PARAMETERS FOR CLASSIFICATION OF FINE-GRAINED LATERITE SOILS OF GHANA

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The available literature indicates that engineering properties and field performance of tropically weathered soils are influenced considerably by factors of soil formation, degree of weathering (or laterization), morphological characteristics, and chemical and mineralogical composition as well as environmental conditions. Consequently, temperate-zone highway and airfield soil classification systems based on particle size distribution and plasticity alone are inadequate for these soils. Numerous failures of highway and airfield pavements built with or on laterite soils, in spite of strict adherence to ASTM grading and plasticity specifications, have confirmed the inapplicability of the present temperate-zone classification system. This paper attempts to propose some useful parameters for classification of fine-grained laterite soils of Ghana. The study has revealed that morphology and general characteristics (including chemical and mineral composition) of Ghana soils are influenced considerably by the weathering systems. For a given genetic soil group, the consistency parameters, colloidal activity, compaction characteristics, specific gravity, field moisture equivalent, and linear shrinkage have fairly good correlations with the amount of clay content. The different degrees of weathering (or laterization) of the soil types from the different climatic-vegetational zones have considerable influence on the relation between the clay content and the properties of soils over different parent rocks. The conclusions reached suggest that the residual fine-grained laterite soils of Ghana may be most adequately classified for highway purposes on the basis of such factors as parent materials (geological formations), climatic-vegetational conditions, degree of weathering (or laterization), amount of clay content, and linear shrinkage.

• SOIL classification tests for temperate-climate soils have been standardized for the determination of the particle size distribution and the plasticity parameters. From knowledge of these properties, some general engineering characteristics can be inferred based on information available on other soils of similar classification. In spite of the successful use of this classification system for over 40 years, it is now realized that soil behavior in the field does not depend on particle size distribution and plasticity alone. Certain factors such as genesis, geological history, morphological characteristics, clay mineral type, nature of exchangeable ions, and actual moisture conditions would enhance the technical importance of the existing classification systems.

The use for tropical soils of the temperate-zone classification systems based on particle size distribution and plasticity parameters alone has been very disappointing. In spite of strict adherence to ASTM particle size distribution and plasticity specifications, numerous failures of highway and airfield pavements built on or with laterite

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soils continue to occur in many tropical countries. The adoption of particle size distribution and plasticity alone for classification of laterite soils has proved unsuccessful for three reasons:

1. These classification tests do not yield reproducible results because they are influenced considerably by methods of preparation and handling of the material (10, 42, 48, 56).
2. Because the material is a decomposition material, it may contain materials with different degrees of weathering. Thus, these tests could not yield adequate indications of the engineering properties without some definition of the degree of weathering (or laterization) (4, 19, 44).
3. The engineering properties and field performance of laterite soils are influenced considerably by chemical and mineral content, genesis, morphology, and the environment (7, 17, 24, 51, 57).

The problem of classifying laterite soils is to evolve a simple system that takes account of the fact that the material is a decomposition (or laterizing) material with different degrees of weathering (or laterization) and different chemical and mineralogical contents formed in different environments. The application of the system should involve the use of simple tests that yield reproducible results. One such simple test was found useful for identifying fine-grained laterite soils in linear shrinkage (6, 25, 27, 55).

In this paper an attempt is made to propose some useful parameters for classification of fine-grained laterite soils of Ghana. It is hoped that this study will contribute toward a more rational and realistic approach to the identification and engineering classification of tropically weathered soils.

REVIEW OF LATERITE SOIL CLASSIFICATION SYSTEMS

The greatest problem encountered in the study of laterite soils is the difficulty of evolving a definition or classification system acceptable to chemists and geologists as well as soil scientists. Although there are numerous factors that influence the formation of laterite soils in tropical and subtropical climatic conditions, three basic criteria based on common characteristics have been identified by the soil scientists, chemists, and geologists. These criteria are the physical property of in situ hardening or hardening on exposure to air (14), chemical composition (26, 33, 36, 41), and the morphological characteristics of the laterite soil profiles (45).

The difficulties of defining and classifying laterite soils have been carried over to engineering studies. Different methods of classifying laterite soils have been proposed. The first attempt to group laterite soils for engineering purposes was based on the pedogenic characteristics of the soils (16). Little (38) proposed a method of classification based on morphological characteristics and on an estimate of the degree of weathering on the parent rocks, following the work of Lumb (39). This is of limited application, however, to laterite soils because the formation of these soils is complicated by the enrichment of iron or aluminum or both.

Classification systems based on climatic vegetational conditions, morphology, topography, and drainage conditions were also suggested (9, 15, 17, 46). Laboratory studies backed by field experience in many African countries (28) have revealed that none of these methods is completely adequate for general application. The fact that some success was noted with some of these methods in some countries only reveals the importance of these factors to the engineering properties and field performance of laterite soils.

FORMATION OF SOILS IN GHANA

The aim of the study reported here was to determine the most important parameters by which a highway soil classification system could be established for the laterite fine-grained soils of Ghana. To accomplish this, it was necessary to investigate the formation and distribution of these soils as determined by such factors as climatic-vegetational conditions, parent rocks, topography, and drainage conditions.

Geology and Distribution of Rock Types

Figure 1 is a simplified geological map of Ghana. It shows that the most important rocks are gneisses in the coastal savanna zone; granites and phyllites in the semideciduous forest zone; and granites, sandstones, and shales in the deciduous woodland savanna zone. The geomorphology and physical features depend mainly on the geology; most of the hills and ranges consist of hard resistant rocks such as quartzites, whereas the valleys and lower grounds are carved out of softer rocks such as shales, sandstones, phyllites, and schists.

Climate and Vegetation

The rainfall, temperature, and relative humidity are generally very high, as is typical of a tropical climate. The vegetation depends mainly on the intensity and distribution of rainfall.

Based on rainfall intensity and vegetation type, Ghana was roughly divided into three climatic-vegetational zones. The coastal savanna zone receives average annual rainfall of less than 1,000 mm, whereas the corresponding values for deciduous woodland savanna and the semideciduous forest zones are 1,000 to 1,250 mm and above 1,250 mm respectively (Fig. 2).

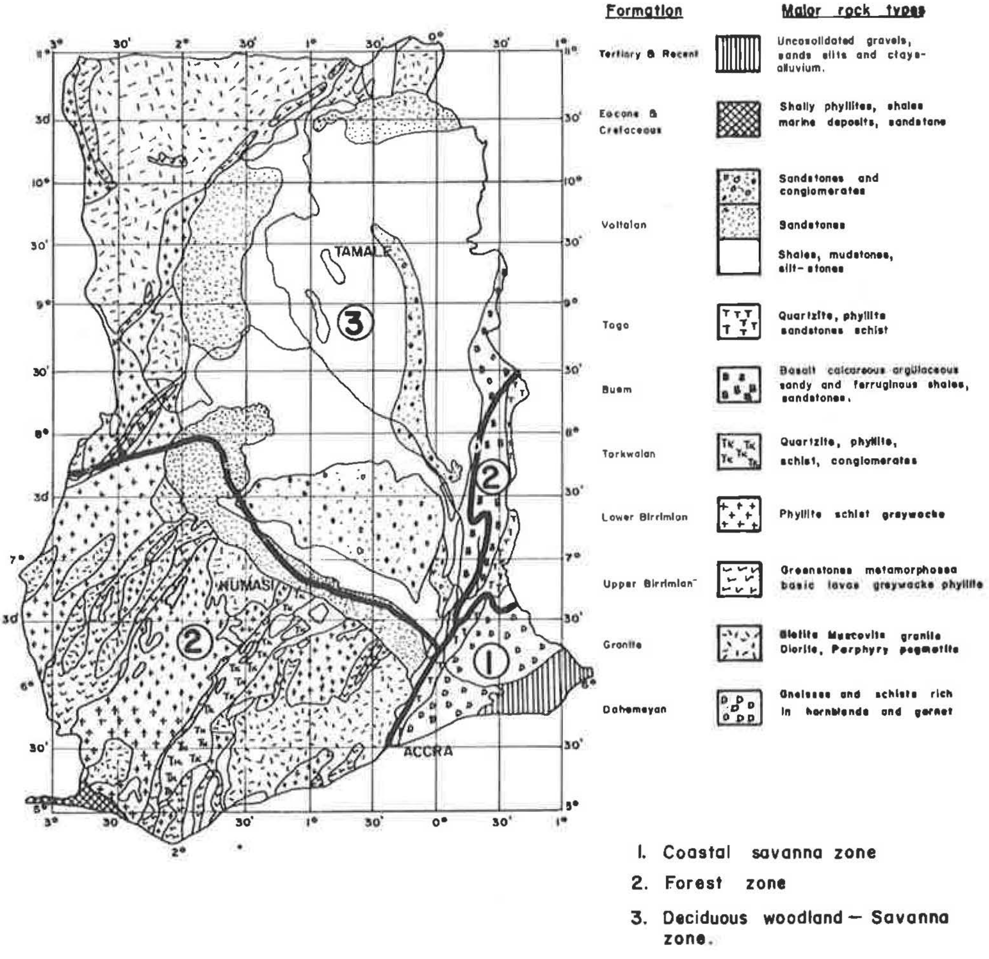


Figure 1. A simplified geological map of Ghana [after Bates (11)].

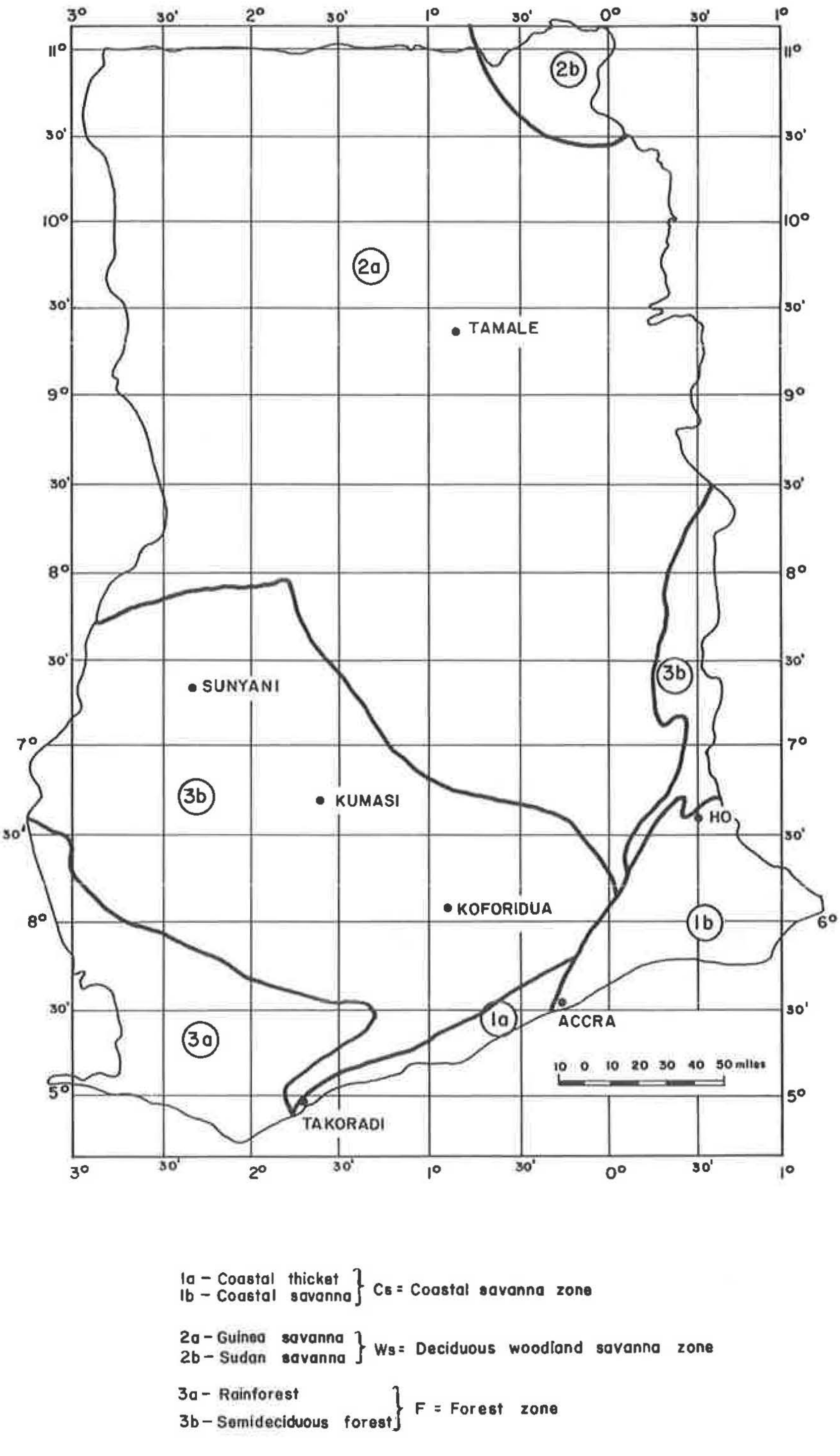


Figure 2. A simplified climatic-vegetational map of Ghana.

Tropical Weathering and Laterization

Weathering is started by the physical breakdown of parent rocks resulting from differential expansion and contraction of the rock-forming minerals due to temperature variations.

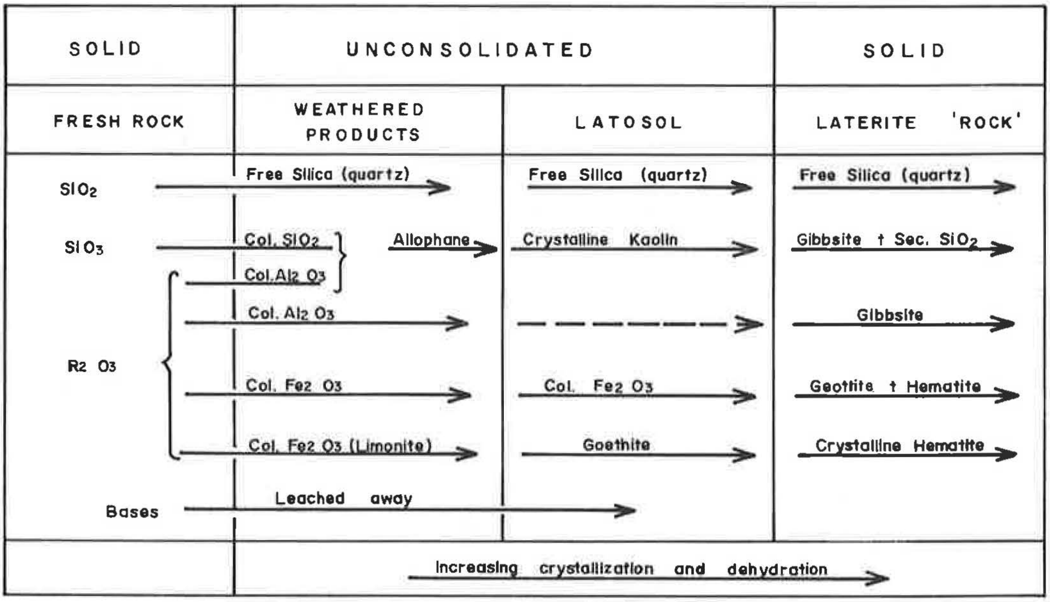
The rock particles, however, still retain their original chemical and mineralogical compositions. Chemical weathering involves the chemical breakdown of unstable primary minerals and the formation of new minerals. Water containing biochemical products of vegetable decay and other corrosive compounds attacks the parent rock pieces. The weathering process is selective; less stable minerals such as biotite are attacked first, whereas quartz is more resistant. The weathering process advances until only very stable primary minerals are left. This summarizes a very complex weathering process that is affected by the factors of soil formation, parent rocks, climatic-vegetational conditions, local topography, and drainage conditions.

The process of laterization that follows involves the leaching in solution of the weathered materials, mainly combined silica and bases, which leaves the residue relatively rich in hydroxides and oxides of aluminum, iron, and titanium (laterite constituents). Sometimes soluble laterite constituents migrate themselves; good internal drainage is a very important factor here.

The presence of laterite constituents in the parent rocks or in adjacent uplands is thus one of the most important prerequisites for the laterization process to take place. In an earlier study (27) it was shown that most Ghanaian rocks contain fairly large amounts of laterite constituents, which accounts for the fact that laterite profiles are found on most of these parent rocks.

The mineralogical stages of laterization of soil over granite under Ghanaian conditions were investigated (30), and the results are shown in Figure 3. It is seen that, as laterization advances, the degree of crystallization and dehydration of the laterite constituents increases.

The literature has emphasized the chemical, mineralogical, and physical (hardening) aspects of laterization; however, the engineering significance of the physicochemical



Col. = Colloidal. $R_2O_3 = Al_2O_3 + Fe_2O_3$, Bases = CaO, MgO, Na_2O, K_2O, Sec = Secondary.

Figure 3. Chemical and mineralogical stages of laterization under Ghanaian conditions [after Hamilton (30)].

aspect involving the coating of the soil particles by free alumina or iron oxide gels has been ignored. It is assumed in this study that the coating of the soil particles is one of the most important factors that underlines the physicochemical and physical differences between laterites and temperate-zone soils. The author maintains that the coating considerably influences the surface activity of the clay minerals and hence of soils containing these minerals.

The cementation of the laterite soil is due to the presence of free iron. The free iron oxide is generally found in three different forms: hematite, limonite, and geotite. The increasing degree of laterization results in an increase of the thickness of free iron oxide (hematite) coating of the soil particles (42). The soil particles later coagulate into larger clusters with subsequent reduction in specific surface. It is the reduction in specific surface that is of interest in soil mechanics.

DISTRIBUTION AND GENERAL CHARACTERISTICS OF SOILS IN GHANA

The field identification studies carried out by the author combined with available pedological, geological, and engineering information revealed that the pedological soil map proposed by Branner and Wills (13) gives the best picture of the distribution of subsoil types in Ghana. Because this soil classification is based on the consideration of soil-forming factors, the soil map forms a sound basis for the preliminary classification of soils. The pedological soil map was therefore simplified by considering modes of formation and morphological characteristics as well as texture and color of soils (Fig. 4).

Variation of Soil Color With Local Topography

The color of soil (below the humus topsoil) changes from red or reddish brown on the summits and upper slopes through orange-brown on the middle slopes to yellow-brown on the lower slopes. These color variations reflect changes in the degree of hydration of iron or alumina present in the profiles, which depend on changes in internal drainage conditions in different parts of the local topography. In poorly drained areas the soil color varies from yellow, through grey-black to white. Where soil profiles are subjected to alternate reduction and oxidation (due to waterlogging and drying out respectively) mottles are formed (patches of yellow, orange, or red in an otherwise grey soil profile). A rough assessment of the degree of laterization in terms of color of the soil based on the available literature and field studies is suggested as follows:

1. Coastal zone tropical clays over gneiss are of low degrees of leaching and laterization;
2. Coastal zone reddish residual soils over gneiss are of medium degrees of leaching and laterization; and
3. Forest zone residual soils over granites and phyllites are highly leached and laterized.

Chemical Characteristics

Regarding the chemical characteristics of Ghana soil groups, Figure 5 shows that there is fairly good negative correlation between the total silica and the sesquioxides for the nonresidual soils, tropical clays, and residual soils; however, the relation breaks down for the laterite rocks. The total sesquioxide content of the nonresidual soils and tropical clays ranges between 0 and 20 percent. For residual laterite soils and the laterite rocks, corresponding values are between 20 and 50 percent and more than 50 percent respectively. The large silica content in the nonresidual and tropical clay soils may be due to the concentration of dissolved silica in these profiles and to the very finely divided quartz remaining in the residual wash that has been carried to lower flat grounds.

Mineral Characteristics

Results of petrographic and mineralogical studies on different soil types of the various pedological groups (29, 30, 47, 50) and at the Ghana Geological Survey Department

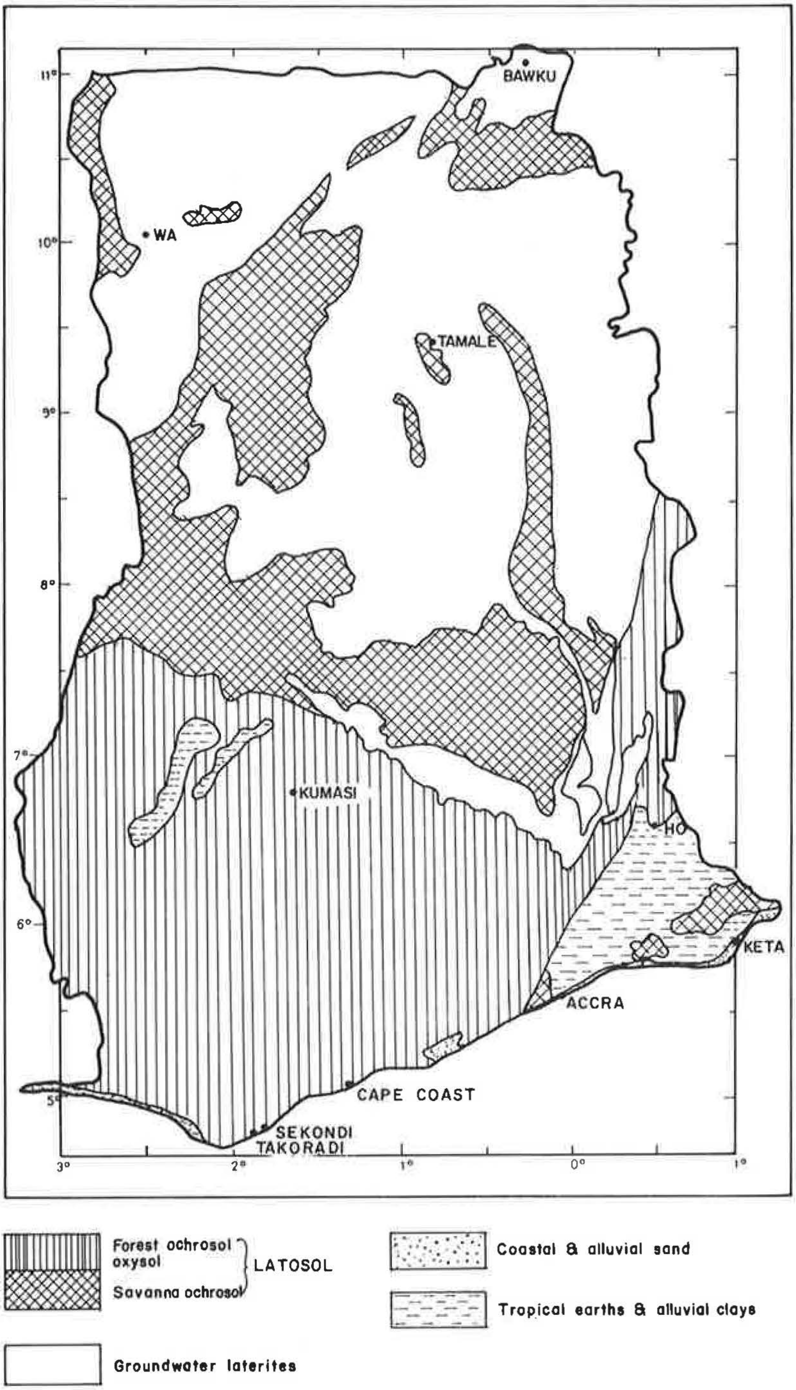


Figure 4. A simplified pedological map of Ghana [after Branner and Wills (13)].

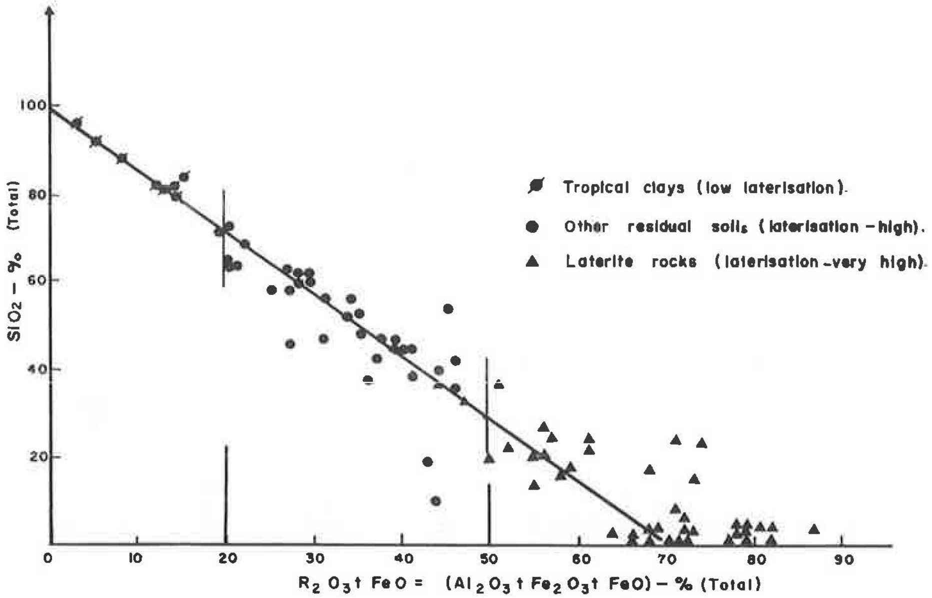


Figure 5. Generalized chemical characteristics of soils in Ghana.

(for the Building and Road Research Institute) have revealed that, owing to the intensity of the chemical weathering processes under Ghanaian conditions, all the unstable primary minerals are either partially or completely broken down and/or transformed into secondary minerals. The most frequently encountered unweathered common primary minerals in the laterite profiles are quartz, garnet, staurolite, illite (muscovite), feldspar (microcline), hornblende, and rutile; these minerals are stable under laterite conditions. The particular mineral available depends on the parent rock type. The chief clay mineral observed was kaolinite, with mica (sericite and illite) in the latosols. Montmorillonite and sometimes vermiculite are also present in the poorly drained tropical clays. The secondary minerals resulting mainly from the laterization processes are gibbsite, geotite, limonite, and hematite. Sometimes magnetite was noticed, but neither manganese nor titanium minerals were observed in significant amounts.

BASIC GROUPING OF LATERITE SOILS

On the basis of field and laboratory experience with laterite soils in Ghana and elsewhere, the laterite soils of Ghana may be texturally classified into three main groups, as shown in Figure 6. All textural groups may be either residual or nonresidual formations. The three groups are as follows:

1. Laterite rocks and boulders—These are concretionary laterite rocks and rock pieces that are extensively used in some African countries as concrete and road surfacing aggregates. Because natural aggregates are fairly abundant in Ghana, however, very little interest has been shown in these materials, and they are therefore not covered in this study.
2. Laterite and laterite-quartz gravels—These gravels form the most important naturally occurring gravels and are extensively used as base and subbase materials in Ghana. These materials have therefore been extensively studied. Some proposals on the classification of these gravels have already been published (19), and further studies are in progress; these gravels are therefore not considered in this paper.
3. Laterite fine-grained soils—These soils have been given very little attention in the past, but recent highway subgrade and shallow foundation failures have em-

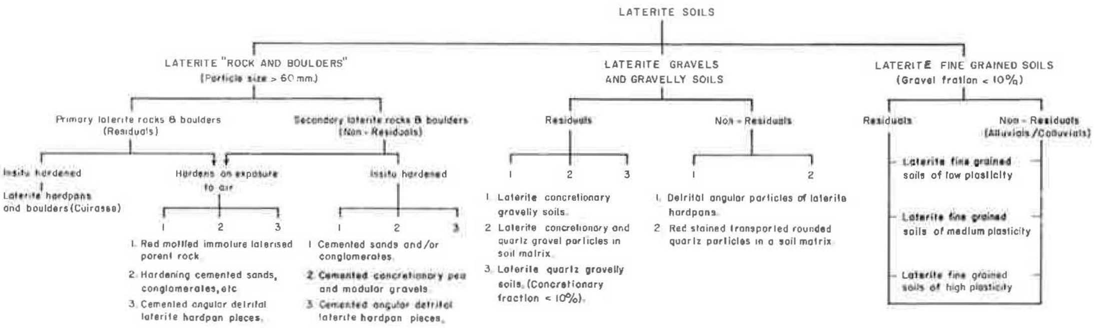


Figure 6. Pedogenic-textural groups of laterite soils in Ghana.

phasized the importance of studying and understanding them. The study is restricted to this soil group.

Because highway construction and housing schemes are being concentrated at the moment in the southern part of the country (coastal savanna and the forest zones), the soils from this region have been selected for study. Only residual fine-grained soils were studied in this program. In order to isolate the effect of depth, the samples were taken from the first 6 ft below the ground surface.

SELECTION OF SOILS FOR STUDY

In selecting the fine-grained soils for the studies, consideration was given mainly to the occurrence of the soil types and their importance as road-making materials. The latosols developed over granites and phyllites in the forest zone form the most widely distributed road-making materials in Ghana. Although they are not widely distributed, the coastal savanna residual gneissic soils and tropical clays form a group of slightly expansive to highly expansive soils.

In all, 97 soil types were examined in this study. They are distributed as follows: 31 soils over gneisses in the coastal savanna zone, 29 soils over granites, and 37 soils over phyllites in the forest zone. The locations of the soils are shown on the pedological soil map in Figure 7.

LABORATORY TESTS

The following four genetic soil groups were subjected to detailed laboratory tests:

1. Coastal zone tropical residual black and brown clays over gneiss (Cs-Gn-Tc),
2. Coastal zone reddish residual soils over gneiss (Cs-Gn-R),
3. Forest zone reddish residual soils over granite (F-Gt-R), and
4. Forest zone reddish residual soils over phyllite (F-Ph-R).

The physical properties determined were particle size distribution, consistency parameters, specific gravity, optimum moisture content and maximum dry density (standard Proctor), field moisture equivalent, and linear shrinkage.

The particle size distribution, consistency, specific gravity, and compaction tests were carried out according to the specifications described in British Standard No. 1377 (1961). The field moisture equivalent was determined according to the procedure proposed by Hogentogler (31).

Linear shrinkage was determined on soil fractions that were passed through a B.S. No. 36 sieve, oven-dried, and mixed thoroughly with distilled water to a moisture content approximately equivalent to the liquid limit. The soil was packed into a waxed metal trough 0.5 by 0.5 by 6 in. and then oven-dried to constant weight. The decrease in length of the paste after oven drying is expressed as a percentage of the 6-in. dimension.

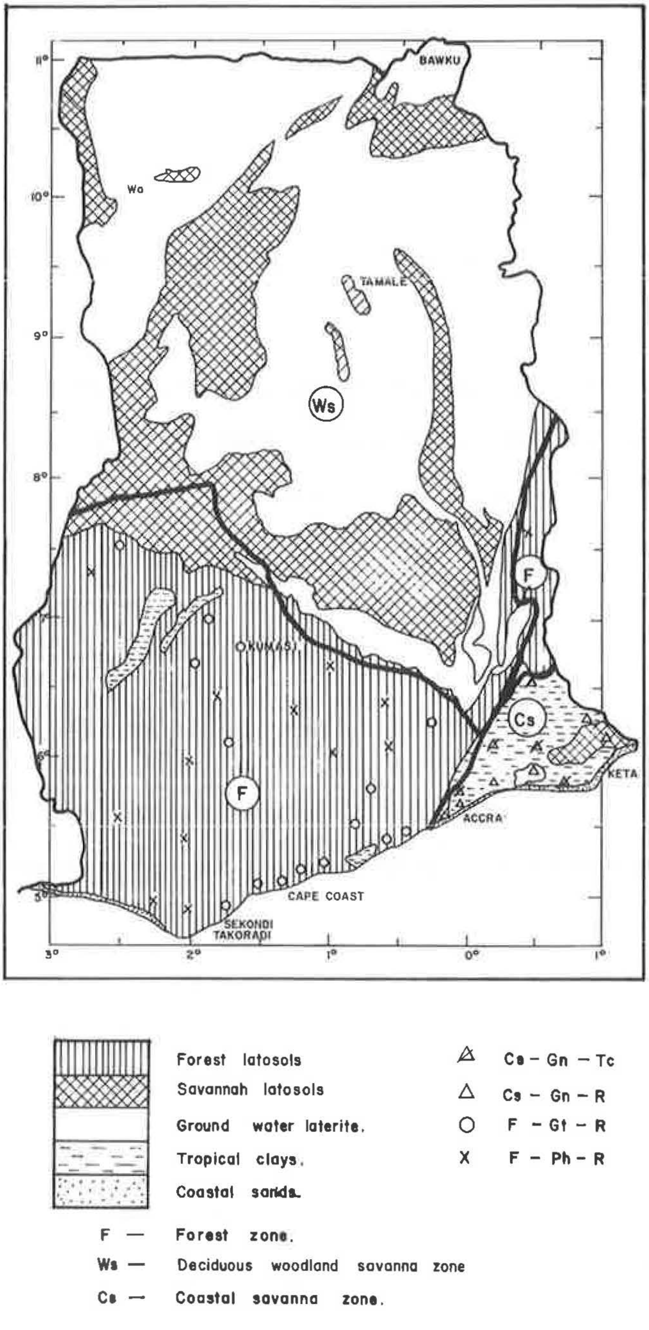


Figure 7. Locations of the soils studied.

Discussion of Test Results

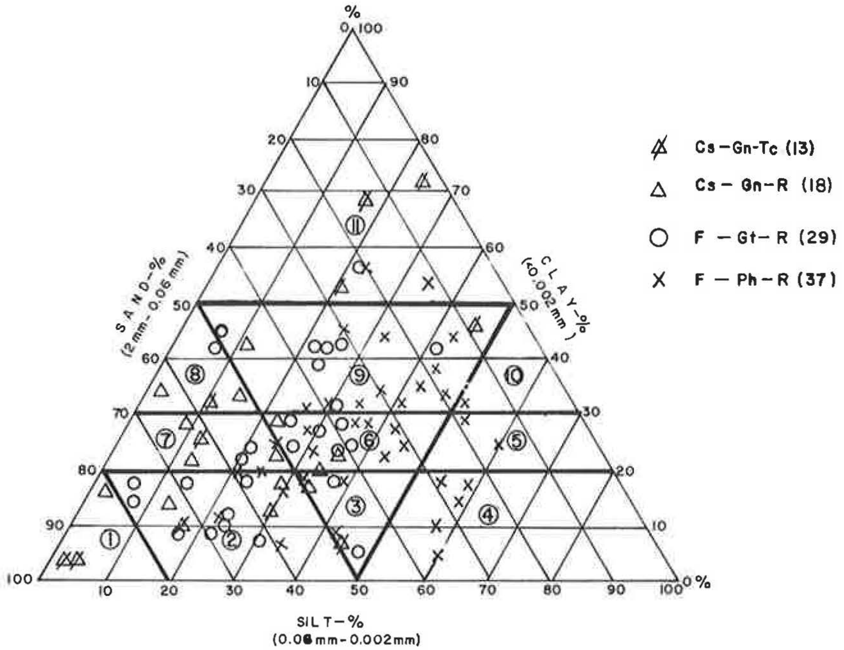
The physical test results were interpreted in the light of the following factors: (a) climatic-vegetational zones, (b) parent rocks, (c) degree of leaching and laterization, (d) clay content, and (e) linear shrinkage.

Texture of the Soils—The textural classification of the soil groups over the different parent rocks is shown according to a triangular chart in Figure 8. Tropical clays range from sandy loams to heavy clays. The other residual soils over gneiss are mainly sandy clay loams, sandy loams, and loams. Granite soils range texturally from sandy loams and clay loams to lean clays.

Phyllite soils on the other hand are richer in silt and clay fractions. The most important soil types developed over phyllite are clays and clay loams. Although the texture of these soils is influenced to some extent by the degree of weathering, the petrographic characteristics of parent rocks seem to account more for the textural differences in the soils over the different parent rocks.

Consistency Characteristics—Figure 9 shows the relation between liquid limit and clay content for the different soil groups. It is seen that there is a fairly good correlation between the two properties. The influence of the clay content on the liquid limit is more pronounced for the tropical clays (soils of low degree of laterization) than for other fairly laterized soils.

Figure 10 shows the relation between plastic limit and the clay content for the different soil groups. Except in the case of phyllite soils, the clay content does not seem to influence the plastic limit in the soils studied.



1. Sand
2. Sandy loam
3. Loam
4. Silty loam
5. Silty clay loam
6. Clay loam
7. Sandy clay loam
8. Sandy clay
9. Lean clay
10. Silty clay
11. Heavy clay

Figure 8. Textural classification of the soil types studied.

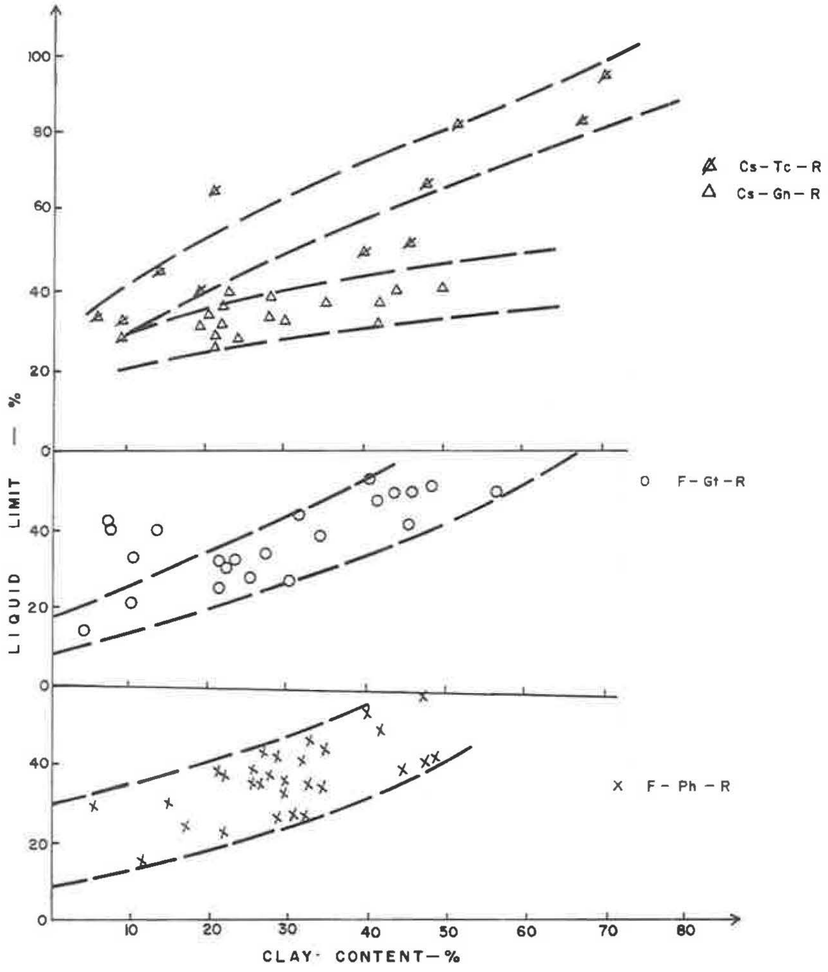


Figure 9. Relation between clay content and liquid limit.

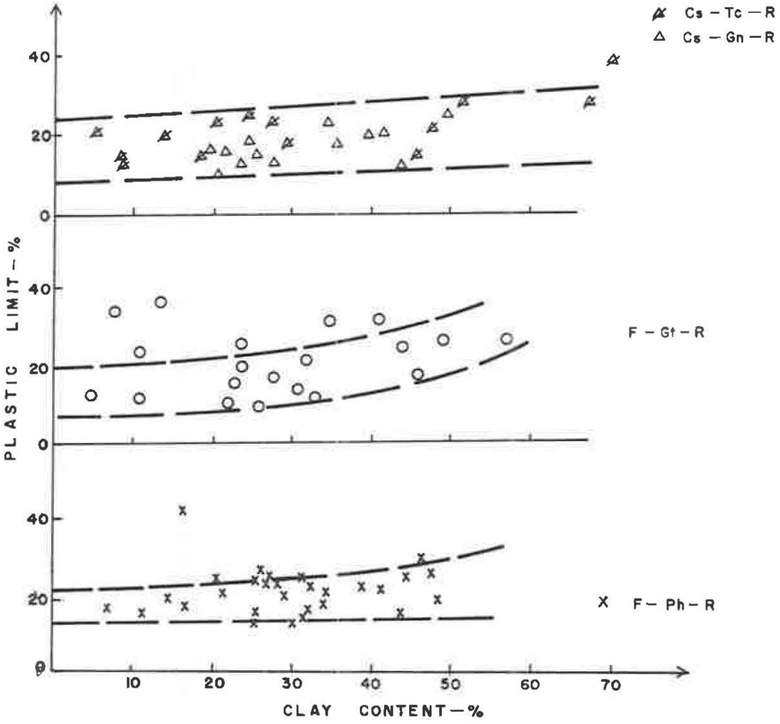


Figure 10. Relation between clay content and plastic limit.

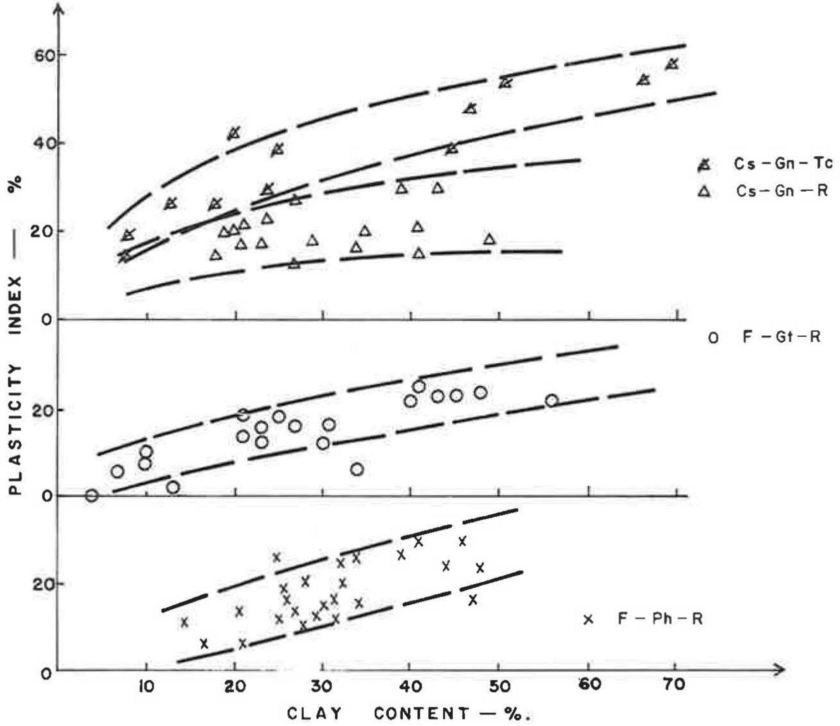
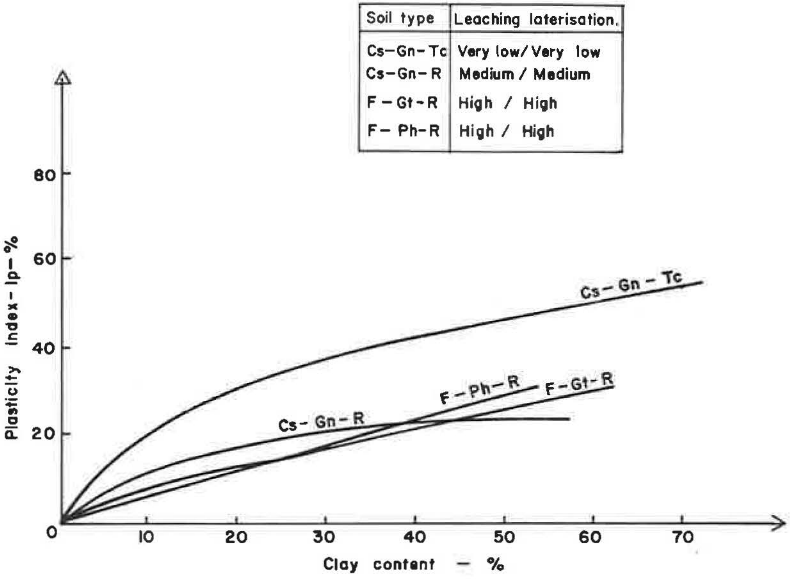


Figure 11. Relation between clay content and plasticity index.



Soil type	Leaching laterisation.
Cs-Gn-Tc	Very low/Very low
Cs-Gn-R	Medium / Medium
F - Gt - R	High / High
F- Ph-R	High / High

Figure 12. Average curves of the relation between the clay content and the plasticity index.

The plasticity index gives the percentage of water in relation to the dry soil that is required to change the soil from the semisolid state to the flow state. This moisture property is very important because it reflects the amount and type of clay, mineralogical composition, exchangeable ions, and base exchange capacity in the soil. In a sense it is a parameter by which the potentiality of a soil to absorb water is assessed. Figure 11 shows the relation between plasticity index and clay content for the soil groups. There is a fairly good correlation between the two properties for all the soil groups. From the average curves in Figure 12 it is seen that the increase in the plasticity index with clay content is more pronounced for the tropical clays, compared to the other laterite residual soils. This illustrates the fact that soils of a low degree of laterization (the tropical clays) are influenced more in terms of plasticity by the amount of clay content.

Figure 13 shows the plasticity characteristics of the soil groups on the Casagrande chart. It is seen that residual soils that generally fall above the A-line have liquid limit values mainly below 60 percent. Higher liquid limit values were recorded for tropical clays. Micaceous granite residual soils that have been found to fall below the A-line are generally of medium plasticity.

Figure 14 shows the relation between clay content and colloidal activity for the soil groups. For all except the tropical clays, colloidal activity ranges between 0.4 and 1.0. For tropical clays, the value is generally more than 1.0. It is seen that colloidal activity is higher for the less laterized tropical clays compared to the other soil groups. The differences in colloidal activity values can also be explained in terms of soil genesis. Tropical clays, by virtue of their mode of formation, contain some montmorillonite (50), which is responsible for the higher colloidal activity. The forest-zone highly laterized soils with kaolinite type of clay mineral (29) have activity ranging between 0.4 and 1.0. The relation between clay content and field moisture equivalent is shown in Figure 15.

Compaction Characteristics—A fairly good correlation was found between clay content and optimum moisture content (standard Proctor) and maximum dry density. The relation between clay content and optimum moisture content is shown in Figure 16. No

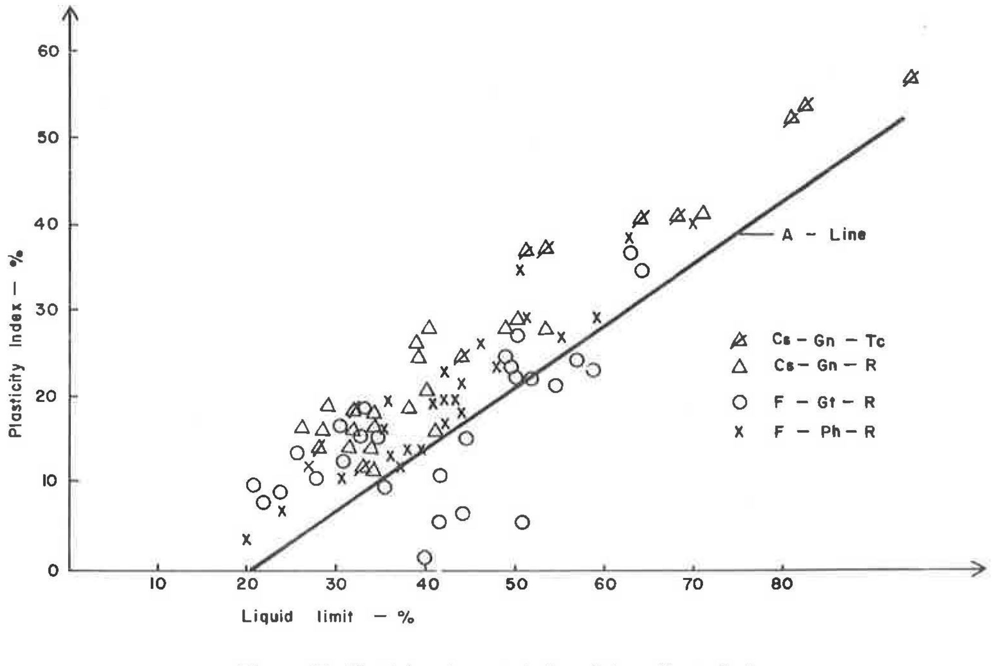


Figure 13. Plasticity characteristics of the soils studied.

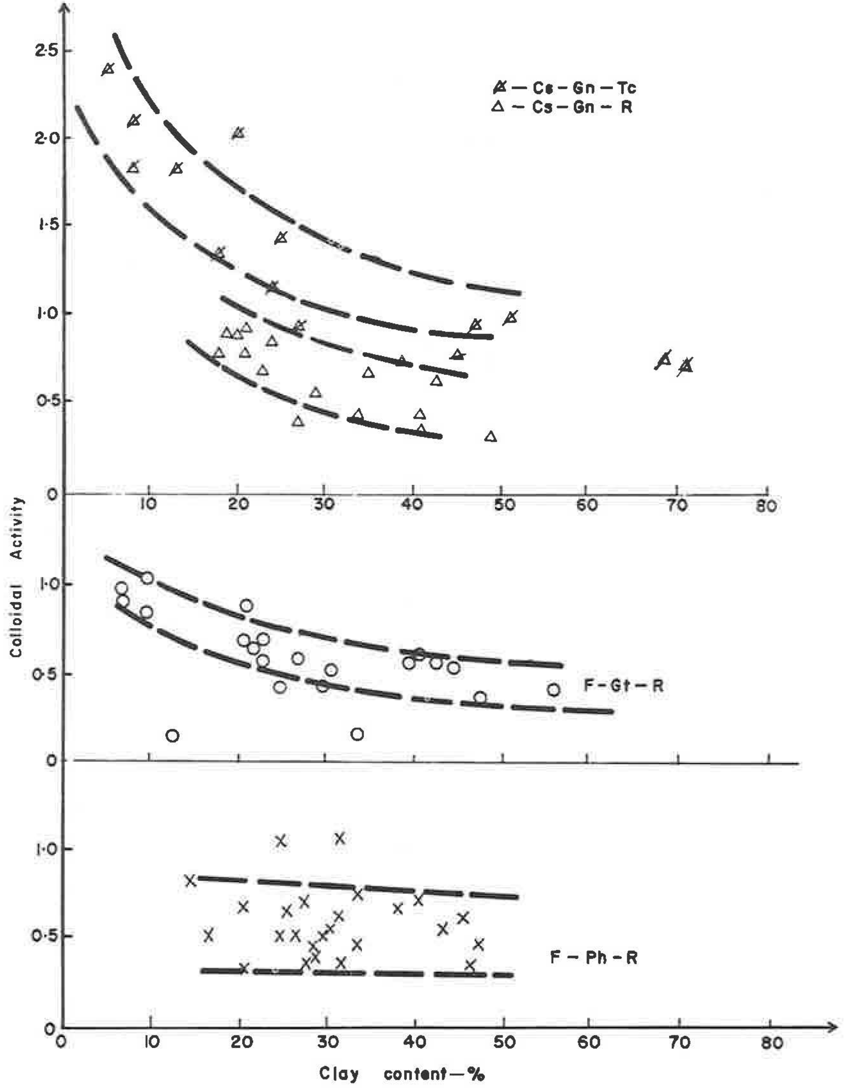


Figure 14. Relation between clay content and colloidal activity.

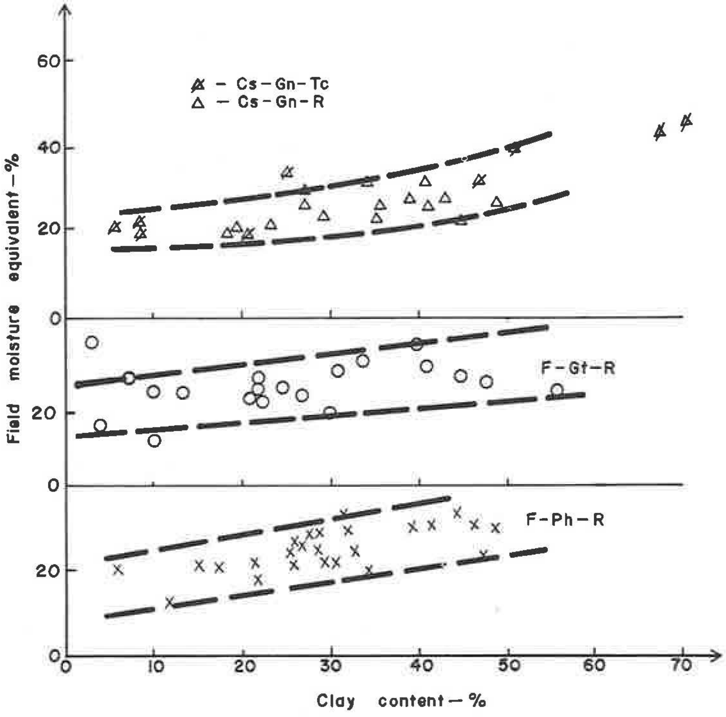


Figure 15. Relation between clay content and field moisture equivalent.

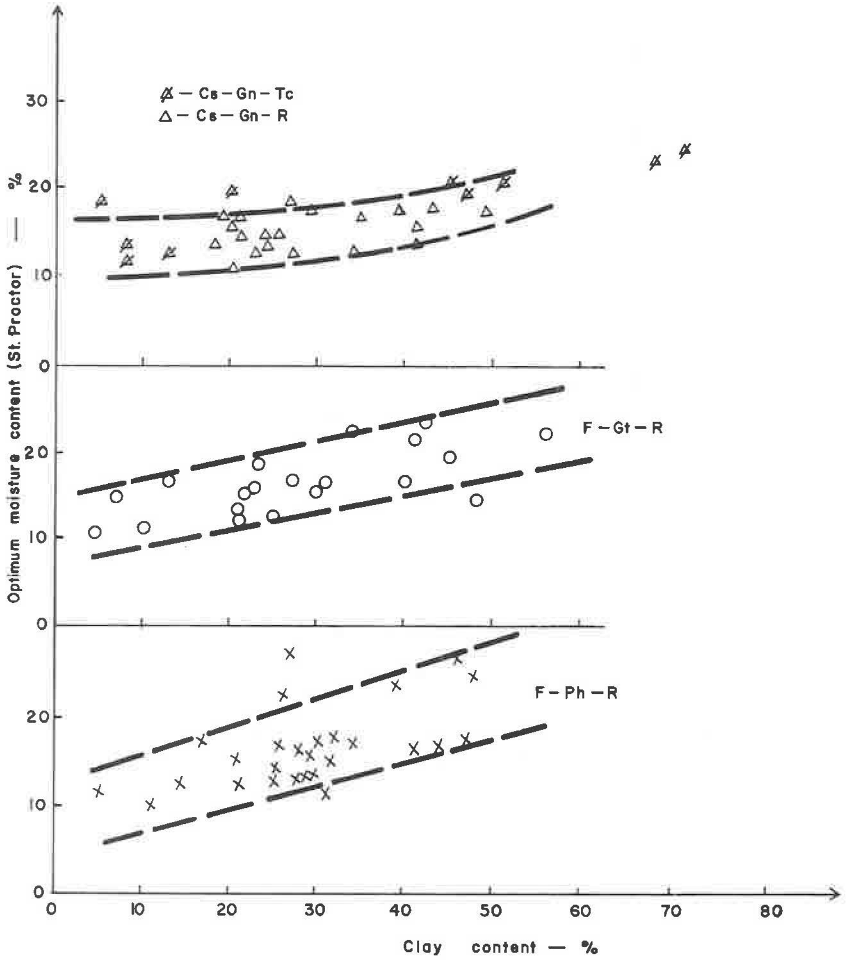


Figure 16. Relation between clay content and optimum moisture content (standard Proctor).

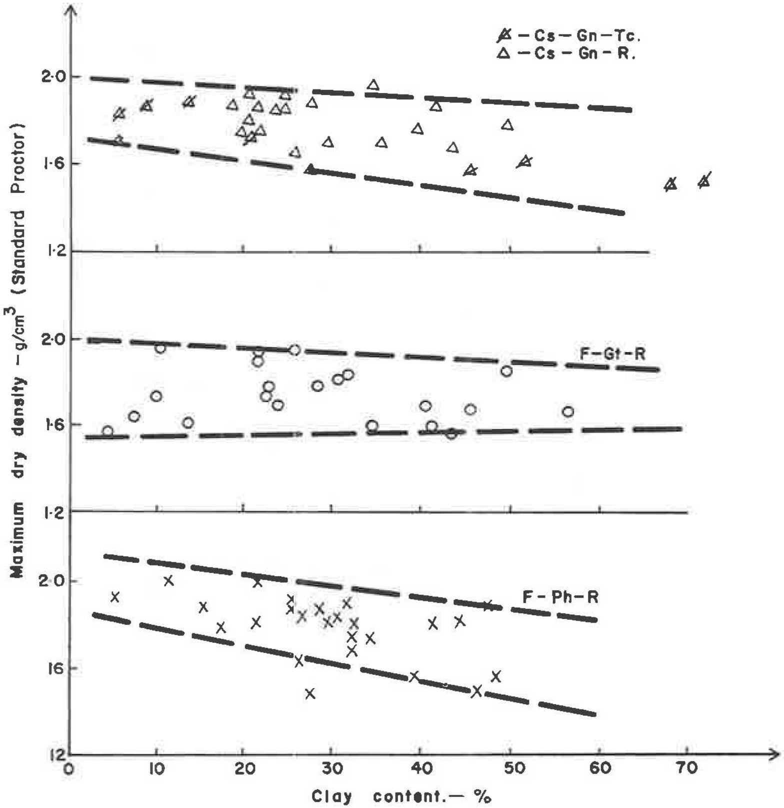


Figure 17. Relation between clay content and maximum dry density (standard Proctor).

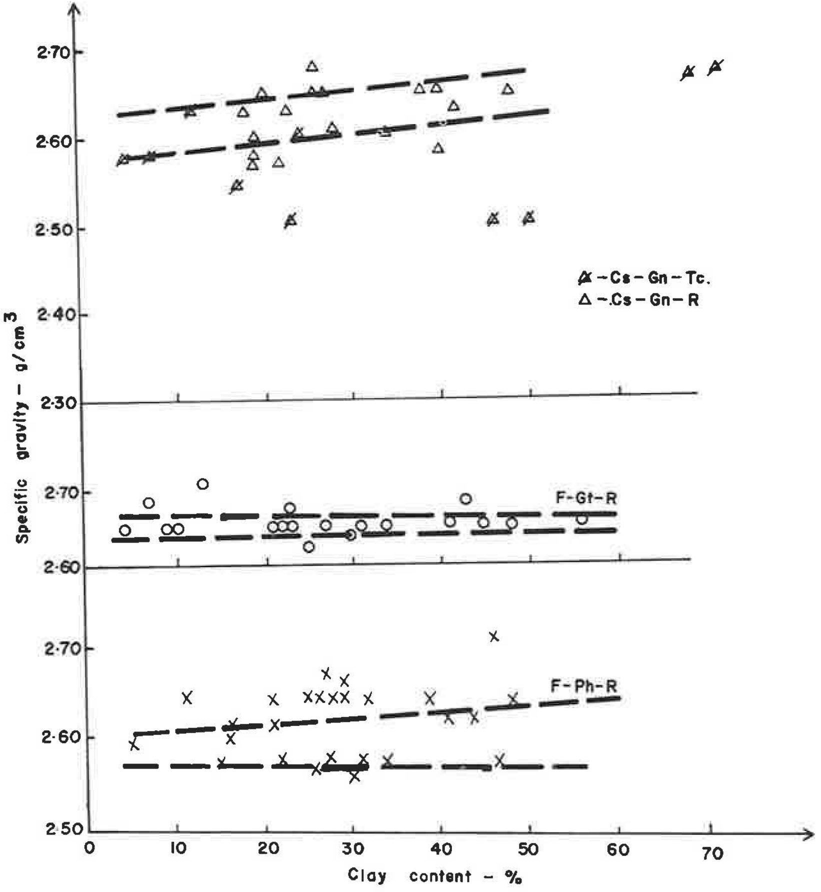


Figure 18. Relation between clay content and specific gravity (for fraction smaller than 2 mm).

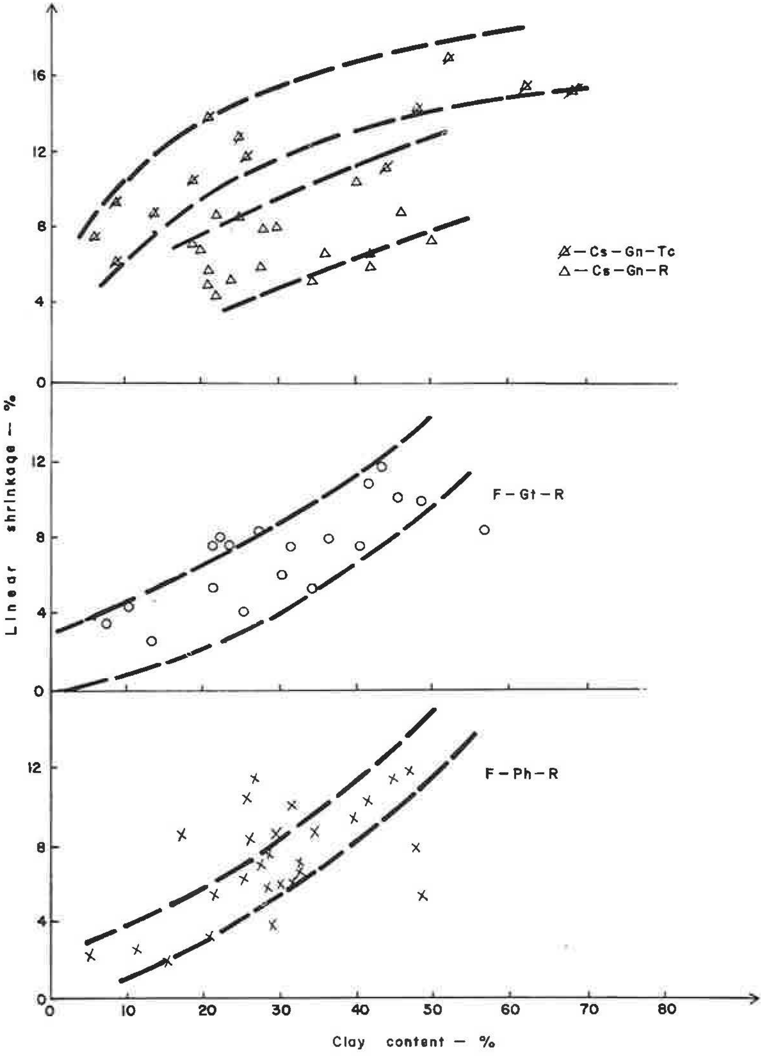


Figure 19. Relation between clay content and linear shrinkage.

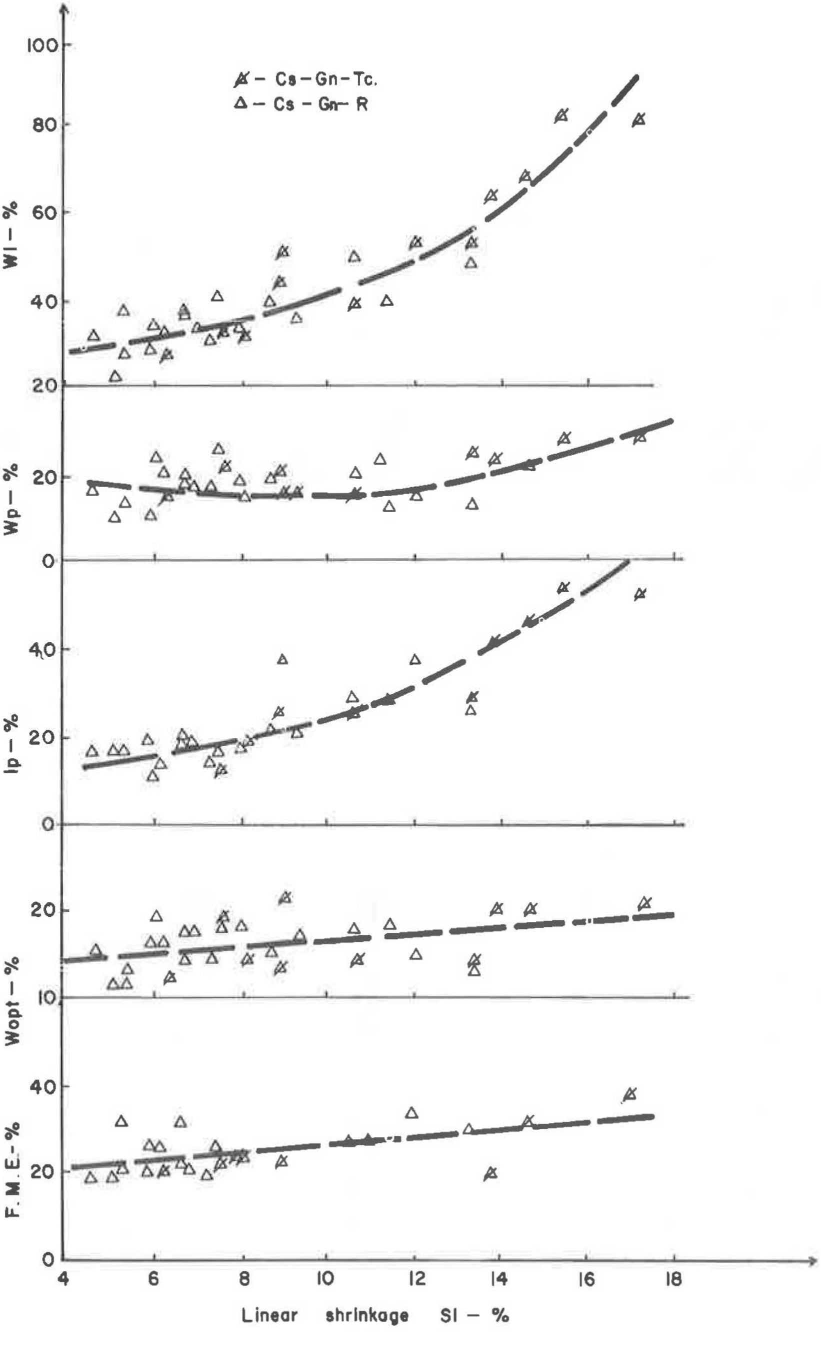


Figure 20. Average curves of the relation between clay content and linear shrinkage.

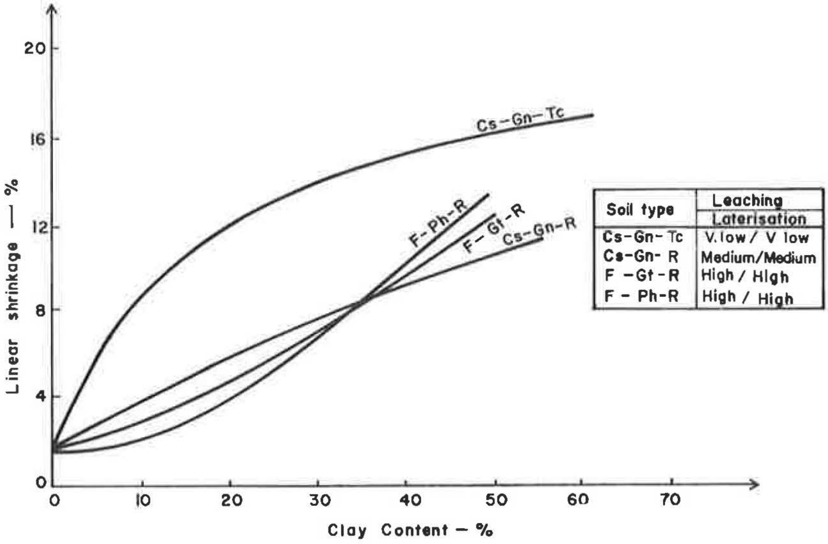


Figure 21. Relation between linear shrinkage and other moisture parameters for coastal savanna zone gneissic soils.

difference was found between the relation for the tropical clays and the other residual soils over gneiss. The effect of laterization does not seem to influence this relationship because the main factor controlling the optimum moisture content is the filling of the soil pores with water and the arrangement of the soil particles. Figure 17 shows the relation between maximum dry density and clay content. It is seen that in general maximum dry densities decrease for all soil groups with increase in clay content.

Specific Gravity—Figure 18 shows the relation between clay content and specific gravity for the soil groups. There was no correlation for the tropical clays and very poor correlation for phyllite soils. Although it is generally believed that all tropical residual soils have rather high specific gravities, it was found that the specific gravity ranged between 2.55 and 2.70. The specific gravities, however, are higher for the laterite gravels in whose fraction laterization is more pronounced. Earlier studies showed that the specific gravity for the laterite gravels is between 2.8 and 3.2, which is attributed to concentration of the iron oxides in the gravel fractions (27).

Shrinkage Properties—Figure 19 shows the relation between clay content and linear shrinkage. A fairly good correlation exists between these two properties. There is also good correlation between linear shrinkage and all the other moisture parameters for each genetic soil group. Figure 20 shows, for example, the relation between linear shrinkage on the one hand and liquid and plastic limits, plasticity index, optimum moisture content (standard Proctor), and field moisture content for the coastal zone gneissic soils. From the average curves in Figure 21 it is seen that the influence of clay content on the linear shrinkage is more pronounced for the tropical clays than for other residual soils. On the basis of a very simple laboratory linear shrinkage test it may be possible to obtain approximate value of other moisture parameters for a genetic soil group.

CONCLUSIONS

The field identification studies carried out by the author and available geological, pedological, and engineering information on the tropically weathered soils of Ghana have revealed that the morphology and general characteristics of these soils are influenced considerably by the weathering systems—the parent material (geological formation), climate, vegetation, topography, and drainage condition—which determine whether the weathering conditions are productive of kaolinite or a montmorillonite type of mineral or some less-known secondary mineral.

Because pedological soil classification is based on the consideration of the major factors of soil formation and because the pedological soil map suggested by Branner and Wills (13) gives the best picture of the distribution of the surface soils, the pedological map is suggested as a sound basis for the initial engineering grouping of Ghanaian subsoils.

The laterization process has a pronounced effect on the chemical and mineralogical composition of Ghana soils. Chemical studies on the soil formations have revealed that the sesquioxide content of the tropical clays and nonresidual soils is generally less than 20 percent, is between 20 and 50 percent for residual soils, and is more than 50 percent for the laterite rocks. The three textural groups of laterite soils (laterite rocks, laterite gravels, and laterite fine-grained soils) reflect definite stages in the process of laterization.

For each genetic fine-grained soil group, consistency parameters, colloidal activity, compaction characteristics, specific gravity, field moisture equivalent, and linear shrinkage have fairly good correlations with the amount of clay fraction content. The different degrees of leaching and laterization of the different soil types in the different climatic-vegetational zones have considerable influence on the relationships between the clay content and soil properties of soils over different parent rocks.

Linear shrinkage has a very good correlation with liquid limit, plastic limit, plasticity index, optimum moisture content, and field moisture equivalent and may be useful as a means of determining these properties for a genetic soil group.

The conclusions reached in the foregoing suggest that the residual fine-grained laterite soils of Ghana may be most adequately classified for highway purposes on the basis of such factors as parent rocks, climatic-vegetational conditions, degrees of weathering (or laterization), and amount of clay content and linear shrinkage.

The conclusions reached, although based on studies in Ghana, may be of practical importance to soils formed under similar conditions in other countries.

It may be of interest to start a basic study on the definition of the degree of laterization in terms of the cementation or increasing thickness of free iron-oxide coating on the soil particles. It would then be possible to investigate its influence on the physicochemical and physical, as well as mechanical, properties of laterite soils. This would considerably improve the present level of knowledge on laterization and properties of laterite soils.

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Pages 74 and 75, the captions for Figures 20 and 21 should read:

Figure 20. Relation between linear shrinkage and other moisture parameters for coastal savanna zone gneissic soils.

Figure 21. Average curves of the relation between clay content and linear shrinkage.