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Engineering performance of soils of the humid tropical zone of Southern Nigeria

Performance technique des sols de la zone tropical humid du sud du Nigeria

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ABSTRACT

The principal factor to which the observed engineering performance of the soils in the humid tropical zone of Southern Nigeria can be attributed has been determined to be the laterization phenomenon. During the process, oxides and hydroxides of iron and aluminum accumulate as the cementing agents binding the soil particles together. Clay-size particles aggregate into coarse grains giving the impression of a granular texture. The soil mass, in turn, correspondingly exhibits characteristics reflecting this texture when undisturbed in the field. When subjected to mechanical reworking or remolding however, such as in the process of pre-test sample preparation, the grains are disaggregated releasing a large quantity of fines. The laboratory test results therefore usually differ from predictions based on field observations.

This paper presents a broad framework, which can be used for a preliminary estimate of the engineering performance of the soils as well as formulating a generalised soil classification scheme for the area. The framework has been realised from a synthesis of selected previous works on the soils, a task, which included detailed evaluation of all the soil formations in the whole area and correlation of their engineering properties with various physical characteristics. The genetic and climatic factors and the post-formation alterations, which influence the engineering behaviour of the soils, were also investigated, with emphasis on their significance in engineering design and construction.

RÉSUMÉ

Le phenomene de la laterization a été identifié comme facteur principal des performances techniques observeés des sols de la zone tropical humide du sud du Nigeria. Durant ce processus les oxides et hydroxides de fer et d'aluminum s'accumulent et deviennent des agents qui soudent les particules du sol ensemble. Les particules d'argile s'agregé en de gros grains donnant l'impression d'une texture granulaire. Le sol á son tour montre des caracteristiques qui reflectent cette texture dans le champ. Quand le sol est soumis a des travaux mechaniques, tels que la preparation des echatillons de test, les grains se desintegrent et produisent une grande quantité de gravel fin. Les results des tests de laboratoire different d'habitude des predictions baseés sur les observations sur le terrain.

Ce papier presente un large cadre de travail qui peut être utilise pour une estimation preliminaire des performances techniques des sols tout autant pour formuler une schema de classification des sols pour cette region. Le cadre a été réalisé a partir de la synthèse des travaux précédents, comprenant une évaluation détaillée de toutes les formations dans cette region et la corrélation de leurs propriétés techniques avec différentes caracteristiques physiques. Les facteurs génériques et climatiques et les changements post-formation qui influencent le comportement technique des sols ont été aussi investiguer, avec un accent particulier sur leur importance dans le domaine de la conception et de la construction.

1 INTRODUCTION

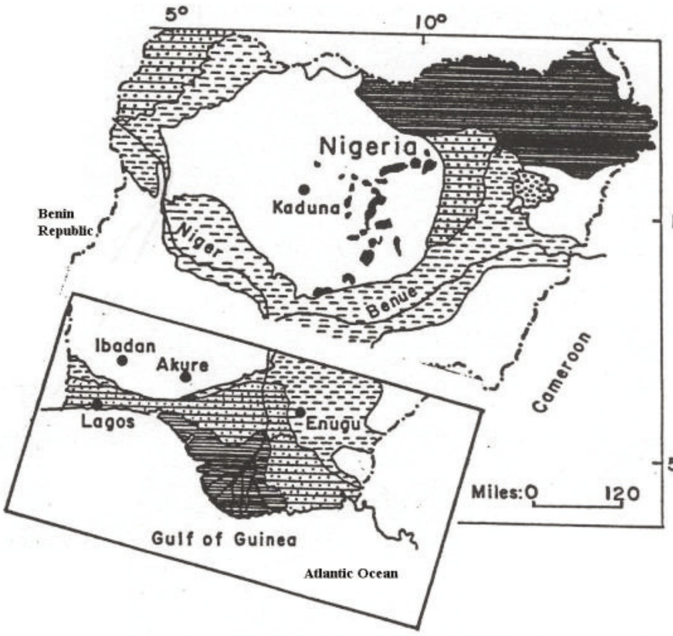
Southern Nigeria lies within the Humid Tropical Region, and many soils here exhibit behaviour that is inconsistent with the expectations and predictions based on conventional soil mechanics theory. This anomaly has however been shown to be typical of tropical soils the world over and has commonly become the rule rather than the exception, as exemplified by the work of Mitchell and Sitar (1982). These soils often show large variations in engineering properties, which are mainly due to weathering and chemical composition. Under conditions of tropical weathering soils are selectively leached of silica, leaving high concentrations of iron and aluminum sesquioxides (Ejezie et al., 1983). This process is the well-known laterisation phenomenon. The soils so affected usually possess unique properties that sometimes render their engineering behaviour difficult to predict using available models.

The study area covered in the work presented in this paper is shown in figure 1. It is bounded in the north by the latitude of the Niger-Benue confluence, in the south by the Gulf of Guinea (Atlantic Ocean), in the east by the republic of Cameroon and in the west by the republic of Benin. It is hoped that the findings reported here will provide a future opportunity for developing a comprehensive picture of engineering performance of soils for the whole of Nigeria.

2 GEOLOGY OF SOUTHERN NIGERIA

The geologic setting of Southern Nigeria essentially consists of two rock groups namely, the Basement Complex and the Sedimentary rock formations. The rocks of the Basement complex are mainly of Precambrian age (about 20% only are of Jurassic and latter age) and consist of igneous and metamorphic rocks. The sedimentary rocks, on the other hand, are of Cretaceous to Recent age. They include sandstone, shale, and limestone. Weathering of these rocks has also resulted in extensive accumulation of clays and peat in the area.

Figure 1 also shows the area distribution of the rocks in Southern Nigeria. The Basement Complex rocks occupy most of the west, while the sedimentary rocks predominate in the east and the Niger Delta. In addition to this general picture, outcrops of Basement Complex rocks also occur further to the east along the Cameroonian border, while relatively shallow sedimentary rock deposits are found in the west along the area adjoining the



Legend: Shaded area represents Sedimentary Formations.
Un-shaded area represents Basement Complex.

Figure 1. Study Area, Southern Nigeria.

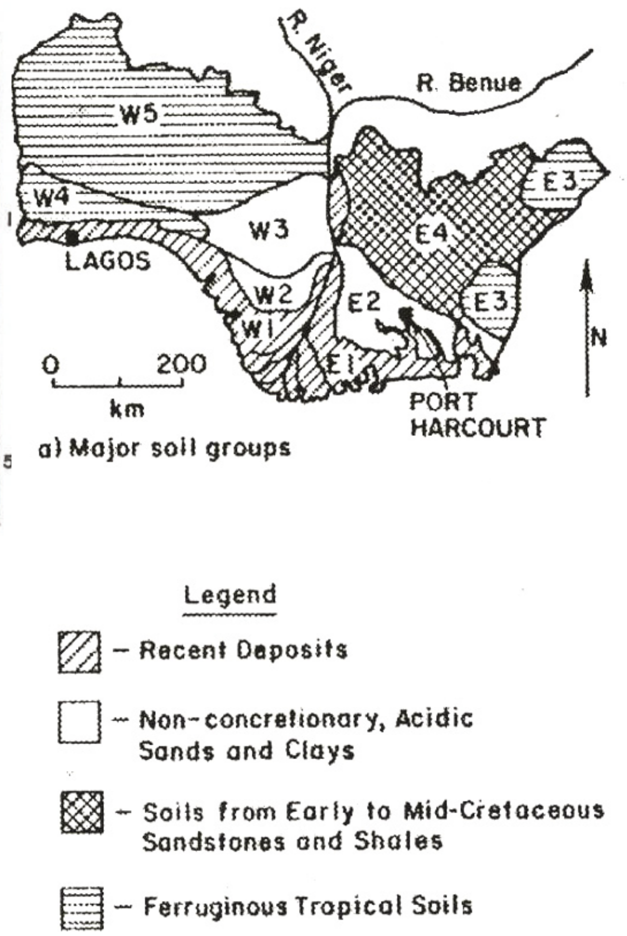


Figure 2. Major Soil Groups of Southern Nigeria (After Ejezie, 1982)

ocean. The sedimentary formations are separated from the Basement complex by a long gap of geologic history as evidenced by the age difference – Precambrian to Cretaceous. This gap is marked by a pronounced unconformity. The sedimentary sequences in the west and east are unified by appropriate stratigraphic correlation (Reyment, 1965).

3 WEATHERING AND SOIL FORMATION IN SOUTHERN NIGERIA

The processes of weathering and soil formation are governed primarily by the nature of the parent rocks and climate, which are also the major factors responsible for the physical or morphological characteristics of the resulting soils. The soil materials may be removed by erosion to new environments, or they may remain at the location of the parent rock as residual soil.

The soils of Southern Nigeria are residual in places, particularly in the continental environments dominated by Basement Complex rocks. In marine and coastal environments however, they occur as sedimentary deposits. The significance of this observation is that their formation and area distribution are closely linked to the geological setting of the area as well as the prevailing tropical climate. The residual variety has been formed from pronounced in-situ chemical weathering of parent bedrock that is sufficiently near the surface without movement of the weathering products to a new location. The sedimentary, on the other hand, resulted from intensive erosion of the landmass, and subsequent sediment transportation and deposition in the low-lying coastal areas.

In terms of the intensity and degree of weathering, the residual continental soils can generally be categorized under the "Advanced Weathering" stage typical of soils of the humid tropical region. The marine and coastal soils, on the other hand, are largely young soils and relatively non-laterised.

The climate of Southern Nigeria features high temperatures all the year round, and heavy rainfall, which is usually distributed such that the year falls into two main seasons, namely, the wet season and the dry season. These climatic conditions are very favourable for weathering and soil formation.

4 CLASSIFICATION AND PROPERTIES OF SOILS OF SOUTHERN NIGERIA

The soils of southern Nigeria are varied, as shown in figure 2, and exhibit a high degree of anisotropy. The different types and their pattern of area distribution are largely controlled by lithological features and changes that occur in different parts of the area. For example, soils found in the basement areas generally exhibit good textural gradation (from clay to gravel) and contain both stable and weatherable minerals. In the sedimentary areas the soils frequently exhibit poor gradation resulting from the depositional processes associated with their formation. The predominant minerals here are relatively stable and resistant to weathering.

The overall effect of these conditions is that laterization is very pronounced and relatively faster in the residual soils of the basement complex zone, unlike the sedimentary basins, where the stable and resistant minerals are not susceptible to chemical decay and hence, laterization process is not as pronounced. In fact, it is common to observe soil profiles with red staining that results from sesquioxides and hydroxides being flushed downwards by infiltrating rainwater in areas of relatively high rainfall such as in the rain forest belt. Typically, the soils occur in the form of young soils, lateritic soils, and non-laterised black clay.

Weathering of the basement complex in the Southeast, where basalt is predominant, yields soils composed mainly of kaolinite and goethite. In general, kaolinite is the main component of the clay fraction of soils in free-draining areas while montmorillonite is the dominant component in the poorly drained zones.

4.1 *Major Soil Groups*

Ejezie (1982) has developed a generalised grouping of the soils in Southern Nigeria by combining the works of Ackroyd (1967), Madu (1976, 1980) and an unpublished report by Nigeria Foundation Services and Soils Research Company Limited (1977). This scheme is presented in figure 2, where the identified major soil groups are superimposed on a map of Eastern Nigeria. This grouping involves considerable overlap, but at the same time essentially recognises approximate limits of areas where soils of similar characteristics, and which constitute specific major soil groups, are predominant and have a controlling influence on the overall engineering behaviour of soil. These groups depict area zoning of the soils and this is used here to examine the engineering properties and behaviour of the soils. They include: Recent deposits; Non-concretionary acid sands and clays; Cretaceous sandy Clays and clayey Sands; and Ferruginous soils.

4.2 *Soil Properties*

The properties have earlier been broadly categorised into physicochemical, textural, and engineering properties by Ejezie et al (1983). This approach is adopted in this paper with more emphasis on the engineering properties since these are the ones that are directly associated with the engineering performance of the soils (which is the subject of discussion here). Each soil group is considered separately in terms of these properties. Micro-variations within the groups are ignored and average values adopted instead. It is pertinent to note that though there is appreciable overlap in properties between these soil groups, the general trend still conspicuously distinguishes them from one another thereby validating the classification scheme.

4.2.1 *Recent Deposits*

This group occurs in various forms mainly along the coastal areas and river channels. The soils of this group are mainly products of primary weathering as well as fragments of resistant minerals. Most common types include: pale brown loamy alluvial silts and clays; dark grey mangrove soils (organic silty clays and clayey silts); and brownish yellow, fine sand derived from beach deposits.

The physicochemical properties are typified by predominantly neutral P^H with an average value of about 7.0; variable organic matter content and cation exchange capacity - values range from low to high.

Texturally, the group consists of fine-grained alluvial silt and clay with little sand and gravel. The fabric is described as single-grained for sand and deflocculated plate-like aggregate for clay. Cement is lacking except for occasional clay binder and organic matter.

The engineering properties include predominantly low-medium plasticity with values of plasticity index between 9% and 15% (Ejezie et al. 1983); generally higher in-situ density for sandy deposits than for clays with reported values in the range: 10.6 – 19.6 kN/m^3 (Ejezie, 1982). Permeability varies widely and is dependent on clay content. Strength is generally low for clay and relatively high for granular deposits. Available data on unconfined compressive strength of the soft clay give the range to be about 3.0 – 34 kN/m^2. The clay also exhibits appreciable sensitivity in some areas, with computed values in the range: 4 – 18. This is further indicated by the natural moisture content which is observed to be consistently higher than the liquid limit in these areas. The soft clay deposits are highly compressible, with compression index ranging from about 0.2 to 0.5.

4.2.2 *Non-concretionary Acid sands and Clays*

This group includes the various types of reddish brown soils, texturally porous, and derived from unconsolidated sandy deposits, sandstone, and shale. Typical examples are the poorly-graded, fine-medium red Benin Sands and the uniformly graded silty Delta Sands. The fabric is predominantly single-grained while cement is generally lacking, except for occasional trace of hydrated ferric oxide. This group occurs extensively over the sedimentary areas, extending from parts of the west to the extreme east, and limited in the south and along river valleys by the occurrence of the Recent Deposits along the coast and creeks.

As the name implies, the environment of this soil group typically has low/acidic P^H (4.3). This can be explained by the fact that the soils are sufficiently porous and permeable and, as a result, infiltrating water from the heavy rains in the area effectively flushes out the alkaline ions released from the decomposing soil minerals, thus creating an acid medium. The rate of removal of these basic ions from the medium exceeds their rate of release from the soil minerals. The resulting acidity enhances the leaching of sesquioxides thus retarding the laterization process. Both the organic matter content and the cation exchange capacity are low.

The engineering properties are marked by general absence of plasticity; variable in-situ density, usually higher for less porous deposits; high permeability; frequently low strength resulting in instability of exposed hillsides and extensive gullying; and generally low compressibility.

4.2.3 *Cretaceous sandy Clays and clayey Sands*

This is the group comprising the reddish-brown, gravely, clayey Sands and sandy Clays derived from Cretaceous sandstones and shales. They are generally referred to as laterized soils, and are confined to the areas of the Southeast underlain by Early to Mid-Cretaceous sedimentary rocks.

The physicochemical properties include low/acidic P^H (4.3 - 5.7), moderate organic matter content (3 - 8%), and low cation exchange capacity (21 – 45).

The textural properties are typified by well-graded and single-grained structure, aggregation into granular concretions resulting from laterisation, predominance of hydrated ferric oxide cement and relict structures in the form of bedding and grain orientation.

The Engineering properties are dominated by a wide range of plasticity (7-42%), medium-high in-situ density, variable permeability, very low compressibility, and field strength performance much better than laboratory predictions. Available data on field vane strength range from 22 to 109kN/m^2.

4.2.4 *Ferruginous Soils*

This group consists of laterites which occur extensively over the Basement Complex in the Southwest and part of the adjoining sedimentary area. They are also found in the extreme south-east boarder with the Cameroon Republic – also a region of Basement complex rocks.

The physicochemical properties are marked by typically high P^H values, low organic matter content, and low cation exchange capacity.

Texturally, the soils are well-graded with single-grained fabric. They consist of aggregated grains of clay platelets, sand particles with surface coatings of clay, sesquioxide and hydroxide cement, and relict form and cleavage structures.

The engineering properties include low - moderate plasticity, with available data on plasticity index in the range: 9 – 28%, in-situ density range of 10.2 – 18.0 kN/m^3, low to moderate permeability, very low compressibility and high strength, with low strain at failure. Unconfined compressive strength range is 47 – 190 kN/m^2.

5 PREDICTION OF ENGINEERING PERFORMANCE

A scheme for predicting the engineering performance of the major soil groups in Southern Nigeria is presented in Table 1 below. This scheme is based on certain soil characteristics, which are considered to have a controlling influence on soil performance. It specifically focuses on some chosen engineering performance indices of relevance in Tropical soil engineering, namely: in-situ permeability, time-dependent consolidation, collapsibility of soil structure, in-situ shear strength, excavation ease, pile drivability, suitability as road construction material, reaction on exposure, suitability for low cost housing, and amenability to stabilisation. These are evaluated as having a high, moderate or low likelihood of occurrence within a given soil group. Hence, the scheme can conveniently be used to develop a preliminary estimate of engineering behaviour of the soils in the area.

It is evident from the table and the preceding section that the degree of laterisation has a strong influence on the soil characteristics. The highly laterised Ferruginous and Cretaceous soils are subject to sesquioxide and hydroxide cementation, which develops a relatively low permeability as well as high in-situ shear strength, and may lead to difficulties in excavation and pile driving. Also, the granular texture associated with these laterised soils makes them suitable as a base course for roads and generally susceptible to treatment with soil stabilisers like lime.

On the other hand, the granular texture and low to moderate degree of laterisation associated with the acidic soils generally give them high in-situ permeability and related performance ratings as shown in the table. The permeability of the Recent Deposits varies widely because of the variability of this soil group.

Table 1: Engineering Performance of Major Soil Groups in Southern Nigeria

Engineering Performance Index	Soil Group			
	Recent Deposits	Acidic Soils	Cretaceous Soils	Ferruginous Soils
Low in-situ Permeability	●	○	◑	◑
Time-dependent Consolidation	●	○	○	○
Collapsible Soil Structure	○	◑	○	○
Low in-situ Shear Strength	●	◑	○	○
Difficulties with Excavation	○	◑	●	●
Difficulties with Driven Piles	○	○	◑	●
Suitable for Base Course	○	○	◑	●
Hardening upon Exposure	○	◑	◑	◑
Suitable for Low Cost Housing	○	◑	●	●
Amenable to Stabilisation	○	◑	●	●

Legend:

● High Likelihood

◑ Moderate Likelihood

○ Little or no Likelihood

6 CONCLUSION

A framework has been developed for predicting the engineering performance of soils in Southern Nigeria. This is particularly helpful in the preliminary estimation of the engineering behaviour of the soils in the area prior to any civil engineering project take-off.

Laterisation is the most influential factor controlling the behaviour of the soils. The process aggregates fine-grained particles into coarser grains, yielding a pseudo-granular texture. The laterised soils generally are characterised by high in-situ strength and bearing capacity, and are generally stable even on steep slopes. The unique behaviour exhibited by the soils is evidenced principally by the index tests in which sample preparation has substantially different consequences on results than that predicted by conventional soil mechanics theory. For example, a wet sieve analysis often yields a high proportion of fine-grained particles because the water and the mechanical sieving action disrupt the cement bonds and disaggregate the soil particles. Similarly the remoulding and the addition of water that precede liquid limit test increase the clay fraction thereby increasing the plasticity index of the soil.

The framework developed here, though customized for soils of Southern Nigeria, can equally be applied to other parts of Nigeria as well as other areas of the humid tropical region. Such extended application will, however, require additional confirmatory in-situ field tests, representative sampling and laboratory tests.

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