIA

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ABSTRACT

Identification and classification of the various grades of tropically weathered residual soils for engineering purposes is a problem that geotechnical engineers repeatedly face in Ethiopia, as well as in other tropical countries. This paper investigates the applicability of conventional laboratory testing, classification and evaluation systems, which were principally developed for temperate climate sedimentary soils, to the tropically weathered residual laterite soils of Ethiopia. The construction of a new highway project from Bako to Nejo in western Ethiopia, with extensive laterite soils, forms a study site that has allowed detailed inspection and sampling of soils for this research project. Testing of these laterite deposits has revealed that they are sensitive to handling and disturbance. Revisions to sample preparation and testing procedures are considered necessary and are proposed in utilizing these soils for civil engineering purposes.

It is concluded that the plasticity chart should be regarded as a guidance tool only for evaluating the likely properties of laterite soils. It should not be used to classify them based on conventional methods without due deference to their genesis. Unlike soils for which the Casagrande Plastcity Chart, as adopted in the United States Classification System (USCS), was developed, laterite soils that plot well below the A-line generally have good engineering properties. A combination of classification based on structure, mineralogical composition, and geo-morphological impact on soil formation together with conventional classification systems is suggested and can result in a good indication of the engineering properties of laterites.

Key Words: laterite, air-dried, as-received, oven-dried, sesquioxide, mineralogy

INTRODUCTION

Urban and rural infrastructure development in Ethiopia is expanding at a rapid pace (21). The southern and western parts of Ethiopia are characterized by residually formed laterites (7, 8, 9, 10, 11, 12) that are widely used as construction materials and have been found satisfactory for many earthworks applications. For example, they form foundation materials for major roads and are used as fill materials for highway profiles and low-permeability layers in earth fill dams. The major roads constructed in Western Ethiopia, such as the *Nedjo-Jarso-Begi* road, and the earth fill dam in *Gilgel-Gibe* for hydroelectric power generation are projects that utilize these types of soil (11, 12). The laterites sampled and tested in this research are from a road project in western Ethiopia.

Tropical weathered residual soils (TWR) are derived from the in-situ weathering and decomposition of rocks in a tropical environment and can have characteristics distinctively different from those of transported sedimentary soils (1, 2). Only recently have they been the subject of concerted studies in the field of geotechnics. Increasingly findings indicate that the application of laboratory testing and classification methods, developed mainly for soils from temperate climates, are either partly or wholly inappropriate in assessing the properties and suitability of TWR laterite soils for roads, earthworks and other purposes. TWR laterite soils are a specific group of TWR soils which include varying amounts of aggregates or crystals of weathered mineral matter that break down and become progressively finer under continuous manipulation (1, 3, 5). This influences the results of laboratory tests and their interpretation. From an engineering viewpoint, laterite soils frequently display significant property differences from those predicted from conventional laboratory test results. For example, despite relatively high liquid limits and moderate particle size they have good engineering properties. They are remarkably stable, exhibit high shear strength, low compressibility and do not normally give rise to swelling or shrinkage problems. Secondary properties, which may be considered somewhat abnormal, are low plasticity index despite high liquid limit, and irreversible changes that can take place on drying, affecting particularly the results of Atterberg limit and particle size tests (5).

The identification of the suitability of TWR soils for use in earthworks operations is imperative. However, soil sample preparation, laboratory testing procedures and classification of TWR in Ethiopia is not consistent. Differences in interpretation are apparent in the evaluation of the geotechnical properties, leading to different conclusions by engineers on the suitability of the same type of soil. The sensitivity of TWR soils to drying and remolding has been shown to be a result of destructuring, the influence of dehydration (desiccation) and the mineralogy of the soil (6). Hence, a generalized approach to the identification and evaluation of the different grades of TWR materials without regard to the origin, degree of decomposition, laterization or desiccation may be misleading and lead to erroneous conclusions (13). More precise definitions, evaluation and standardization of appropriate laboratory testing in TWR characterizations is imperative in deciding on the acceptability of these materials in earthworks construction in Ethiopia.

REVIEW OF DEFINITIONS AND SOIL PROPERTIES

The paper focuses on TWR laterite soils that are found in the Ethiopian tropical environment and are strongly influenced by the clay minerals present. They include the halloysite subgroup soils and the sesquioxide influenced subgroup soils in Wesley's residual soil classification scheme (1, 14). The latter type of residual soils are abundant in Ethiopia (7, 8, 11, 15). In humid tropical regions, as decomposition leaching and dehydration proceed during chemical weathering, a wide variety of laterite soils can be produced from the parent rocks (17). Some common terminology used for these materials, though some are misleading or incorrect, are red clay, tropical red clay, lateritic clay and laterite, or the soils are referred to as reddish brown lateritic, ferruginous tropical, ferrallitic, ferralsols, acrisols or nitosols (16).

Laterite soils are rich in sesquioxide (Fe_2O_3 + Al_2O_3) and low in bases and primary silicates but may contain appreciable amounts of quartz and kaolinite (18, 19, 20). Due to the presence of iron oxides, these soils are red in color ranging from light through bright to brown shades. Reddish color, well drained topography and volcanic parent rocks are useful indicators of tropical red laterite soils (1). They are heavily leached soils having a granular or nodular appearance and range from silty clay to silty gravel with sand texture (3).

Historically, the first systematic study of TWR soils in Ethiopia was a study of the different properties of tropical residual volcanic soils by Morin and Parry in Lyon Associates Institute Inc. (1971). Using different soil sample pretreatments and laboratory procedures, the properties were correlated with the mineralogy and the origin of the residually formed volcanic soils for road construction. After several years, further studies were initiated into the geotechnical properties of TWR soils in different parts of Ethiopia (7-12, 22-24). Studies of TWR soils in different parts of Ethiopia have increased in recent years because of increased construction operations, but these have adopted conventional testing and classification systems in engineering property characterization. Several researchers agree that TWR soils require careful identification and characterization with special field and laboratory procedures to obtain reliable and consistent test data (25). The study of TWR laterite soils depends primarily on the selection of appropriate physical properties as indicators of engineering behavior and the establishment of suitable tests for their investigation (25). Despite the large coverage and use of the residually formed soils in Ethiopia, there has been no systematic research, standardization in testing, classification or description of these materials. These gaps in knowledge have led to this research that is aimed at characterization of the basic geotechnical properties of TWR laterite soils, by assessing the effects of sample preparation and testing protocols, and the significance of standard classification procedures.

MATERIALS, TESTING METHODS AND PROCEDURES

Laterite samples for laboratory testing were obtained from a new highway project along the *Bako-Nekemet-Gimbi-Nejo road* in western Ethiopia as shown in Figs. 1 and 2. Detailed field studies of the geology, climate and topography of this area were also made. A number of test pits were excavated at different sections of the project and two distinct residual soils were exposed. To supplement the data, more than sixty nine selected laboratory test results from similar studies on neighboring sites, such as the Nejo-*Mendi* road, *Assosa*, *Weliyta-Sodo*, *Nedjo-Jarso-Begi* road and *Nejo-Mendi-Assossa* road areas have also been taken into account.

Site Description and Soil Sampling

The study site includes the section from *Bako to Nekemte* (study site A: where the first four pits Pit 1 to Pit 4 were excavated), the section from *Nekemte to Gimbi* (study site B: where Pit 5 and Pit 6 were excavated), and the section from *Gimbi* to *Nejo* (study site C: where Pits 7 to 10 were excavated). The relief of the route in the study area comprises several plateaus with altitude varying from 1100 to 2250m cut with a V-shaped valley. Figure 1 shows the location of the study site and Fig. 3 shows soil sampling at study site C.

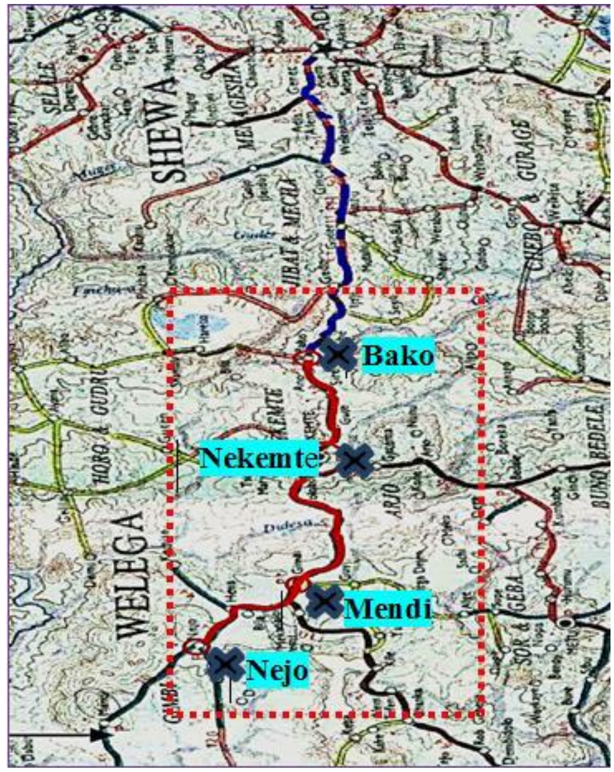

Fig. 1. The main study site location along highway alignments from: *Bako-Nekemte-Gimbi-Nejo*

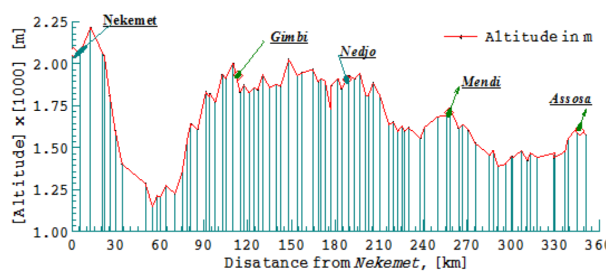

Fig. 2. Partial Elevation versus distance along the study site: Nekemet–Gimbi-Nedjo-Mendi-Assosa

Laboratory Experimental Methods and Procedures

Suites of tests were carried out in the investigation of the properties of the laterite soils. These included mineralogical analysis using a Philips X-Ray Diffractometer (PW-1729) and geochemical analysis. Other tests reported herein are moisture content determinations; liquid limit and plastic limit determinations (on material passing a 425μm sieve); specific gravity determinations and particle size distribution analyses.

Tests were undertaken on air-dried (AD), oven-dried (OD) and as-received (AR) soil samples using different preparation procedures to investigate the influence on the results and classification of the soils based on the testing methods prescribed by the ASTM. The AR samples were carefully stored so as to maintain their in-situ moisture content prior to sample preparation and testing. The AD soil samples were prepared in accordance with the methodology of Lyon Associates Institute Inc. (1971), Fookes, (1997) and Blight (1997) using an oven at a temperature of 50ºC and relative humidity not exceeding 30% (for at least 5 days) until the soils were sufficiently dry to achieve constant weight under normal room temperature. The OD samples were prepared by drying the soils thoroughly at 105ºC.

Fig. 3 Typical undisturbed sampling using a thin wall tube sampler around ***Nejo*** in western Ethiopia

Sample Preparation - Wet sample preparation was carried out on all AR soil samples in accordance with ASTM D2217- 85, procedure B. For index properties that portion of soil passed while it was washed on the 425μm sieve was used. The samples were allowed to dry at room temperature until the mass reached a putty-like consistency (15-25 drops of the cup in the liquid limit test).

Dry sample preparation was carried out for all AD samples in general accordance with ASTM D421-85. A similar procedure was also adopted for all OD samples. For the index properties, the samples were prepared from the portion of the soil samples passing a 425μm sieve and were kept wet for a period of 24hrs before carrying out Atterberg limit tests) .

Plastic and Liquid Limit tests – Both plastic and liquid limit detrminations were carried out by reducing the moisture content (from wet to dry) (22). The mixing times for the liquid limit tests were first limited to 5 minutes, and the mixed samples were left to dry overnight before testing. After the moisture content for each liquid limit test point was determined, the remainder was mixed for a further 25 minutes before determining the liquid limit again. The Casagrande cup method was used for the liquid limit determinations.

Specific Gravity determinations **-** The specific gravity determinations were used in the particle size distribution analyses and to assess any pre-test drying effects. They were carried out in accordance with ASTM D854-92.

Particle Size Distribution (PSD) - The potential mechanical stability of the lateritic soils was studied using particle size analyses tests**.** Separate specific gravity tests were first made for fine and coarse fractions on each soil sample and if significantly different, the grading was calculated by modifying the mass proportions as well as adjusting the mass proportions for analysis (27).

Wet preparation was used for the AR samples. For the AR samples, no form of pre-test drying was used. During the sample preparation, the test samples were soaked until the coating material was fully softened noting that it was important that the fines adhering to coarser particles were removed and the fracturing of weak coarse particles was prevented (22, 27). The soaked samples were washed in the manner stated in section 6.1.2 of ASTM D 2217-85 and procedures recommended by Lyon Associates (1971), using 2.00 mm and 0.075-mm sieves. Hydrometer testing was used in the determination of particle-sizes less than 0.075 mm in accordance with the procedures stated in

ASTM D 422-63. Sodium Hexa-Metaphosphate was used as a dispersing agent and proved successful in dispersing the Ethiopian lateritic soil particles (7, 22).

Dry preparation was used for the AD and OD samples. The aggregations were broken down thoroughly in a mortar with a rubber-covered pestle before they were screened through the nest of sieves. Then the test samples were separated into two portions by sieving with a 2.00mm sieve. The retained particles were used for coarse sieve analysis, while the particles passing were subject to hydrometer analysis as for the AR samples.

CLASSIFICATION OF THE SOILS

The effects of the different sample preparation and testing procedures on the soil classification has been investigated. In particular, the applicability of the Unified Soil Classification System (UCS) (ASTM D 2487-93) and the AASHTO Soil Classification System (AASHTO M 145-87) has been explored. Soil grouping based on mineralogical composition, as proposed by Wesley and Irfan (1), and on the genetic basis and soil-forming factors as proposed by Duchaufour (1982) have also been investigated.

RESULTS AND DISCUSSIONS

Field Study: Effects of Climate, Topography and Geology on Laterite Soil Formation

The identification and evaluation of laterites for construction appears to depend on simultaneous consideration of all the major factors that affect the behavior of the soils. Although parent material, topography and climate are together regarded in the tropics as the factors controlling the soil formation, the climate has the predominant effect on a continental scale (13).

Climate: Temperature and Rainfall - The Ethiopian climate is mainly controlled by the seasonal migration of the Inter Tropical Convergence Zone (ITCZ) and the associated atmospheric circulations of air as well as by the complex topography of the country (28). The altitude of the study area is generally above 1600m and occasionally above 2000m. The yearly mean monthly temperature is above 20ºC with long periods of high temperatures. Using local metereological data, the annual precipitation for the *Bako-Nekemte*, Study Site A, is above 1839.37mm/yr. For *Nekemte – Gimbi* (study site B) and *Gimbi–Nejo* (study site C) it is 1860mm/yr. According to the Köppen-climate classification, the areas are grouped as Bsk (i.e. B = dry/arid, evaporation exceeds precipitation, ***s*** = semi-arid climates; steppe and *k* = mid-latitude dry climate/cold) with humid aridity dominating from 25 April to 26 October. About 80% of the mean annual rainfall occurs during a period of 4 months. This indicates cyclic wet and dry periods. The climate in these areas is favorable for the formation of TWR laterite soils.

Topography and Drainage - Topographical and drainage characteristics seem to have a strong and consistent influence on the weathering process, and thus on the type of clay minerals formed, especially in the wet tropics of western Ethiopia. This area is characterized by hilly and mountainous land with plateaus and valleys. The soil in the higher ground is generally well drained and seepage flow has a strong downward component. This leads to the formation of low-activity clay minerals, especially kaolinite. The well-drained upland soils are frequently reddish, red or brown or brown-red and such red colors denote a non-hydrated iron oxide (Fe_2O_3) in the soil. In the middle and lower slopes, soil drainage is poorer than in the upper slopes and summit and hydrated iron oxides are produced, mainly goethite ($Fe_2O_3.H_2O$) and lomonite ($Fe_2O_3.1.5H_2O$). Their presence is responsible for the change in color down-slope from reddish brown to warm brown or orange brown and then to yellow or even brown yellow on lower ground.

Granites, basalts and metamorphic rocks including gneisses and schists characterize western Ethiopia. Very deep and intense weathering processes have taken place and rock exposures are mainly evident only in the areas underlain by granites and gneisses (7, 12).

Results of Laboratory Testing

Geochemical and Mineralogical Soil Characteristics - In accordance with the USCS system**,** the laterite soils encountered in the fieldwork may be classed as Silty Gravel with Sand texture (Group A) other than those soils in Pit 5 and Pit 6 that comply with Elastic Silt/Clayey Silty textured (Group B); Group A soils having <35% fines of silt and clay and Group B >35% fines. The two groups of soil are derived from granite gneiss. It is these soils and their weathering with depth for which testing has been carried out. Average oxide compositions of Group A and B soils are shown in Table 1. The extent of soil laterisation and weathering conditions were evaluated using the following three indices.

[1] $$\beta_i = \frac{SiO_2}{Al_2O_3},$$

[2] $$\chi_i = \frac{SiO_2}{Fe_2O_3},$$

[3] $$k_i = \frac{SiO_2}{\left(Al_2O_3 + Fe_2O_3\right)}$$

Table 1. Average geo-chemical oxide composition in percentage for Western Ethiopian laterite soils with depth

	Group A Soils[◊]		***Group B Soils***[+]	
Oxides	***0.0-1.5m*** %	**1.5-3.m** %	***0.0-1.5m*** %	**1.5-3.m** %
SiO_2	**32.990**	**33.80**	**40.37**	**38.23**
Al_2O_3	**24.800**	**24.77**	**22.89**	**25.00**
Fe_2O_3	**24.495**	**24.46**	**18.04**	**17.02**
LiO	**8.860**	**7.360**	**11.17**	**11.97**
H_2O	**4.870**	**6.240**	**3.530**	**3.460**
TiO_2	**2.111**	**1.760**	**2.070**	**2.310**
K_2O	**0.371**	**0.500**	**0.700**	**0.711**
Na_2O	**0.369**	**0.220**	**0.490**	**0.333**
MgO	**0.273**	**0.250**	**0.430**	**0.360**
P_2O_3	**0.250**	**0.280**	**0.410**	**0.154**
CaO	**0.230**	**0.240**	**0.311**	**0.063**
MnO	**0.200**	**0.210**	**0.124**	**0.131**
β_i	**1.330**	**1.365**	**1.763**	**1.529**
χ_i	**1.347**	**1.381**	**2.238**	**2.247**
k_i	**0.669**	**1.382**	**0.986**	**0.910**
Remark	**Laterite**	**Laterite**	**Laterite**	**Laterite**

[◊] **Group A: Test results on Silty/Clayey Gravel with Sand laterite soils**

[+] **Group B: Test results on Elastic Silt/Silty Clayey textured laterite soils**

The results of analysis in Table 1 and the Lateralisation Indices Fig. 4 indicate that the soils tested are true laterites. The lowest k_i ratio (i.e. molecular silica: sesquioxide ratio) is recorded for the granite gneiss derived Group A laterite soils at a depth less than 1.5m, and indicates more lateritization than the granite gneiss derived Group B laterite soils at the same depth. However, while weathering decreases with depth for both groups, laterisation increases with depth for Group B laterites. The presence of bases and feldspar in some soils shows that the soils are capable of undergoing further weathering. Silicon is the most abundant element found in both textured soils within both depths. Apart from silicon, only iron, aluminum, and lithium are expressed significantly. Combined water is also present in appreciable amounts. The triangular representation of major oxides (SiO_2, Al_2O_2, Fe_2O_3), as shown in Fig. 5, indicates all laterites are localized toward the Fe_2O_3 pole confirming their ferruginous nature. It is also noted that all points stretch on a straight line perpendicular to the SiO_2 and Al_2O_3 axis, confirming the importance of alumino-silicate minerals identified as kaolinite in mineralogical tests.

Mineralogical identification reveals that, these soils are composed of *kaolinite, quartz, hematite, vermiculite, illite, borax, dickite, and nacrite*. The clay mineralogy is dominated highly by weathered 'mature' kaolinite ($Al_4Si_4O_{10}(OH)_8$) and quartz (SiO_2), generally associated with smaller amounts of hematite and sometimes gibbsite.

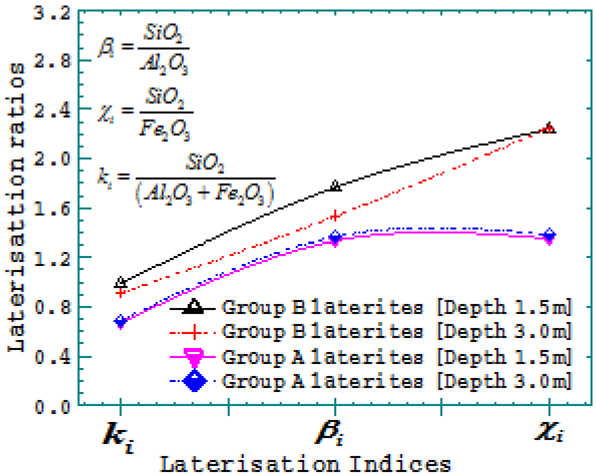

Fig. 4. Average Laterisation indices of Group A and B Ethiopian laterite soils with depth.

Soil rich in poorly ordered kaolinite is typical for a mature tropical soil formed by intense weathering and leaching and is rarer in temperate climates. However, quartz-rich parent rocks tend to produce gravelly materials containing more coarse quartz particles than the concretionary ones. The laterites have been formed in the absence of humus/organic matter. The Laterisation Indices for Group A and B Ethiopian laterite soils with depth in Fig 5, support the above conclusions.

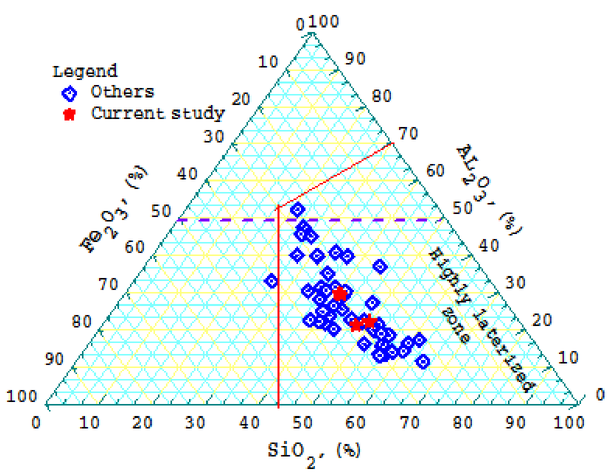

Fig. 5. SiO_2 - Al_2O_3 - Fe_2O_3 triangular diagram indicating the position of the degree of laterization of Ethiopian laterites.

There were no allophane or halloysite clay minerals present in the soil, and the relatively high plasticity is due to the high water retention capacity of the minerals present and the micro aggregate structure. The study has shown that there is a great concentration of sesquioxide of aluminum and iron, no amorphous materials, and limited feldspar particularly associated with the coarser soils. The dominance of acidic rocks such as granite, granitic gneiss and schists from geological studies is supported by the mineralogy test results. Moreover, the weathering has led to congruent dissolution of kaolinite and quartz with a less pronounced formation of gibbsite.

Moisture Content and the Effect of Testing Temperature - In-situ moisture contents were determined by oven drying at 50ºC and 105ºC. As expected, the measured moisture contents showed a general increase with increase in drying temperature. Both testing temperatures led to a normal distributed plot (within 0.05 significant level of accuracy). Figure 6 shows the results with all results in the scatter plot below the line of equality towards drying temperatures of 105ºC. Moreover Group B laterite soils show generally higher values for both drying temperatures. The natural moisture contents for Group A laterite soils range from 24.4 to 28.3% and for Group B laterites range from 29.1 to 31.6% .

The difference in moisture content obtained between the two drying temperatures was less than around 4% for both textured laterite soils. This indicates that Ethiopian laterite soils do not contain a considerable amount of 'water of hydration' or 'structural water' which leads to irreversible changes on drying. It is concluded that for general purposes the moisture content tests for the soils can be conducted using the conventional oven drying (105ºC) method. As a result, ASTM D:2216–98, standard test method for laboratory determination of moisture content is considered acceptable for determining the natural moisture content of Ethiopian laterites. It is recommended to use three or more duplicate samples of AR soil with weighted average to obtain the most accurate results.

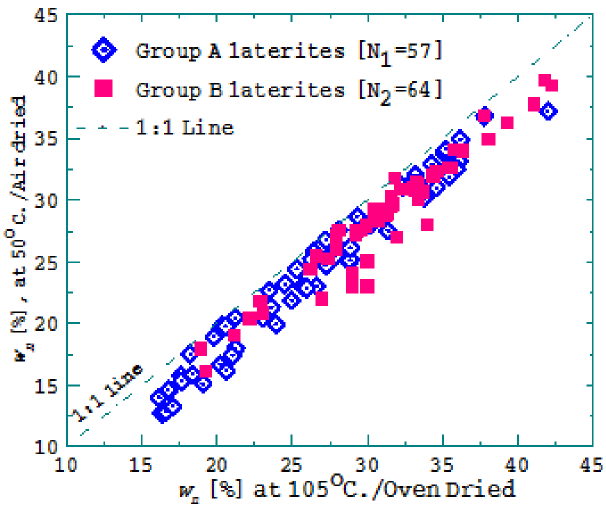

Fig. 6. The relationship between natural moisture content using oven drying of 50^{0}C and 105^{0}C for a range of *TWR* laterite soils of Ethiopia.

Effect of Pretest Drying, Remolding and Testing Procedures on Atterberg Limits - Atterberg limit laboratory tests were conducted to study:

(i) the effects of pretest drying of the soils prior to remolding and testing;

(ii) the effect of the degree of remodeling of the soil samples prior to testing; and

(iii) to assess the most effective method of achieving meaningful and repeatable limit results applicable to site conditions.

It is generally recognized that limit tests are normally reproducible within 5 to 6% (22, 26). While bearing this in mind, the following substantial body of results (Figs. 7, 8, 9 and 10) indicate consistent trends for a mix of Group A and Group B soils.

Regarding objective (i), the AR samples give liquid limites somewhat greater than those of the AD samples, which in turn give values greater than those of the OD samples. The difference between the AR and OD samples is typically around 5%. The results are in general agreement with the conclusions made by Blight (1997) and the results of previous research conducted on western and southern Ethiopian laterites (7, 9, 10, 12, 23).

Regarding objective (ii), comparison of the differences of the liquid limits for 5 and 30 minutes remolding time for each of the three pretesting preparation cases (AR, AD and OD) indicates increased mixing increases the liquid limit by around 5%. Excessive manipulation prior to testing leads to excessive breakdown of the soil structure and disaggregation resulting in loss of lateralization that would not be expected to occur under field conditions. Disaggregation results in increased fines and higher liquid limit values. The data suggest that the time of mixing causes a greater change in the liquid limit data than the pretest drying proceedures considered.

Regarding objective (iii), it is recommended that AR soils are used for plasticity index determinations and that mixing times are limited to not more than 5 minutes with fresh soil used for each moisture content point in the Atterberg limit tests. The soils should be broken-down by soaking in water, and not by drying and grinding, as is suggested for temperate zone soils. Pretesting treatment should reflect the field conditions at the time of construction as represented by AR conditions. The test samples should not be over-dried prior to testing, as the soils would not be expected to experience such high temperatures in the field (1, 7, 12, 22). In support of this, the plots of Figs. 11 and 12, based on compilation of similar studies made in Ethiopia, show that greater liquid limits are obtained for AR samples than for AD and OD samples for Group A and B soils tested at 5min mixing time.

The relationship between liquid limits using 5 and 30 min mixing time on AR, AD and OD for a range of TWR laterite soils presented in Fig. 13 supports the conclusion that increased manipulation results in an increase in liquid limit. Average PI value of 21.8% and 22.3% for the AR soil samples of Group a and Group B respectively, obtained for 5 minutes mixing time, have been used for classification purposes (7-12, 23 and 24).

The Effect of Pretest Drying on Specific Gravity

The in-situ specific gravity of the laterite soils studied ranged from 2.69 to 3.02 with the maximum value higher than that of most temperate soils, which are typically in the range 2.65-2.70. The specific gravity of coarse-grained Group A laterite soil is greater than that of fine-grained Group B textured soil and there is a general trend of increase in specific gravity with depth. This is interpreted as due to a high concentration of iron oxide. Specific gravity values for different pretreatment conditions are indicated in Fig. 14. There is a clear trend of higher specific gravity for the AR (no pre-drying) samples. The reason for this possibly lies in the loss of water of crystallization (or intra-particle or inter-layer water) from the clay (or other) minerals on oven drying, and hence a reduction in the density of the solid matter.

It is concluded that laterite soils should be at their natural moisture content for specific gravity analysis; avoiding pretest drying as it tends to reduce the measured specific gravity compared with that at the natural moisture content.

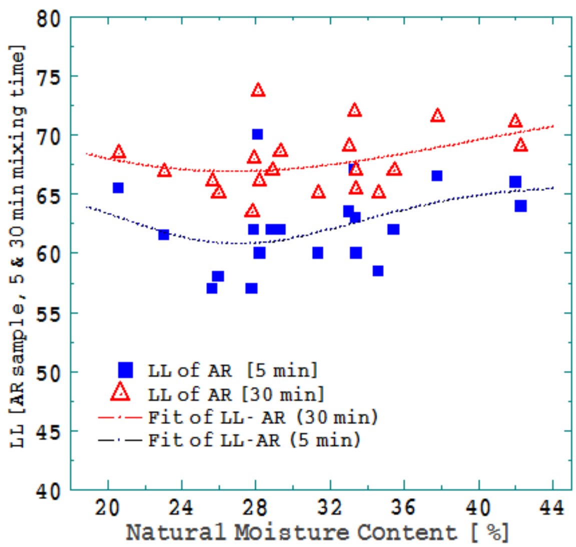

Fig. 7. Variations of liquid limit using AR soil sample tested at 5 and 30min mixing time with natural moisture content for a range of TWR laterite soils tested

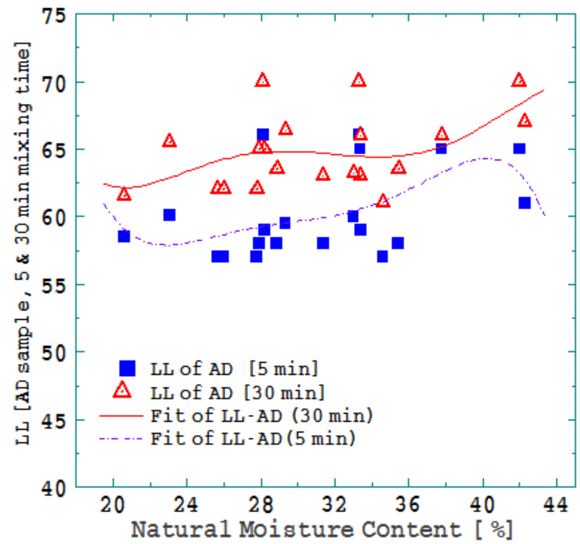

Fig. 8. Variations of liquid limit using AD soil sample tested at 5 and 30min mixing time with natural moisture content for *TWR laterite soils* tested.

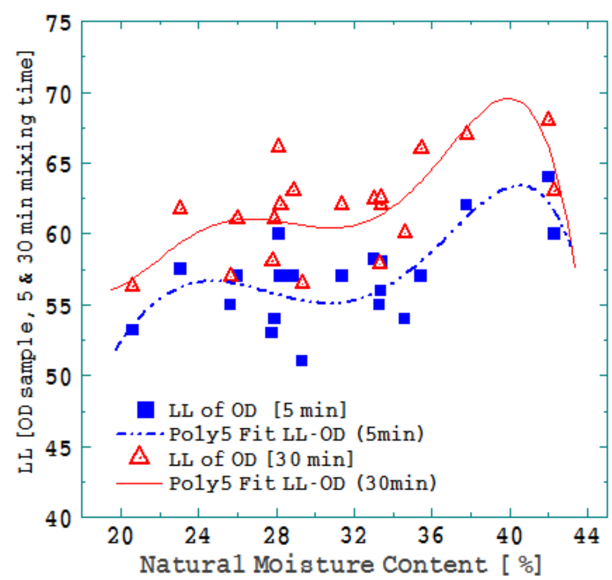

Fig. 9. Variations between liquid limits using OD soil sample tested at 5 and 30min mixing time with natural moisture content for laterite soils tested

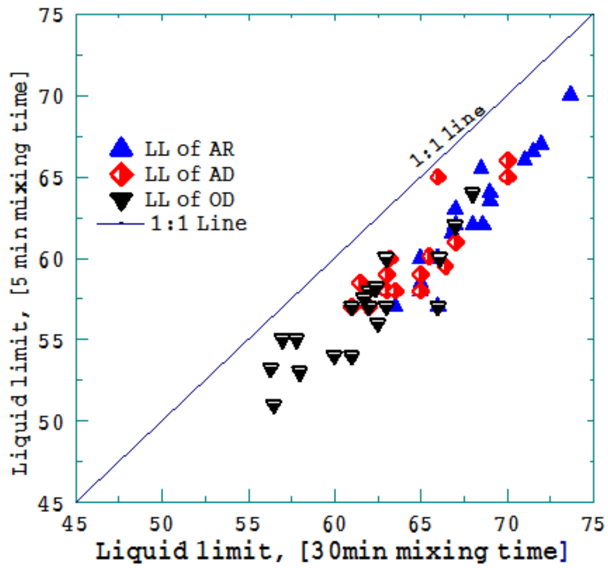

Fig. 10. The relationship between liquid limits using 5 and 30 min mixing time on AR, AD and OD for laterite soils tested

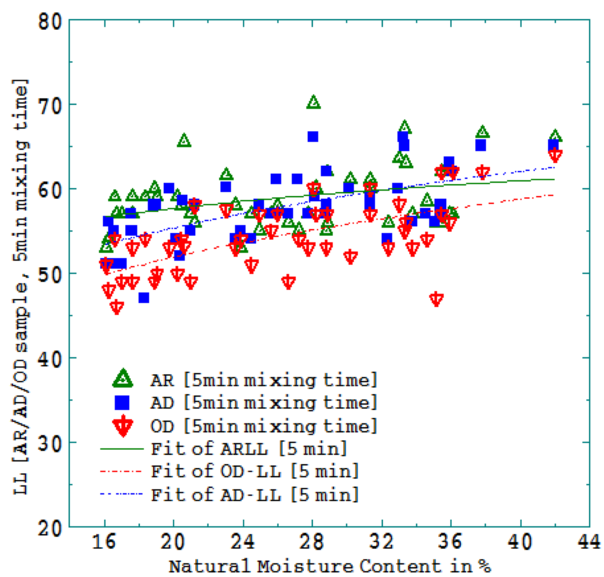

Fig. 11. Variations in liquid limits on AR,AD and OD Group A Ethiopian laterite soils tested at *5min* mixing time

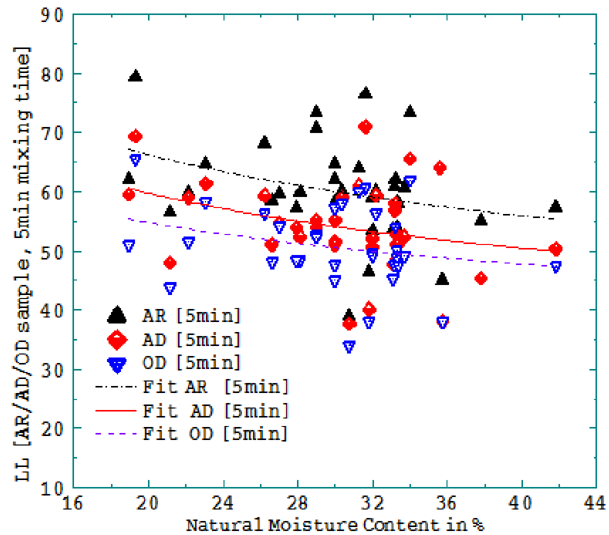

Fig.12. Variations in liquid limits on AR, AD and OD Group B Ethiopian laterite soils tested at *5min* mixing time

Effect of Soil Pretreatments, Testing Procedures, Specific Gravity and Depth on Particle-Size Distribution

The particle-size distribution results were analysed to assess:

(i) the effects of different pre-test drying (i.e. AR, AD and OD) while using the different testing procedures (i.e. dry versus wet sieving);

(ii) to assess the most effective method of achieving meaningful and repeatable grading results applicable to site conditions;

(iii) the effect of using separate specific gravities for the fine and coarse fractions of the test samples; and

(iv) the effect of depth of sampling.

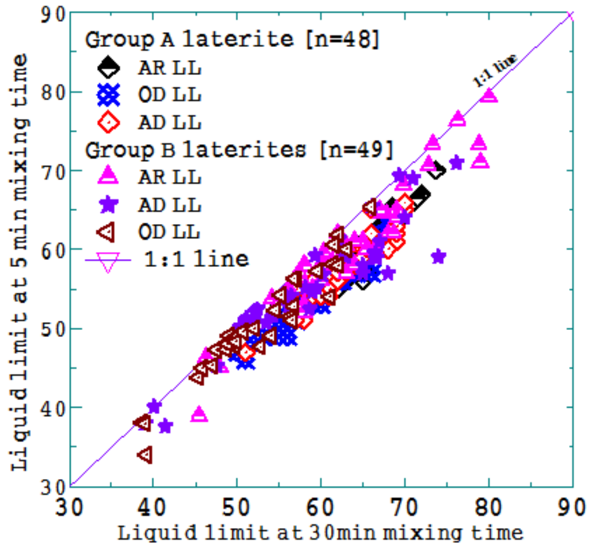

Fig. 13. Liquid limit between 5 and 30min mixing time on AR, AD and OD samples for Group A and Group B TWR laterite soils of Ethiopia

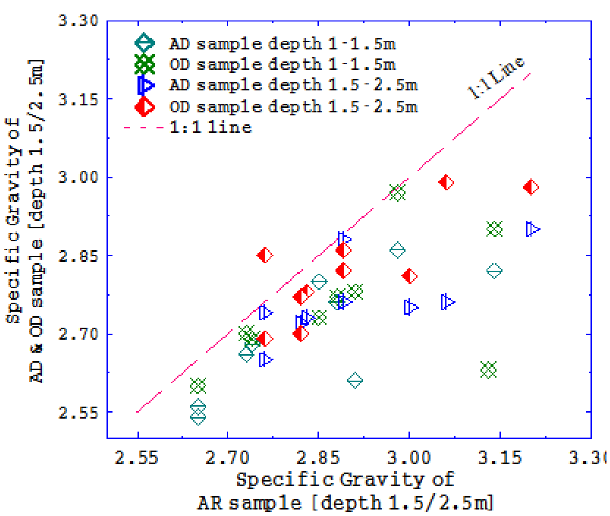

Fig. 14. Line of equality between specific gravity values for ifferent pretest drying treatments

Representative particle size ditribution plots are shown in Figs. 15 and 16.

Regarding objective (i), the AD and OD soil pre-treatments and testing procedures for Group A and Group B laterites resulted in an increase of the finer particles compared to the AR samples with a concomitant decrease in the coarser particles. Generally, the particle-size distributions of lateritie soils change as a result of hydration reaction when soils are dried especially at high temperatures. There is also a possible influence from adherence of fines to coarser particles which were not dislodged during washing and that some laterites experience fracturing of the coarser fractions during sample preparation and testing.

Regarding objective (ii), the variation in percentage of partcle sizes in the different test proceedures is not significant and comparable to that which might be expecetd in testing of temperate soils. Although, pre-drying did not significantly affect the results, it is recommended that pre-test preparation and testing is performed on soils in their natural state (AR soil). It is also recommended that the wet preparation (i.e. soaking the soil until the coating material is fully softened) and the wet sieving procedures should be used in practice.

Dispersion of the soils was effectively achieved using 'standard' sodium hexametaphosphate dispersant, provided the dispersant with the soil suspension was shaken well (7). Testing the soil without pre-drying and using a wet sieving procedure is consistent with normal recommended preparation procedure. In general, consistent and meaningful particle size distributions were not difficult to obtain for Ethiopian laterite soils. The results of Western Ethiopian laterites tests by several researchers also support this conclusion (7, 12).

Regarding objective (iii), though it has been shown that speciifc gravity values vary somewhat with pre-treatmnet conditions, the grading curves using mass and modified mass proportions do not vary significantly, especially for samples tested under wet seiving (i.e. AR pretreatment condition). The need to modify the grading curves using modified mass proportion is not considered important when the wet sieving method on AR soil is used.

Regarding objective (iv), the study has shown a general increase in the percentage of coarse gravel particles with increasing depth and a decrease in the clay and silt fractions consistent with a decrease of weathering. testing procedures considered. The range of grading curves of the soil samples is as shown in Fig. 17 for various AR sample pretreatment conditions.

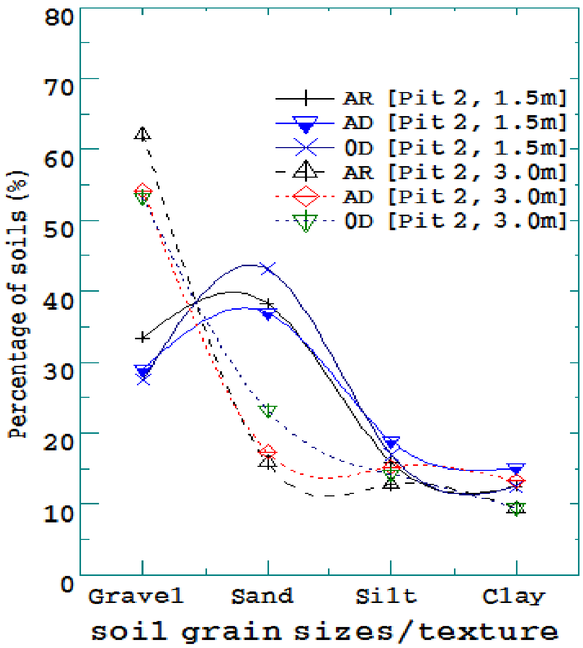

Fig. 15. **V**ariation of the % of the different sizes at different predrying temperature and testing conditions with depth for Group A soils.

Effects of Sample Preparations and Testing Procedures on Classification of TWR Laterite Soils

The laterite soils tested are typical of western Ethiopia having activity indices (AI) of < 1.25 indicating them as inactive or normal. This is attributed to the mode of weathering which involves the coating of the soil particles with sesquioxide resulting in suppression of the surface activity of the clay particles. Density determinations resulted in a range of values with bulk unit weights ranging from 17 to 19.2 kN/m^3 and dry unit weight ranging from 13.7 to 14.9kN/m^3 with a volumetric water content (θ_w) of the soils generally ranging from 0.4 to 0.5% for Group A and Group B materials within the depth investigated. It is an assessment of the appropriate testing techniques and classification of these soils based on the test results that is a prime purpose of this paper.

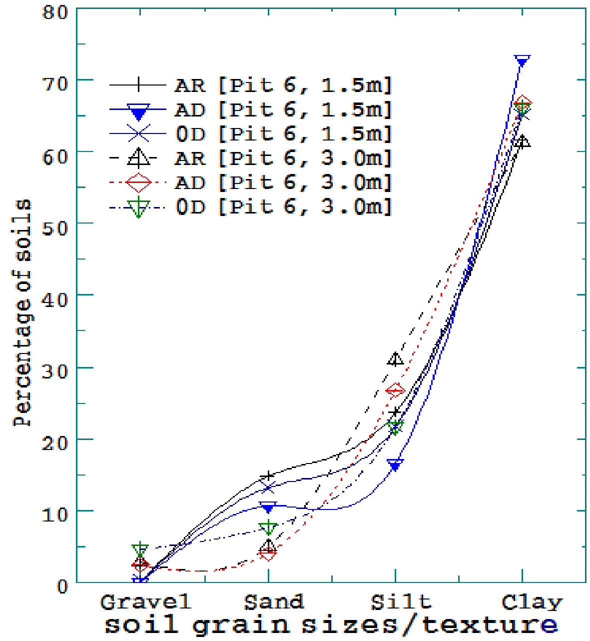

Fig. 16. Variation of the % of the different sizes at different predrying temperature and testing conditions with depth for Group B soils.

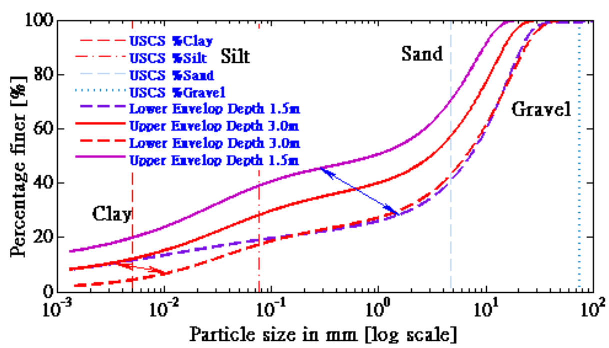

Fig.17. Grading envelop for silty gravel with sand textured laterites with depth for various AR pretreatment conditions

The purpose of a soil classification system is to describe the characteristics of a soil that give guidance on how it will behave as a construction material. Soil classification should not be used as an end in itself but as a guidance tool to material properties and usage. Soil properties such as strength and compressibility also need to be taken into account as does the sensitivity of the soil to testing technique and experience of using the materials in practice. It is these latter two points that are addressed in this paper.

Based on USCS, the majority of the granular soils are classified as SM, GM, GW-GM and GW- GC (Silty Gravel with Sand or Silty Sand with Gravel textured). Figures 18 and 19 indicate the relative position of the soils on the plasticity chart. All samples for material <425μm lie below the A-line in the region of silts, MH category. In general the soils are *Silty Gravel with Sand textured* [Group A] and few of them are of Silty *Clay* textured [Group B] laterites. Both groups lie in the region of kaolinite-dominated soils on the plasticity chart in agreement with the mineralogical tests undertaken. Based purely on the plasticity chart of the USCS the laterites would be classed as having 'poor' engineering properties and considered troublesome and potentially unsuitable for construction purposes. However, according to [5], TWR red clays/or clayey slit soils are considered to possess unusual or abnormal properties, at least when compared with what might be termed normal sedimentary clays of more temperate regions. The most abnormal property from an engineering viewpoint is that despite relatively high liquid limits and small particle size they have good engineering properties and are stable usually having a high shear strength and low compressibility. As a result, in practice, Ethiopian laterite soils generally show good engineering properties especially for construction of subgrades and embankments (5, 29). The classification of these laterite residual soils, using the USCS has shown contradictory results and several studies have questioned the use of USCS for classifying TWR soils (1).

Figures 18 and 19 show the Casagrande plasticity chart for AR, AD and OD samples for 5min and 30 minute mixing times in determining the liquid limit for both Group A and B soils. The effect of the pretreatment conditions on the classification of the soils using the USCS results in no major change in the group name and symbol. However, laboratory results show that drying at high temperatures tends to aggregate soil particles, either through oxidation of free iron or dehydration of clay minerals, or both, and thus decreases the liquid limit and plasticity index. This is counteracted to an extent by increase in plasticity if the longer mixing time of 30 minutes is used as the aggregates tend to break down. Depending on the pre-treatment, the data shifts parallel to the A-Line within the same group. It is stressed that the changes in plasticity because of the pretreatment procedure can have an influence on the selection of earthworks compaction plant and assessment of other soil properties such as strength, compressibility and volume change characteristics when correlation techniques are used. It is important that laboratory techniques yield results that reflect likely site conditions.

Also of great importance is the sensitivity of the laterite soils to pretreatment. This sheds doubt on the applicability of the USCS for TWR laterite soils at least without due consideration to their true nature and in particular to the finer Group B soils. According to the AASHTO M-145 system, the majority of the soils are granular (Silty/Clayey gravel and Sand). These granular soils fall under subgroup A-2-7 with group index less than three and are characterized as a good to excellent subgrade materials, and few samples are fine grained soils (Silty/Clayey Soils) and located under subgroup A-7-5 with group index less than 21, characterized as fair to poor road construction materials. The AASHTO system, even though it appears to appropriately classify the coarse-grained Group A soils, classifies the tropical Group B soils as potentially unsuitable for construction materials. However, these materials for the reasons given previously are good engineering materials in practice. Vargas (1982) showed in the plasticity chart, that most of the soil obtained from decomposed granite, gneiss and schist lay below the A-Line. Hence, the use of the AASHTO system is not advised for classifying Group B textured laterite soils for road construction purposes, though it may work well for Group A laterite soils.

It appears that the most practical way to evaluate the likely engineering behavior is to use the classification systems that utilize plasticity data, structure, and mineralogy and geo-morphological impacts on soil formation, such as the Wesley and Irfan (1997) classification system, combined with AASHTO system. Such a classification together with material properties such as strength and compressibility would arm the engineer with the data needed to decide on the suitability of the materials, compaction requirements and the design parameters in earthworks.

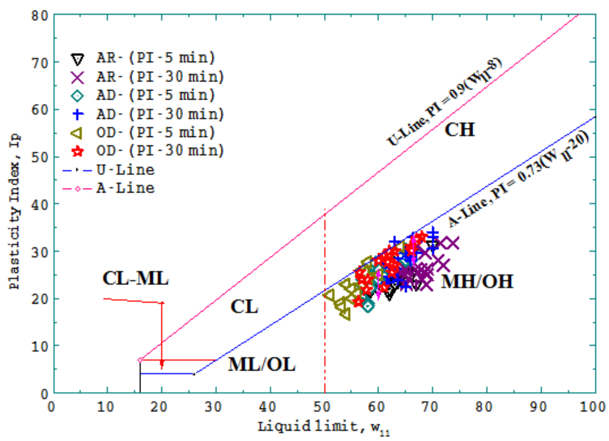

Fig. 18. The locations of the laterite soils studied on the *Casagrande Plasticity Chart.*

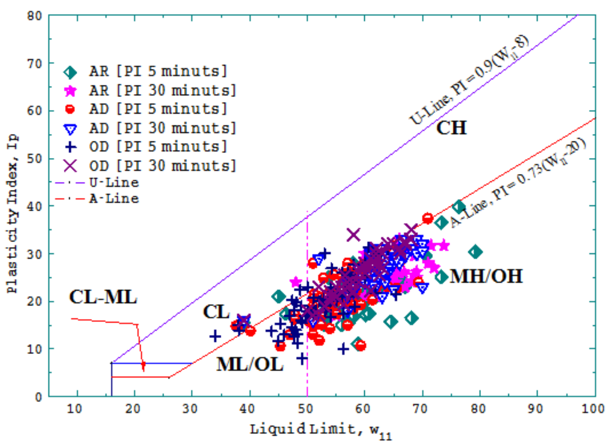

Fig. 19. Locations of Ethiopian laterite soils on the *Casagrande Plasticity Chart* based on several studies (7, 8, 9, 10, 11, 12, 22, 23, 24)

The soils formed in the southern and the western parts of Ethiopia are characterized with a mean annual temperature ranging from of $20 - 30^oC$ and mean annual precipitation greater than 1500mm, therefore according to Summerfield climate zonation cited in (29), the region is a *humid tropical zone*. The geomorphological setting strongly supports the formation of in situ chemical weathering of the soils. In this regard using the Duchaufour (1982) scheme, the development of these soils should be seen as phases in the same weathering process, forming part of a weathering continuum from fersiallitic through to ferrallitic soils. According to the prevailing soil forming factors and genetic basis, the silty clayey (Group B) textured laterite soils (or A-7-5) are grouped under a ferrisol group. Ferrisols seem to cover several varied soils and are generally shallow (about 2m), with higher silt, free iron contents and a horizon of clay or silica gel accumulation.

However, Group A textured soils (A-2-7), with a lesser silica to sesquioxide ratio, are grouped as ferrallitic soils. The ferrallitic process is associated with intensified deep, pale, sandy surface horizons that have evolved especially on quartz-rich granites or sands. Moreover, the soils are all true laterites based on the texture, mineralogy and geo-chemical test results which give a silica/sesquioxide ratio below 1.33 (Laterization Index k_i in Fig. 4) True laterites are very old soils from which practically all the soluble materials have been leached. As a result, the soils based on Wesley (1988) and Wesley and Irfan (1997) classification system is grouped under "*Group C: residual soils strongly influenced by special clay minerals not found in sedimentary soils*". The influence of sesquioxide was detected during chemical and mineralogy tests; as a result, the soils are sub-grouped into "*Soils influenced by the presence of Sesquioxide"*. The principal role of the sesquioxides appears to be as a cementing agent that binds the other mineral constituents into clusters or aggregations.

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions arrived at in this study in relation to the use of laterite soils in earthworks are presented below:

a) Mineralogical identification reveals that the soils are composed of *kaolinite, quartz, hematite, vermiculite, illite, borax, dickite, and nacrite.* The clay mineralogy is dominated by highly weathered 'mature' kaolinite and quartz, associated with smaller amounts of hematite and sometimes-small proportions of goethite and/or gibbsite. No humus/organic matter, no allophane or halloysite minerals were present.

b) No significant water of crystallization (structural water/ chemically combined water, was detected that could lead to irreversible changes on drying) was driven off samples dried at 50 or 105°C. As a result, a conventional drying temperature of 105°c as specified in ASTM D-2216 for moisture content determination was adopted for the TWR laterites tested.

c) It is considered appropriate that laterite soil samples for Atterberg limit testing should be broken down by soaking in water and not by drying and grinding as is conventional practice for temperate zone soils.

d) The laterite soils in Ethiopia are sensitive to handling and manipulation. To obtain consistent and repeatable plasticity data it is recommended that remolding of samples prior to Atterberg limit testing is restricted to no more than 5 minutes with fresh soil used for each moisture content point in the Atterberg limit test on as received soil using the 'drying-back technique.

e) It is recommended to use soils in their natural state (no pretest drying) for particle size tests, as the soils are sensitive to manipulation and pulverization. The use of the wet sieving method is recommended with the soil soaked until the coating material is fully softened. The modification of the grading curves using modified mass proportion is not considered important if the wet sieving method is used.

f) Specific gravity tests should be carried out on samples at their as-received moisture content, rather than on pre-dried samples as temperature can significantly influence the results.

g) The laterite soils plot below the A-line in the USCS classification system casting doubt on their suitability in earthworks. Such soils are however frequently and satisfactorily adopted for such usage and accordingly the plasticity chart should be used with causation. Moreover, it has also been found that the AASHTO system is unsuitable for classifying the finer tropical Elastic Silt/Silty Clayey textured laterite soils for road construction purposes. However, it appears to work well for coarse-grained laterites.

h) Classification systems that take account of plasticity data, soil structure, mineralogical compositions and geo-morphological impacts on soil formation, together with the ASSHTO system, can result to give a good indication of the engineering properties of laterites.

RECOGNITION

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