



ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

**Compaction properties of lateritic soils
(The Case of Assossa)**

By

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April, 2008

Compaction properties of lateritic soils

(The Case of Assossa)

**A thesis submitted to the school of graduate studies of Addis Ababa University in
partial fulfillment of the requirements for the Degree of Masters of Science in Civil
Engineering**

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DECLARATION

I, the undersigned, declare that this thesis is my original work performed under the supervision of my research advisor Dr. Mesele Haile and has not been presented as a thesis for a degree in any other university. All sources of materials used for this thesis have also been duly acknowledged.

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Abbreviations

ARD	-	air dried of test samples
OVD	-	oven dried test samples
SCM	-	standard proctor compaction method
MCM	-	modified compaction method
MDD	-	maximum dry density
OMC	-	optimum moisture content
ARS	-	as received samples
TP	-	test pit of samples
UCS	-	unconfined compression strength
A.A	-	Addis Ababa
SSD	-	samples of sun dried

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Abstract

High temperature and moisture fluctuating in tropical areas, enhancing chemical weathering leads to the formation of lateritic soils when the soil is well-drained. These highly weathered tropical materials may irreversibly change properties when dried, and even simply remoulding the material may cause significant change in properties.

Embankment construction is one of the major activities in Civil Engineering works, which enhance development. Hence, great attention has to be given during construction of such infrastructures when using the tropical soils as construction materials.

Embankments which are constructed using lateritic soils have a great advantage in that they are constructed from locally available materials within sound technical and affordable financial capacity. To use lateritic soils safely and economically, appropriate methods of determining the geotechnical properties, compaction properties, shear strength parameters, unconfined compression strength (UCS) have to be investigated and developed.

Accordingly, in this paper the compaction properties of lateritic soils which are taken from Assossa have been investigated. In addition to this, some peculiar geotechnical and geo-chemical characteristics of these soils have been studied. Accordingly, the soils from Assossa have been obtained to be true lateritic as the geo-chemical test and tests from laboratory indicated.

The soil samples were compacted at optimum moisture content, at drier side of the optimum moisture content and at wetter side of the optimum moisture contents. Then, the UCS tests were done on the soil samples to investigate the variation in strength properties as a function

of time after compaction of these soils. Keeping the compacted lateritic soil samples for a longer period shows an increase in the UCS values and samples compacted at optimum moisture content have higher values of UCS as compared to the once on the drier and wetter sides.

Compaction of these soils has been influenced by depth, drying, mineralogical composition and compaction energy as illustrated in this thesis. Moreover, the effect is higher as the degree of laterization increases.

The effect of permeability of compacted lateritic soils in relation to change in compaction moisture content and time effect after compaction were investigated. Accordingly, the effect of compaction moisture shows that permeability decreases towards the optimum moisture content. In addition to this, the time effect after compaction has been investigated and the test showed that permeability decreases as time after compaction increases.

The soils are less sensitive to expansion when there is fluctuation of water. Further, the soil is highly sensitive to remoulding of samples as the compaction curves and the degree of sensitivity showed.

1. INTRODUCTION

1.1 Back ground of the problem

The warm tropical climate coupled with varying moisture regimes develops unique geotechnical conditions and problems for which the engineer of the temperate zones may be poorly prepared. Much of the classical early development of soil mechanics occurred in the temperate zones of Europe and North America. Only relatively recently have the specific training and experience based on such a classical geotechnical background may found the tropical geotechnical problems surprising and perplexing.

Under the high temperature and moisture regimes existing in many tropical areas, chemical weathering is intense. In well-drained soils, the resulting residual soils often have characteristically high contents of Aluminium and Iron oxides and a loss of silica and bases due to leaching. This process is referred to as laterization and as a result of this the soil is termed as lateritic soil which upon exposure to air quickly becomes as hard as a brick. This hardening characteristic and the properties of lateritic soils have been the topic of numerous papers.

These highly weathered tropical materials may irreversibly change properties when dried, and even simply remoulding the material may cause significant change in properties. This irreversible change in engineering properties on drying or remoulding means conventional laboratory testing that relies on disturbed bulk sampling and usually oven-dried material before testing will give erroneous estimates of in-situ properties. Construction techniques based on temperate climate experiences may have to be modified for lateritic materials. The

self hardening properties that some lateritic materials possess are probably too difficult to reliably ascertain and use for most engineering purposes.

Embankment construction is one of the major activities in Civil Engineering works like dams and roads, hence construction of these infrastructures by using the tropical available soils especially the lateritic are more advantageous in relation to their characteristics as an engineered earth fill. The natural tropical fill materials are placed and compacted, in most of the cases, without the addition of binding agent. However, controlling the compacting mechanical effort not to break much of the cementation of the soils is essential.

Lateritic soils have great advantage because of the cementation due to the presence of cementing agents (sesquioxides) .This binding nature reduces the permeability of embankments, increases the strength of soils and hence the stability of embankments, cut slopes will increase.The geotechnical characteristics of soils have been extensively investigated for temperate climate soils. Also, a great deal of investigations have been carried out to evaluate the influence of compaction on the geotechnical properties of the temperate zone soils with respect to earth dam construction and guide lines have been developed based on the investigated results. In contrast, fewer corresponding investigations have been done on tropical residual soils and there are no well established compaction guide lines that consider the peculiar characteristics of these soils.

One typical example to be mentioned here is the case of the fill material of the Tjipanundjang Dam (first described by Terzaghi and later on by L.D Wesley). The dam is a homogeneous earth dam of 34m height constructed between 1928 & 1939 in West Java, Indonesia. Wesley based on test results, described the fill material of this dam as yellowish brown andosol soil with unusual properties. The soil is formed through the weathering of volcanic material, mainly ash layers. The Liquid Limit of this soil has been obtained to be above 100%, which was attributed to its Allophone and Halloysite mineralogy. The Atterberg limit test results lay below the A-line on the plasticity chart. The grain size distribution of the material indicated

that the clay fraction was above 70%. However, the shear strength test resulted in surprisingly high values of internal friction (35° and above) even though the sample contained about 70% clay.

The dam cut slopes of over 21m height with side slopes of almost 45° with respect to the horizontal have been reported to have remained intact for over 40 years indicating the remarkable stability (strength) of the fill material from which the dam has been constructed (Hunde S).

The points raised above show that the empirical relationships that are based on characteristics of sedimentary clays may not be applicable to tropical soils. In particular, it has been clearly indicated that the general trend towards lower shear strength with decreasing particle size is not applicable. In addition to this, the prediction of lower shear strength with increasing moisture content has been found to be not applicable.

Despite the unusual index properties of the soil from which the Tjipanundjang Dam was constructed, the dam was standing (performing) safely as a result of the peculiar performance characteristic of some tropical soils, which was not identified through the geotechnical tests developed for the temperate climate soil. Moreover, lack of compaction quality control and compaction procedures that may not be applicable to tropical soils have resulted in failures of numerous earth dams. Studies made on failure cases of earth fill dams constructed in Tanzania indicated that lack of compaction quality control was one major cause of failure.

Compaction during the dry season often faced severe shortage of water for compaction, and the inadequately available water was generally hauled from long distances. Facilities for compaction control were often unavailable to most dam sites or inadequate for the few that received them. It was concluded that the state of compaction was characteristically poor and the soundness of the completed embankment dams was essentially unknown.

Failures of some embankment dams have been explained in the Thesis of Sintayehu entitled as 'Investigation of influence of compaction on the stability of earth fill dams of tropical soils'. Some of the dams are as follows (Hunde S.):

Wiyenzele Dam (completed in 1963) failed during the first filling, before the water reached the spillway level. It is mentioned that the central portion was washed away and reconstruction was done after 10 years and failed again in a similar manner. It was reported that an acute shortage of water for fill compaction was experienced during construction.

Ngerengere Dam (completed in 1974) is mentioned to have failed as a result of downstream slope slip and internal erosion of the dam embankment. Studies showed that poor compaction lead to the dam failure and that compaction water had to be fetched far away from the dam site during construction.

Some of the failure embankments in our country are like;

- Zana micro earth dam, constructed in North Gonder (Belesa)
- Atelkayna micro earth dam, constructed in north Gonder
- Mahbere Genet micro earth dam in North Wollo (Sekota)
- Mylomy micro earth dam near Mahbere Genet dam
- Dana micro earth Dam near Woldiya

The above failures are due to seepage, overstressing, shortage of compaction moisture or improper compaction method.

The above indicated problems are in one way or another connected with peculiar characteristics of tropical soils and also improper compaction of the soil. From the points raised so far it is clearly seen that if the guidelines established for temperate climate soils are to be applied to tropical soils, the consequences will be either failure or uneconomical construction. Therefore, there is still a definite need to carry out investigations on the behaviour of local tropical soils with respect to embankment dam construction.

Some peculiar geotechnical and geochemical characteristics of local tropical soils are investigated with samples taken from Assossa. The soil samples are compacted at optimum moisture contents, at drier side of the optimum moisture content, at wetter side of the optimum moisture content and then compaction tests, UCS tests and permeability tests are done on the soil samples to investigate the variations in the soil parameters. Furthermore, chemical tests (x-ray diffraction and geochemical tests) have been done to support the laboratory test results.

1.2 Research Objectives

This research is done to attain the following general and specific objectives:

General objective

- The general objective of this study is to understand the compaction properties of lateritic soils (the case of Assossa lateritic soil).

Specific Objectives

The specific objective of this study is:

- To show the effect of depth, drying and compaction energy on the properties of lateritic soils in detail.
- To know the behaviour of lateritic soils during compaction.
- To identify basic procedures of compaction of lateritic soils.
- To investigate some limitations of the conventional soil mechanics as applied to residual tropical soils.

1.3 Significance of the study

For the practical application of lateritic soils in embankment construction (dams, cut slopes and roads), first we have to have a through understanding on the compaction properties of these soils. Therefore the significance of this research is:

- To reviews the basic behaviour of lateritic soils.

- To includes information about failures of dams and compaction tests which have been done so far in our country.
- To develops more awareness on such type of soils.
- To recommends some ideas about these soils in relation to their compaction properties.

1.4 Research Methodology

The method employed to achieve the objectives of the research are:

- Literature survey about the topic
- From site;
 - field observation
 - sample collection
- Conducting of tests
- Analysis of the conducted tests
- Conclusion and recommendation

1.5 Scope and Limitation of the research

Scope of the research

The scope of the research is to review literature about lateritic soils, along with some failures of dams constructed using lateritic soils. Based on this background, laboratory tests are conducted on samples, UCS values (as a function of moisture content and time effect), compaction properties (as a function of depth, moisture content and compaction efforts), permeability effect (as a function of moisture content and time effect) are done. In addition, some of the samples have been checked for their degree of laterization by determining the oxide contents and mineral composition.

Limitation of the research

This research was conducted only on five test pits which dug in Assosa. Then the information which has been addressed is a bit general. Furthermore, as these soil properties are dependent on time of sampling, topography and location, the results which are found in this paper from the conducted test pits will not be applicable for all lateritic soils.

2. Literature Review

2.1 General characteristics of residual soils

Hunde's (2003) Thesis dealt with the investigation of lateritic soils. He described some properties like the compaction behavior of lateritic soils and he assessed some of the causes of dam failures. He concluded that most of the failures of these dams were due to the less awareness on the properties of the tropical soils and treated when like transported soils. He added that compaction properties of lateritic soils which are tropical soils were highly influenced on the compaction characteristics of these soils. Based on his paper the following conclusions were given:

- Even for soils with high clay content (>50 %), they have high shear strength.
- As the soil gets drier, the increase on the shear strength is high.
- The soils that he conducted were not highly laterised and for soils which are highly laterized, higher value is expected.
- He added that the difference between dry densities of samples sun dried and air-dried obtained is very small. And he concluded that if the soil is oven dried (OVD), the difference will be significant.
- His paper in relation to compaction properties revised on samples of sun dried (SSD) and air dried of test samples (ARD) on the soil samples from Gilgel Gibe (G.G) and Addis Ababa (A.A). Accordingly, the value of maximum dry density increased as the

soil dried. In addition to this, the holding capacity of water decreased as the soil dried; hence, the optimum moisture content varies as the degree of laterization changes.

But the paper was not supported with chemical tests to relate the degree of laterization of the soils with the test conducted. Further more, the effect of profile for a given test pit as a function of depth was not considered. The effect of compaction energy was not systematically investigated. Furthermore, the effect of sample disturbance was not illustrated using the concept of sensitivity.

Another study was made by Zelalem 2005. On the study by Zelalem, samples are taken from Assossa. The conducted result on the compaction properties of lateritic soils are as follows:

- Drying affects on the optimum moisture content and maximum dry density of the soils.
- From his study, the optimum moisture content (OMC) shifts to the right of the compaction curve as more energy is applied and the maximum dry density (MDD) increases. Further the effect of drying is the same with the conclusion of Hunde's paper by supporting the idea using conducted OVD soils.
- The effect of crushing upon compaction has been investigated by using different number of blows during the test. Accordingly; the conducted result indicated that the percentage of passing increases as the number of blows increased which leads for the conclusion of OMC and MDD of lateritic soils.
- UCS tests have been conducted on the variation of moisture content. Accordingly, tests were conducted at OMC, at the drier and wetter sides (4% of OMC) of the optimum moisture content. Results showed that the compacted soil samples at optimum moisture content have less value as compare to the drier and wetter sides

In general, the conducted results were more or less the same as the paper of Hunde's.

Blight's literature shows same idea as described in the paper of Zelalem and Hunde, which are thesis of Addis Ababa University in 2005 and 2003 respectively.

Based on the above papers and other literatures, books web sites etc, the characteristics of lateritic soils will be seen as follows:

Depending upon the relative position of soils in relation to their parent rock location, soils can be classified as:

- transported soils
- residual soils

A residual soil is a soil like material derived from the in situ weathering and decomposition of rock, which has not been transported from its original location. They are simply expressed as local character.

The process of formation of a residual soil profile is extremely complex, difficult to understand and difficult to generalize. In many countries of Africa and Asia, lateritic residual soils are the traditional material for road and airfield construction. Though a good deal of literature is available on lateritic soils and several excellent reviews have been prepared on this subject. There has generally been very little discussion on the engineering behavior of laterites. Until the U.S. Agency for International Development sponsored the study on laterite and lateritic soils of Southeast Asia, the engineering investigations have been isolated studies. The reason for the limited studies is understood to be due to the absence of uniform methods for the preparation of samples and testing and the variable nature of laterites soils. As a consequence, the drawing of any rational conclusions on the engineering properties of lateritic soils has been very difficult, (Layon, 1971). As weathering proceeds from the surface down and inwards from joint surface and other percolation paths, the intensity of weathering generally reduces with increasing depth and reducing intensity of jointing in the material between joint surfaces (Blight, 1997).

According to (Blight, 1997), laterites are highly weathered and altered residual soils formed by the in-situ weathering and decomposition of rocks under tropical conditions. The three major weathering processes are:

- physical weathering
- chemical weathering
- biological weathering

In the weathering process, the parent rock and rock minerals break down, releasing internal energy and forming soils of lower internal energy that are stable. Physical processes increase surface area and fractures so that chemical attack takes place where as biological phenomena includes both of them.

The available data on lateritic soils gives the impression that the red color seems to have been accepted by most authors as the most important property by which these soils could be identified. Other obviously significant basic physical properties such as texture, structure, consistency, etc., often were ignored .It is also noted that the lack of uniformity in pretreatment and testing procedures (resulting from association with different standards in different parts of world) makes it difficult to compare even textural data on the same soils. It is noted that three major factors influence the engineering properties and field performance of lateritic soils. These are;

- Soil forming factors (e.g. parent rock, climate vegetation conditions, topography and drainage conditions).
- Degree of weathering (degree of laterization) and texture of the soils, genetic soil type, the predominant clay mineral type and depth of sample.
- Pretest treatments and laboratory test procedures as well as interpretation of test results (Lyon, 1971).

According to (Blight, 1997), Climate and topography influences the rate of weathering. Physical weathering is more pronounced in dry climates, while the extent and rate of chemical weathering is largely controlled by the availability of moisture and temperature.

Sample preparation and during laboratory testing, many factors influence test results of tropical soils.

It is well known that oven-drying, and even air-drying, affects the properties of soils, although this effect is usually small for transported soils. Because of their origin, by slow in situ decomposition in a largely anaerobic environment, residual soils are particularly prone to changes in properties caused by drying and exposure to air. Drying can cause partial or complete dehydration of the clay minerals and can change them and their properties irreversibly. Even air-drying at ambient temperature can cause changes that can not be reversed by rewetting, even if the rewetted soil is allowed to mature for long periods.

Apart from the relatively well-known effect of drying on index properties of residual soils, drying also affects:

- The compaction properties of the soils (maximum dry density and optimum moisture content of the soils)
- The compressibility
- And the shear strength characteristics of residual soils

Generally, the behavior of residual soils is dependent on:

- The topographic nature of the area
- The drainage condition of the soil
- The parent materials from which they are derived
- The climatic condition of the area (moisture & temperature)
- The rainfall

Climate and topography influence the rate of weathering. Physical weathering is more predominant in dry climates while the extent and rate of chemical weathering is largely controlled by the availability of moisture and temperature. Topography on the other hand, controls the rate of weathering by partly determining the amount of available water and the rate at which it moves through the zone of weathering. It also controls the effective edge of the profile by controlling the rate of erosion of weathered material from the surface. Thus deeper profiles will generally be found in valleys and on gentle slopes rather than high ground or steep slopes as shown (in Blight, 1997).

Laterites are rich in Sesquioxides (secondary Oxides of Iron, Aluminum or both) and low in bases and primary Silicates, it may contain appreciable amounts of Quartz and Kaolinite. Due to the presence of Iron Oxides lateritic soils are red in color ranging from light through bright to brown shades.

2.1.1 Mineralogical composition related to weathering

The distinctive feature of laterite and lateritic soils is the higher proportion of Sesquioxide of Iron and/or Aluminum relative to the other chemical components. The amount of Alumina or Iron oxides is an important factor in differentiating Aluminous and Ferruginous varieties. The base (Alkalis and Alkaline earths) is almost absent in lateritic horizons, except in some Ferruginous crusts developed in Alluvium and some concretionary horizons in Ferruginous tropical soils. Other lateritic constituents are Manganese, Titanium, Chromium and Vanadium Oxides (Lyon, 1971).

The mineralogical composition is considered to be more important in explaining the physical properties of laterite and lateritic soil. The mineralogical constituents can be divided in to major elements, which are essential to laterization, and minor elements, which do not affect the laterization process. The major constituents are Oxides and Hydroxides of Aluminum and Iron,

with clay minerals and, to a lesser extent, Manganese, Titanium and Silica. The minor constituents are residual remainants.

The clay mineral most common in lateritic soils is Kaolinite. Halloysite is also reported. Illite and Montmorillonite are rare which are common in expansive soils. The secondary minerals resulting mainly from the laterization process are Gibbsite, Goethite, Limonite and Hematite. Neither Manganese nor Titanium minerals were observed in significant amounts. From this, we can say that lateritic soils are non-expansive soils.

2.1.2 Formation, Occurrence and Distribution

Tropical decomposition tends to favour formation of the clay mineral Kaolinite. This is the most common clay mineral in tropical residual soils. Under suitably moist conditions, Halloysites will be formed. Under prolonged decomposition, Silica can be removed to the extent that free Alumina and Iron Oxides are present (Blight, 1997). The lateritic soil formation involves three major processes, which are identified as follows:

Decomposition: Physico-chemical breakdown of primary minerals and the release of constituent elements (SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , K_2O , Na_2O , etc), which appear in simple ionic forms.

Leaching: removing of combined silica and bases and the relative accumulation or enrichment of oxides and hydroxides of Sesquioxides which is called laterization.

The level to which the second stage is carried depends on the nature and the extent of the chemical weathering of the primary minerals. Under conditions of low chemical and soil-forming activity, the physico-chemical weathering does not continue beyond the clay-forming stage, and tends to produce end products consisting of clay minerals predominantly represented by Kaolinite and occasionally by hydrated or hydrous oxides of Iron and Aluminum.

Desiccation /dehydration/: Dehydration (either partial or complete) alters the composition and distribution of the Sesquioxide rich materials in a manner which is generally not reversible upon wetting. Dehydration also influences the formation processes of clay minerals. In the case of total dehydration, strongly cemented soils with a unique granular soils structure may be formed (Blight, 1997). Dehydration may be caused by climatic changes, upheaval of the land, or may also be induced by human activities, for example by clearing of forests.

Laterite occurs mostly in the tropical and sub-tropical regions with hot, humid climatic conditions. It has been suggested that a mean annual temperature of around 25°C is needed for their formation, and in seasonal situations there should be a coincidence of the warm and wet periods. If there is high rainfall during the cold season, laterites do not develop freely. The minimum annual rainfall required for laterite formation is generally at least 750 mm. The higher the rainfall above this value, the greater is the leaching effect, which removes free silica, reduces the silica/sesquioxide ratio and therefore increases the degree of laterization (Blight, 1997).

Regarding topography and drainage, the slope angle controls the amount of water available to move downward through the weathering zone. On steep slopes run-off is greater than infiltration; erosion is active; and conditions are generally not suitable for the development of deep weathering. Conversely on flatter slopes run-off is not so marked; only limited erosion takes place; and long uninterrupted periods of weathering can occur, producing deep soil profiles. On level ground, however, where drainage is impeded and the ground is waterlogged, black Montmorillonite soils dominate at the expense of red soils.

Two aspects of the parent rock affect the formation of laterite. One is the availability of iron and aluminum minerals. These are more readily available in basic rocks. The other is the quartz content of the parent rock. Where quartz is a substantial component of the original rock, it may remain as quartz grains.

2.1.2.1 Regional Distribution

Laterites are soils which cover extensive areas in tropical countries with intermittently moist climate. The six main regions of the world in which laterites occur are Africa, India, South-East Asia, Australia, Central and South America. It should be emphasized that, because of shifts of climatic zone in the geological past, important areas of laterite can be found in areas now outside the tropics (Blight, 1997). But a clear cut of laterization areas in Ethiopia are not known, however, the western part of the country has these lateritic soils as some thesis works show like in Assossa area.

2.1.2.2 Profile of weathering

The alteration of rock by the process of chemical weathering takes place progressively through a number of events and stages which result in a profile of weathering. Those who have worked with tropically weathered residual soils have noted the frequent occurrence of an upper clayey zone a few feet thick, underlain by a silty or sandy zone which, in turn, pass through a very irregular transition in to weathered and finally into sound rock.

The thickness of each member of the profile varies from site to site because of the complexity of the interrelationships among the controlling soil forming factors which are explained as follows:

- rainfall
- temperature
- time
- Character of the parent rock
- Nature of the area (topography, vegetation cover and type)
- The drainage condition of the area.

Soils formed under similar weathering profiles will have similar characteristics (Lyon, 1971).

The starting point of any engineering use of soil if in situ, borrow pit. Many tropical and sub tropical environments are characterized by frequent or seasonal rainfall. Handling of the soils under these conditions may be difficult and the characteristics of the soils themselves may add further complexity to the problem of effective compaction.

2.2 Lateritic soils and their use of as construction materials

lateritic soils are residual soils with Silicon dioxide (Silica) to Sesquioxide ratio of between 1.33 to 2.0. Morin W.J. and Todor P. C, (Blight, 1997) used the term lateritic soil for all reddish tropically weathered materials, irrespective of the presence of or absence of concretions. They behave like fine-grained sands, gravels, and soft rock, which typically have a porous or vesicular appearance. Some particles of lateritic soils tend to crush easily under impact, disintegrating in to a soil material that may be plastic. They could be self-hardening when exposed to drying; or if they are not self-hardening, they may contain appreciable amounts of hardening laterite rock or laterite gravel.

Concretionary laterites are valuable road pavement materials, widely used in the tropics as sub-base, base material and for surface of gravel roads. The term laterite, however, has tended to be indiscriminately applied in tropical highway engineering to any red soil, and as a result the usefulness of laterites for road construction has been under-estimated. Laterites are a good material for embankment construction.

Laboratory testing run to check the suitability of concretionary laterites as road pavement materials should take into account how these materials are affected by the testing procedures (CIRIA, 1995). Some lateritic soils are sensitive to pre- treatment and testing procedures. So laboratory testing should be simulated to site condition.

Main characteristics of lateritic gravels and gravelly soils as mentioned by Morine W.J. and Todor P.C. is the high content of fines. Consequently, such materials do not fit into the existing temperate zone classification systems for coarse-grained soils (Lyon, 1971). In addition, laterites undergo property changes during construction. The most sensitive property is gradation as the nodules tend to crush under heavy compaction.

Some laterites are gap-graded with a depleted sand-size fraction, containing variable percentage of fines, and having coarse particles of variable strength, which may break down in performance, limits their usefulness as pavement materials on high traffick roads. Such laterites need to be improved by appropriate stabilization measures. Lime and cement treatments are common in tropics (Blight, 1997).

Laterites which are used as road and embankment construction material are generally thin strata occurring at shallow depth. Great care should be taken during material investigation and excavation for construction material production. Lateritic is likely to vary in thickness, depth and quality (CIRIA, 1995). Hence, care should be taken to prevent contamination of laterite while removing overburden and stockpiling the laterite.

2.3 General Laboratory procedure

2.3.1 Moisture content determination

The conventional test is based on the loss of water when a soil is dried to a constant mass at a temperature between 105°C and 110°C. In many residual soils, some moisture exists as water of crystallization, within the structure of the minerals present in the solid particles. Some of this moisture may be removed by drying at the above temperature, that is not only the free water but also the structural water will be removed from the soil.

In general, water exists as:

- Structural water, which is bounded chemically with the soil structure
- Free water, which is not bounded chemically, plays a great roll in the compaction process

Therefore, the recommended procedures will be as follows:

Three test specimens should be prepared for moisture determination;

- One specimen should be oven dried at 105 °c.
- The second specimen should be air-dried until successive weighing show no further loss of mass.
- The third specimen should be oven dried at a temperature of not more than 50 °c. And a maximum relative humidity of 30 percent until successive weighing show no further loss of mass.

If the above results show different moisture content, therefore, there is structural water, which is removed by oven drying at a temperature of 105 °c. This water forms part of the soil solids, and should therefore be excluded from the calculation of moisture content. Hence, for all tests involving moisture content, we have to apply at the lower temperature (air drying or at a temperature of 50 °c).

2.3.2 Atterberg limits determination

In this test the effect of:

- pre-test drying
- duration of mixing
- method of mixing has to be taken in to consideration this is because lateritic soils

are affected by wetting and drying due to the presence of sesquioxides which have the effect on the cementation nature of the soils.

In order to address this problem, the following procedure is recommended:

- The mixing time of the specimen should not be more than 5 minutes.
- The mixed specimen should be left for moisture content equilibration overnight before testing.
- Make use of fresh soil for each moisture content point
- The soil should be broken down by soaking in distilled water, and not by drying and grinding.

2.3.3 Compaction test

2.3.3.1 Background

In this test, the effect on the maximum dry density and optimum moisture content will be seen by using the same sample for a given compaction curve and fresh sample of the soil. The sampling is done as follows:

- As received soil samples (ARS)
- Air dry soil samples (ARD)
- Oven dry soil samples (OVD)

Furthermore, the theoretical explanation of lateritic soils show a decrease in the degree of laterization as variations in temperature and moisture fluctuation is higher at the top part of the surface of the earth (for a given profile of soils) and it will be checked by taking samples at a depth of 1m, 2m, and 3m. The degree of cementation will be discussed based on the compaction characteristics of the soil, which is taken from the site along depth variation. Drying, depth of samples and compaction energy can highly affect the compaction properties of

lateritic soils; hence the correct procedure to be followed will be must if appropriate results are required.

2.3.3.2 Rational behind the tests

Compaction is one of the major processes under taken to increase the bearing capacity, reduce permeability and settlement of road basses and embankment earthworks like in dams as well as in roads, by means of rolling, tamping and vibratory machines. The main factors which affect compaction are the soil type, moisture content and amount of compactive effort. All of these are inter-related.

Compaction can be defined as the process of densifying soil and reducing air voids by applying mechanical energy. Densification leads to improvement in the engineering properties of strength, compressibility and stiffness, and to reduce in permeability.

There are some basic scientific principles involved in the compaction process. However, the means of achieving the desired degree of compaction involves a combination of technology and judgment, and the recognition that soil materials are inherently variable. Efficient compaction is an art that is dependent on engineering skill and judgment. Compaction is undertaken in the field using the best available technology. The compacted product requires compromises between energy, cost and the value of the result obtained. Engineering design must recognize the reality of what can be achieved in the field.

Residual soils are widely used as construction materials, mainly as fill for embankment dams and embankment of roads and as selected layers in highways and airfield construction. Certain residual soils, such as those containing Smectite or Halloysite clays may be unsuitable for these uses, either because of inadequate strength, or excessive change of volume with varying water content, or because of loss of strength on wetting. However, Smectitic and Halloysitic materials have been used to form impervious layers in water-retaining embankments. Examples of such

uses are Sumua Dam described by Terzaghi (1958) and the Arenal Dam described by Rodda et al. (1982).

The parent rock is usually variable in composition, particularly if it is an igneous rock. The degree of weathering will also be variable. Hence the selection of representative samples for testing can be a major problem. For the same reason good control of quality in compacted fills of residual material may be extremely difficult to achieve.

Drying of the soil from its in situ water content may change both its index and compaction properties. Hence soil samples have to be treated and tested with the greatest care if the results of compaction tests are to be at all meaningful. The influence of sample preparation and laboratory procedure on the compaction characteristics of a lateritic soil (Gidigas 1974) is well illustrated. Not only was the optimum water content of the soil significantly altered by air- or oven-drying before compaction, but the maximum dry density was also considerably changed.

The compaction characteristics of residual soils may be very dependent on the method of applying the compactive energy. In particular, laboratory compaction curves may bear little resemblance to the compaction curve achievable in the field. This phenomenon (which may also apply to transported soils) can be compared roller and laboratory compaction curves for a weathered lateritic soils. In one case it was not possible to achieve laboratory maximum dry density in the field because the optimum water content for roller compaction was more than 3 percent lower than for laboratory compaction. In the other case, it was not possible to achieve laboratory maximum dry density with roller compaction.

Compaction often results in progressive breakdown of the particles in residual soils. For example, the progressive breakdown of particle size under compaction of quartzite gravel and a lateritic gravel both residual from the weathering of granite is common. In cases like this, it becomes imperative to use a fresh soil sample to establish each point on the compaction curve,

otherwise, the compaction characteristics of the soil will change progressively as the compaction test proceeds, and the test result may be meaningless.

2.3.3.3 Compaction mechanisms

Compaction may be undertaken on soils in situ, or soils that have been excavated, transported, and placed. The structure and physical nature of the soil may have a major influence on the choice of compaction method.

Free water (water within the soil mass that is not chemically bound by the clay minerals) can have a controlling influence on the ease with which a given degree of compaction is achieved. Within certain bounds, this free water reduces soil strength, assisting break-down of the soil structure to reduce the air voids. As the free water content increases, there is a stage beyond which the compaction-facilitating effect is offset by the increased energy required to move the air out of the soil. Once the air permeability of the dandifying soil reaches the stage where the air can not escape, void reduction is impeded. The presence of water then becomes a factor that prevents further compaction from taking place. This simple observation leads to the concept of an optimum moisture condition for a given compaction process. The optimum moisture condition is a function of:

- The physical properties of the soils
- Initial structure
- The means by which mechanical energy is imparted to the soil mass

The optimum moisture condition for a given compaction procedure can be illustrated roughly as follows, using the degree of saturation of the soil (S) to distinguish different moisture content states:

$S < 15\%$: air void space is freely interconnected and rapid expulsion of air and densification can occur.

15% < S < 40%: Reduction of soil strength is offset by reducing air permeability of soil. This is the optimum range for compaction,

S > 40%: air voids become discontinuous and further densification cannot take place.

The degree of saturation is however, not a convenient measure for compaction control. The objective of compaction is to achieve maximum densification appropriate to the engineering purpose. Compaction is therefore usually measured in terms of dry density achieved. The optimum moisture content is associated with the achievement of a maximum dry density for a given compaction effort. Usually this occurs at air voids content of between 5% and 3%. Moisture contents in excess of the optimum are associated with air voids of less than 3% which remain almost constant as water content increases. At this stage additional water adds to void space and leads to a direct reduction in the dry density.

All soils exhibit the following traits:

- High strength and void contents in the moisture contents regime drier side of optimum.
- A rapid reduction of strength in the moisture content regime wetter side of optimum, where the curve follows a line of minimum air voids,
- A range of moisture contents around the optimum condition, where the acceptability of the compacted soil can be measured by a variety of methods. In situ strength is often the most appropriate compaction control parameter for residual soils.

In the field compaction process, the choice of compaction equipment should be made with a view to minimizing earthworks costs while achieving the desired engineering properties for the compacted soil. Earthworks design must include a consideration of what range of equipment is

available, and any practical constraints such as weather and site conditions, which may influence what, can be achieved in the field.

The optimum moisture condition for field compaction is best determined for any compaction equipment by a process of field trials. It is recommended practice to include field trials as an initial component of the construction program. The trials can be used to optimize equipment selection and operation, and to identify the field optimum moisture condition. Where the soil being compacted is sufficiently uniform in its physical properties, field trials can also be used to finalize the method of compaction with construction being controlled by this means.

Another factor to be considered is the process of moisture conditioning. It is relatively easy to add water to the soil, but more difficult to ensure that the added water is uniformly distributed within the soil. In high rainfall areas, it may be necessary to dry the soil in order to operate compaction equipment. Air-drying may be slow, and must be aided by ploughing or tilling to turn the wetter soil to the surface and expose it to sun and wind.

The final product should have the desired engineering properties. It is therefore important that adequate supervision and quality control are used during the fill construction process.

3. Sampling Area Description and in-situ properties

3.1 Description of the sampling area

3.1.1 General information

Asossa Town is the capital city of Beneshangul Gumuz Regional Government and located at 675km from Addis Ababa in southwest direction. It is 96km from the Ethio-Sudan border. The town has a flat terrain with an elevation of about 1650m above mean sea level. Some of the urban roads are earth roads of reddish soil and the rest are asphalt roads. The route connecting Asossa to the central part of Ethiopia is under construction (part of it is asphalt and the rest is still earth roads) and to Ethio-Sudan border is an earth road (highly reddish in color, this is due to the high content of the mineral iron oxide in the soil) or easily friable material for a significant length, which creates a problem for the traffic movement in rainy season and not suitable in the dry season too, because of dust.

Asossa area is a flat terrain with fertile land. Most of the area is cultivated following the route connecting Asossa to central Ethiopia and Ethio-Sudan border. Mango is the dominant plant in this area.

3.1.2 Sample Description

Soil samples for this thesis work were collected from Assossa town. Before the soil samples were sampled, site visit was made. Accordingly, five places were chosen (TP-3 is found at low land area but the rest are relatively in flat area) and bulk samples (disturbed and undisturbed samples) have been collected for this research work, each test pits has a depth of 3m and disturbed samples were taken for each meter depth as shown below. In addition to this, undisturbed sample was taken from TP-1.

Table 3.1.2/1 Samples location, depth, color and the designation used for the Samples.

Serial No.	Designation	Sampling depth (m)	color
1	TP-1	1	Reddish
2		2	
3		3	
4	TP-2	1	Reddish
5		2	
6		3	
7	TP-3	1	Reddish
8		2	
9		3	
10	TP-4	1	Reddish
11		2	
12		3	
13	TP-5	1	Reddish
14		2	
15		3	

The red colour of the samples is due to the high content of iron oxides within the soils.

3.1.2 Geology and Climate

According to the Geological map of Ethiopia, 1996, the Geological formation of Assossa town and the surrounding area is flood basalt. The flood basalt is a good crushed aggregate material for concrete works, base course, and asphalt works when it exists in sound form. Granite is also observed during the field investigation around Assossa town existing in sound form.

Furthermore, in Assossa, there is shortage of water in the town, this is because of the fact that the geology of the area is highly covered by fractured rocks like Granite (some boulders are exposed on the surface of the border of the town to the direction of the West, which are good indication of Granite). Therefore, the water will not be accumulated even as perched form because of this, there is shortage of water in the town.

The climatic classification of Assossa town is warm (“Kola”) with a range of temperature 15°C to 33°C. This climatic condition favors for the formation of lateritic soils as the mean annual rain fall is around 1200mm.

Although all the physical and climatic conditions of the area indicate lateritic formation, some index property tests are run to confirm the properties.

3.2 Description of in situ properties

3.2.1 Atterberg Limits and natural moisture contents

Moist samples collected from the representative sampling area were placed in the plastic bags in order to avoid any loss of moisture content.

The natural moisture contents of the soil samples were determined in the laboratory according to AASHTO T262-93 (2000); Blight, 1997; CIRIA 1995. Drying oven temperatures of 105°C and 50°C were used to dry the samples. Two representative samples from each site were taken for moisture content determination. One set of samples were dried to constant weight using drying oven at temperature of 105°C, and the other at a temperature of 50°C with RH 30% taking a minimum of five days to get a constant mass in successive measurements. The values of the moisture content variations are compared and summarized in Table 3.2.1/1. As mentioned in Blight, 1997, moisture variations 4 - 6 % or more indicates that loosely bound molecular water is present. From the test results, one can see that the differences in moisture contents for all soil samples are below 4%, which means that the soil under investigation does not contain loosely bound water of hydration. Hence for subsequent tests execution for the thesis work can be used a temperature of 105°C for the determination of moisture content. In addition to this Table 3.2.1/1 shows Atterberg Limit Test results and Activity number of the soil.

Table 3.2.1/1: Natural moisture content and Atterberg limit test results:

Designation	Depth (m)	Liquid	Plastic	Plasticity	Natural moisture		Activity =PI/% of clay	Swelling In (%)
		limit (LL) (%)	limit (PL) (%)	Index (PI) (%)	content	content		
					(NMC)	(%)		
TP-1	1	47.60	23.50	24.10	25.85	26.5	0.34	18
	2	-	-		24.39	25.3	-	-
	3	46.30	28.90	17.40	26.4	27.08	0.31	20.1
TP-2	1	56.40	30.90	25.50	31.99	33.2	0.35	15.3
	2	-	-	-	32.89	34.3	-	-
	3	58.00	41.20	16.80	19.76	20.56	0.35	16.8
TP-3	1	60.50	39.60	20.90	26.75	27.24	0.27	12.5
	2	-	-	-	25.21	26.3	-	-
	3	43.80	28.70	15.10	24.38	25.3	0.28	7.52
TP-4	1	57.90	32.00	25.90	22.67	23.45	0.32	14.10
	2	-	-	-	20.45	21.23	-	-
	3	53.60	34.20	19.40	17.49	18.21	0.51	15.87
TP-5	1	58.40	32.40	26.00	34.90	36.2	0.36	13.4
	2	-	-	-	34.07	35.2	-	-
	3	57.20	32.40	24.80	28.67	29.32	0.53	14.2

Free Swell: This test gives a fair approximation of the degree of expansiveness of a soil. It is done by pouring very slowly 10 cm³ of dry soil passing sieve No. 40 (0.42mm) opening in to a 100 cm³ graduated measuring cylinder for 24 hours until all the soils settle completely to the bottom of the cylinder and it is given by:

$$\text{Free Swell (\%)} = \left(\frac{V_f - V_i}{V_i} \right) * 100\%$$

Where V_f = final volume and V_i = initial volume

Accordingly one can see from the test that the free swell values for Asossa soils are below 30%. Those soils with free swell of less than 50% are considered to have low degree of expansion (5). Accordingly, the soil of Asossa is non-expansive soil.

Activity: Skempton's colloidal activity is determined as the ratio of the plasticity index to the clay content in the fines. It is generally low for lateritic soils. Skempton observed that, for a given soil, the plasticity index is directly proportional to the percent of clay-size fraction (i.e., percent by weight finer than 0.002mm in size). Activity has been used for determining the swelling potential of clays. The soil classification according to Activity is shown in Table 3.2.1/. Hence; from Table 3.2.1/1 and 3.2.2/1, one can observe that the soil samples are inactive.

Table 3.2.1/2; Degree of Colloidal activity

Activity Number	Soil Type
<0.75	Inactive
0.75 –1.25	Normal
>1.25	Active

3.2.2 Description of particle size in a profile

The particle size of the soil samples (the percentage of clay, silt, sand and gravel) in a given profile are described in Table 3.2.2/1. In general, the amount of fineness decreases as the depth increases.

Table 3.2.2/1; the values of particle sizes for profile analysis:

Depth (m)	Designation	Percentage Amount of Particle sizes			
		Clay (%)	Silt (%)	Sand (%)	Gravel (%)
1	TP-1	71.4	16.5	7.1	5.0
3		56.2	15.7	14.1	14
1	TP-2	72.3	20.8	5.0	1.9
3		48.4	23	17.9	10.7
1	TP-3	76.5	20.1	3.4	0.0
3		54.4	39.5	2.1	4.0
1	TP-4	79.9	18.2	1.9	0.0
3		38.4	25.6	22.4	13.6
1	TP-5	71.4	24.2	4.4	0.0
3		47.2	24.6	23.6	4.6

4. Laboratory Test Results and Analysis

4.1 Compaction Test

4.1.1 Test procedure

In the laboratory, both standard (SCM) and modified (MCM) compaction equipments were used to compact the soil samples. The following procedures were followed in order to compact all the soil samples.

- Soil specimens (ARS, ARD or OVD), passing sieve number 4 (4.75mm) were soaked for different moisture contents for overnight
- Samples were compacted in a cylindrical mold either using SCM or MCM
- The weight of the compacted samples were measured using a very sensitive balance
- Moisture contents of the compacted soils were determined by taking samples at the top, middle and bottom of the compacted soils

A temperature of 105⁰C was used in a preparation of OVD samples. Air drying samples (ARD) are simply exposing the wet soil samples to the atmosphere and spreading on the floor of the ground of the labalotory. Compaction tests on wet samples were carried out for each point on the curve by taking the natural moisture content of the soil as an initial minimum moisture content of the compactive curve but the rest points were obtained by adding water (for ARS samples).Recompactd soil samples and fresh samples were treated independently during the Construction of the compaction curves.

As the difference of oven drying of the samples and moisture content of the soil samples at 50% was less than 2% (Blight), then oven drying of the samples were considered to determine the moisture content of the test.

4.1.2 Results of compaction

4.1.2.1 Effect of degree of laterization in a given profile

This helps to understand the degree of laterization in a given profile and helps to judge whether in a given profile varies the degree of laterization or not. Theoretically, higher degree of laterization can be expected at the top part of the profile considering that the parent rocks are same in the profile. Chemical weathering is intense at the top layer of the soil due to the fluctuation of temperature and moisture that favors for the formation of the lateritic soils at this layer of the given profile.

To determine the effect of degree of laterization on the maximum dry densities and the corresponding optimum moisture contents, the compaction test data was summarized for the samples as received from site as follows:

Table 4.1.2.1/1; Compaction test data (for soils as received, using SCM)

Location of sample	Depth (m)	Moisture Content (%)	Dry density (Kg/m ³)	Location of sample	Depth (m)	Moisture Content (%)	Dry density (Kg/m ³)
TP-1	1	26.5	1120.54	TP-3	1	25.32	1003.78
		31.26	1232.32			38.43	1289.1
		35.95	1312.56			42.85	1180.1
		40.1	1220.21			45.58	1053.26
	2	25.3	1101.01		2	26.3	1069.75
		33.25	1235.32			38.1	1356.03
		36.2	1281.03			41.89	1267.30
		41.02	1165.23			45.65	1095.4

	3	27.08 27.98 37.1 42.56	1099.08 1123.54 1253.95 1056.2		3	27.24 35.51 40.84 45	1120.56 1457.89 1364.73 1170.5
TP-2	1	33.2 37.25 40.25	1375.21 1303.04 1198.89	TP-4	1	23.45 27.11 30.5	1365.5 1410.52 1476.89
	2	34.3 38.25 41.26	1317.82 1230.2 1112.96			34 39.2	1450.23 1365.12
	3	20.56 31.2 35.63 41.21 -	1056.75 1310.32 1235 1068.57 -		2	21.23 31.01 35.5 39.24 41.89	1289.25 1423.25 1420.3 1340.25 1229
TP-5	1	36.2 39.5 43.2 48.6	1260.01 1225.32 1132.65 1052.89		3	18.21 25.24 32.5 36.85 41.21	1210.75 1330.45 1409.46 1380.27 1235.36
	2	35.2 39.18 42.85 46.89 29.32	1245.63 1210.69 1102.96 1012.3 1023.52				
	3	34.99 38.89 43.26 48.95	1201.2 1194.31 1056.2 956.23				

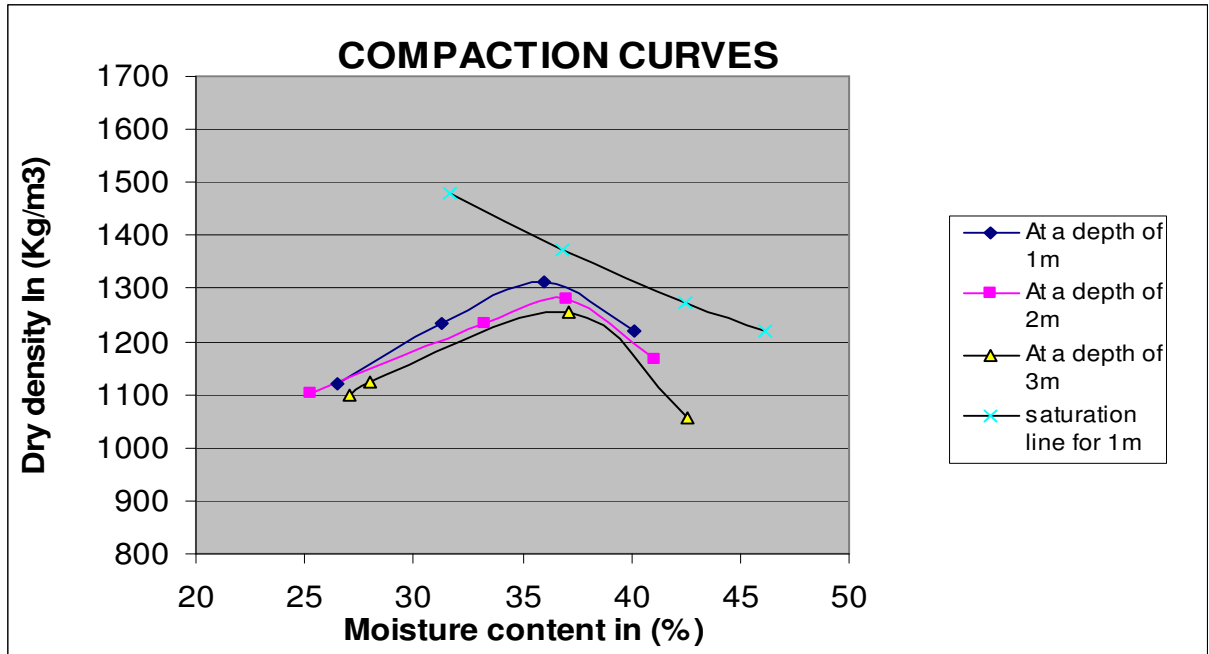


Fig.4.1.2.1/1; The influence of degree of laterization on compaction characteristics of lateritic soil, TP-1 (with G=2.72 at 1m).

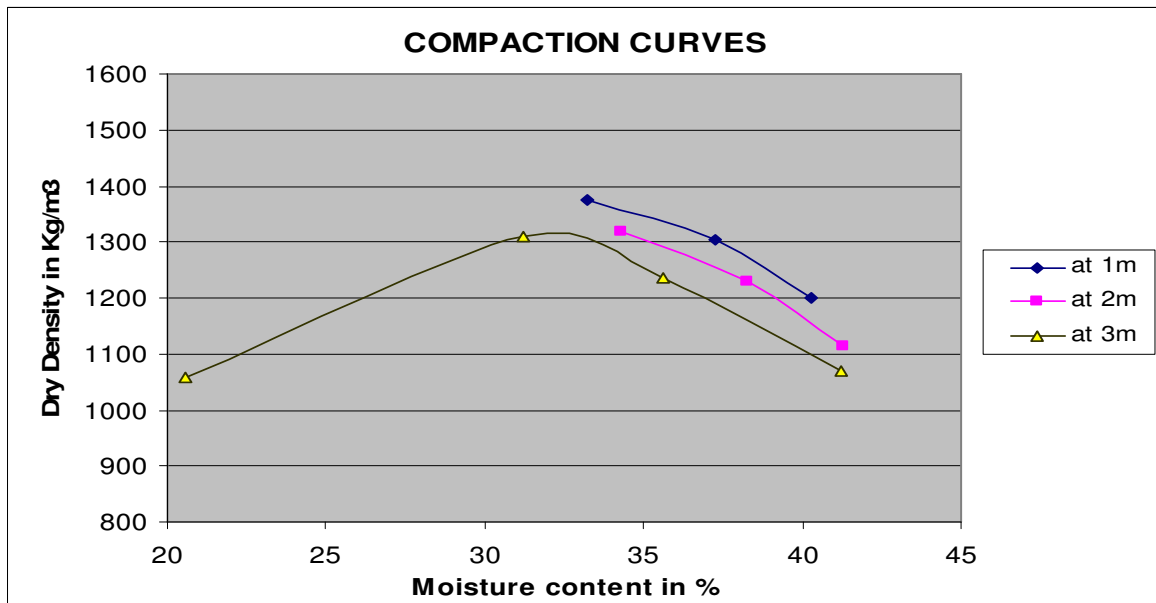


Fig. 4.1.2.1/2; the influence of degree of laterization on compaction characteristics of lateritic soil, TP-2.

In Fig.4.1.2.1/2 above indicates that soils with moisture content above the optimum moisture content are impossible to attain the maximum dry density and the optimum moisture content since the initial in-situ moisture is greater than the optimum moisture content of the soil.

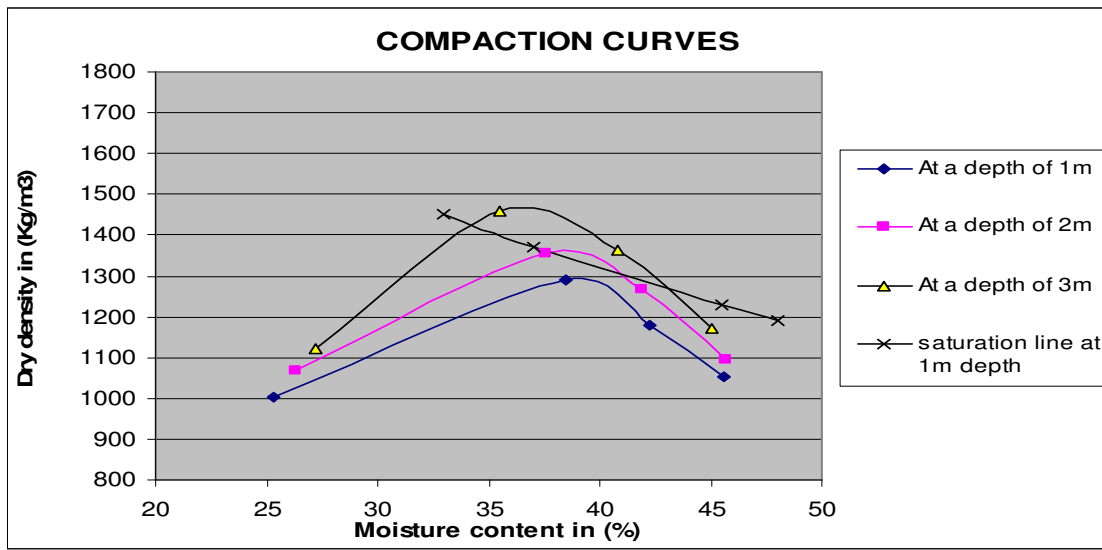


Fig.4.1.2.1/3; The influence of degree of laterization on compaction characteristics of lateritic soil, TP-3 (with G=2.79 at 1m).

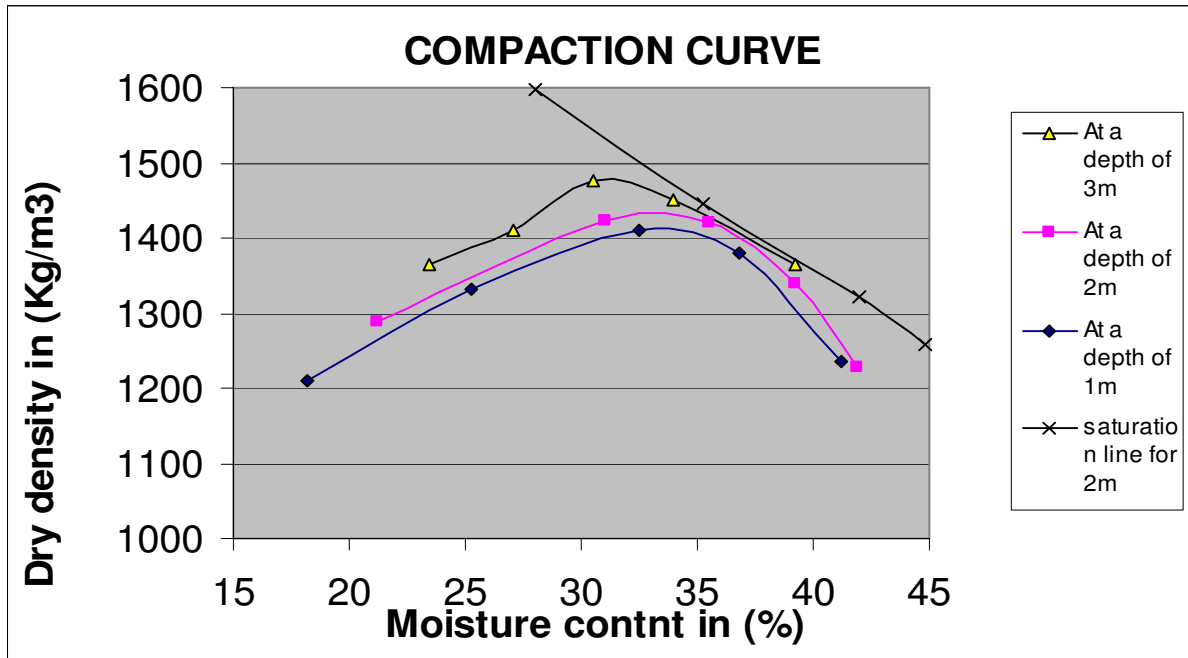


Fig.4.1.2.1/4; The influence of degree of laterization on compaction characteristics of lateritic soil, TP-4 (with G=2.89 at 2m).

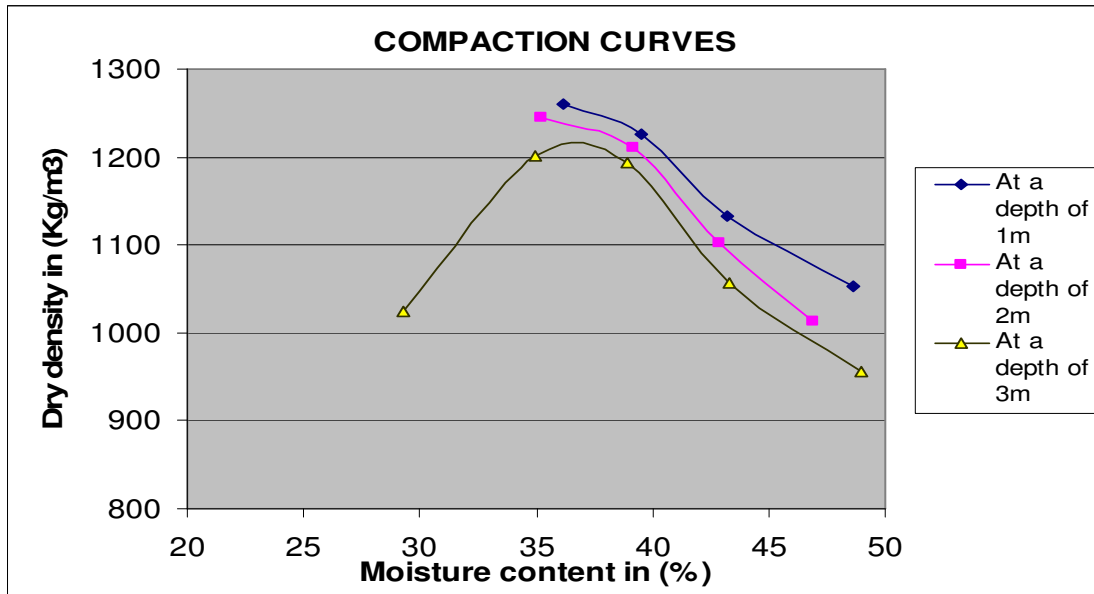


Fig. 4.1.2.1/ 5; Influence of degree of laterization on compaction characteristics of lateritic soil, TP-5.

Fig.4.1.2.1/5 like that of Fig.4.1.2.1/2, it was impossible to get very distinct single maximum dry density and the optimum moisture contents because the natural moisture content is greater than the optimum moisture content of the soil. And also, the above data and figures illustrates the variability of material from a single borrow pit for a given profile which shows a significant change in both the dry density and the optimum moisture content mainly due to the mineralogical effect in the soil.

From the first, third and fourth figures, the optimum moisture content of the soil shifts to the right as the depth increases because the soils are less cemented and then water can pass easily to the soil particles.

4.1.2.2 Effect of drying

To determine the effect of drying of samples on the maximum dry densities and the corresponding optimum moisture contents. Air-drying for Tp-1, 2 and 3 were used, and oven dried for TP-2 at depths of 1m and 3m was added. The compaction test data was summarized for the samples as follows:

Table 4.1.2.2/1; Compaction test data (for soils after drying, using SCM)

Location of sample	Depth (m)	Moisture Content (%)	air drying	oven drying	Location of sample	Depth (m)	Moisture Content (%)	Dry density (Kg/m3)
			Dry density (Kg/m3)	Dry density (Kg/m3)				
TP-1	1	15.65	1186.09		TP-3	3	15.12	1130.4
		21.23	1289.78				23.45	1425.56
		28.96	1465.8				29.98	1635.16
		32.56	1506.85				33.75	1591.53
		35.85	1456.02				41.3	1303.31

		38.86	1353.26			2	19.21	1141.04
	2	17.02	1120.57				24.45	1271.06
		23.54	1202.32				28.28	1393.85
		30.58	1285.32				33.3	1482.7
		33.89	1302.08				36.75	1421.78
		35.2	1285.45				42.56	1101.41
		40.1	1165.98			1	17.77	1098.2
	3	16.52	1085.46				23.23	1198.7
		22.63	1160.89				27.99	1329.64
		29.35	1209.3				33	1408
		34.1	1269.78				35.9	1401
		36	1250.96				39.1	1278.14
		42.5	1002.89					
TP-2	1	14	1179.5	1352.41			12.3	
		20.9	1402.1	1586.28			17.25	
		24.8	1510.06	1806.61			25.1	
		28.91	1545.6	1706.23			32.12	
		33.89	1498.5	1602.54			34.89	
		39.78	1350.89	1426.31			38.74	
	2	18.6	1201.38					
		23.86	1298.02					
		28.12	1356.59					
		30.89	1410.86					
		35.1	1360.28					
		40.8	1202.01					
	3	17.65	1120.4	1120.85			14.5	
		24.42	1268.21	1356.19			23.42	
		30.12	1341.2	1465.82			27	
		33.87	1373.09	1445.18			32.59	

		36.21	1298.12	1286.25			38.59	
		41.89	1123.06	1125.46			44	

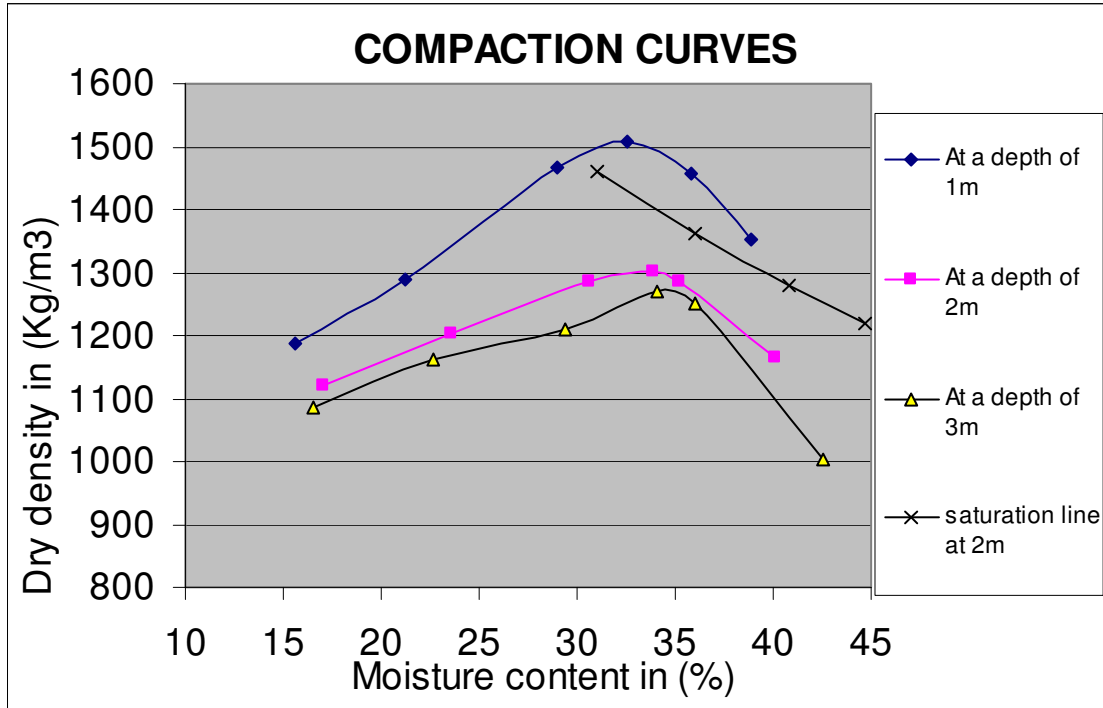


Fig.4.1.2.2/1; The influence of drying on compaction characteristics of lateritic soil, TP-1 (with $G=2.67$ at 2m).

The above results shown in Fig.4.1.2.2/1 can be compared with Fig.4.1.2.1/1. We can clearly observe that loss of moisture content affects both maximum dry density and the optimum moisture content of the lateritic soils.

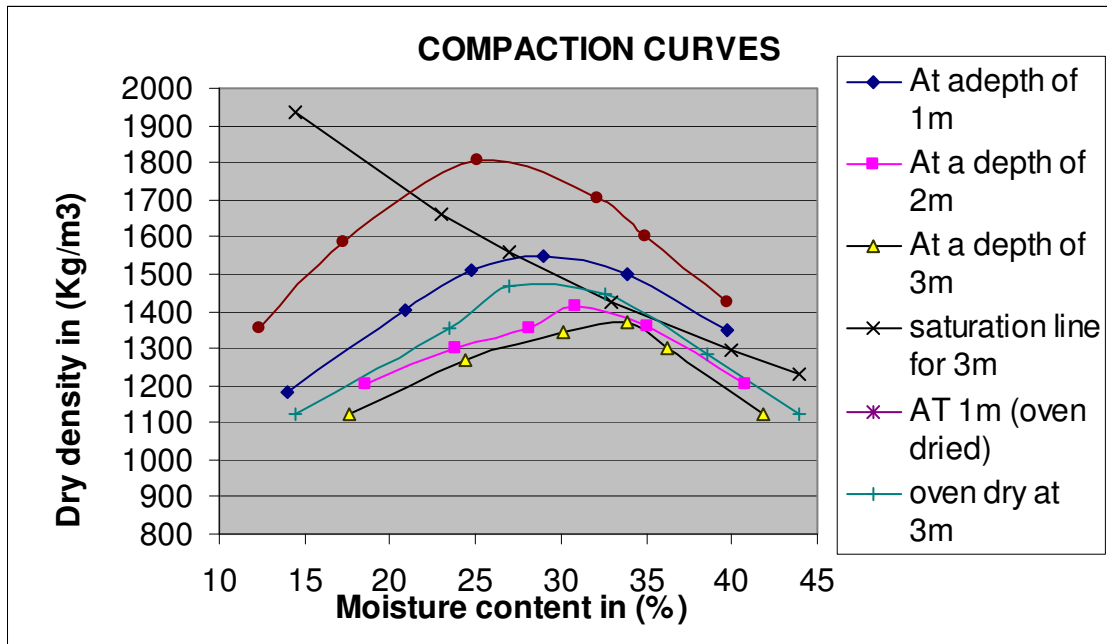


Fig. 4.1.2.2/2; The influence of drying on compaction characteristics of lateritic soil, TP-2 (with $G=2.69$ at 3m).

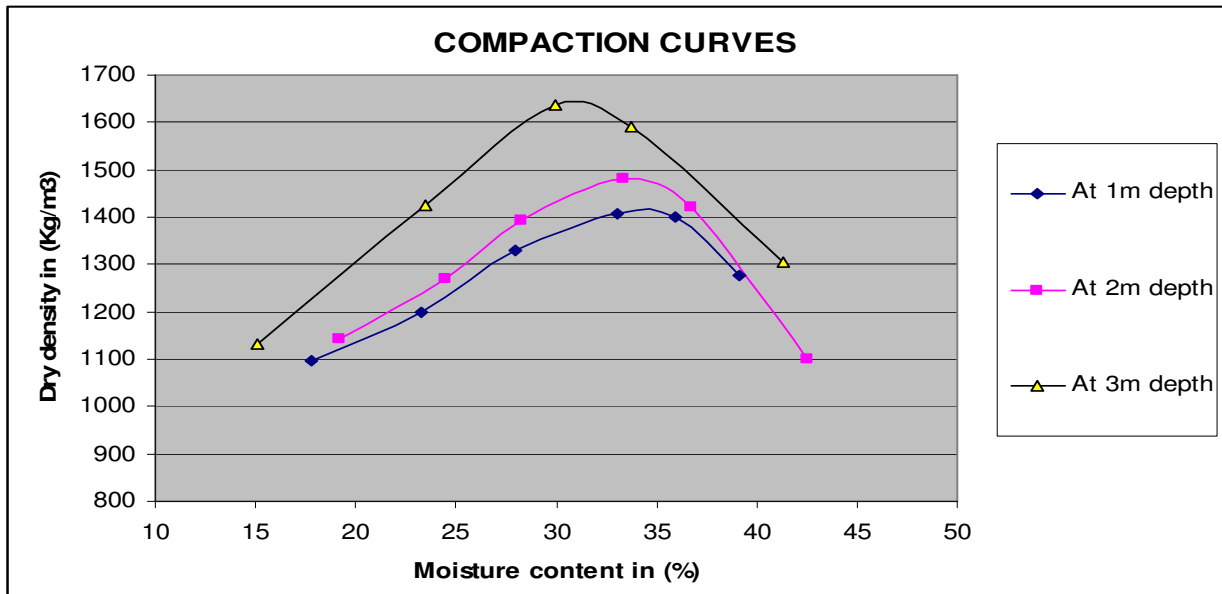


Fig. 4.1.2.2/3; the influence of drying on compaction characteristics of lateritic soil, TP-3.

The plots of dry densities versus moisture contents for the drying effect were illustrated in the above three figures. Drying of the soil from its in situ water content could change its compaction properties (see the above figures). Hence soil samples have to be treated and tested with the greatest care if the results of compaction tests are to be at all meaningful. Not only was the maximum dry density of the soil significantly altered by air-drying or oven drying before compaction, but the optimum water content was also considerably changed.

4.1.2.3 Effect of compaction energy

To determine the effect of compaction energy on the maximum dry densities and the corresponding optimum moisture contents, standard and modified compaction tests were carried out on fresh and recompacted soil samples and the test data was summarized in Table 4.1.2.3/1.

Table 4.1.2.3/1; Compaction test data (for soils after drying, using SCM & MCM).

Location of sample	Depth (m)	Moisture content (%)	Dry density (Kg/m ³)	method of compaction	type of sample
TP-4	1	13.9	1256.28	SCM	fresh
		18.78	1406.53		
		27.1	1579.8		
		31.2	1610.49		
		36.89	1521.13		
		42.28	1446.69		
	1	15.4	1445.68	SCM	recompacted
		21.63	1602.54		
		28.1	1723.9		
		33.2	1756.2		
		37.59	1652.8		
		43.35	1489.1		

	2	13.01 19.85 27.8 32.1 38.18	1185.6 1345 1530.7 1550.4 1435.9	SCM	fresh
	2	41.03 14.5 20.3 26.1 33.5 35.9 40.94	1376.2 1286.5 1420.8 1532.54 1599.89 1560.73 1450.9	SCM	recompacted
	1	11.65 18.78 28.71 34.5 38.7 43.42	1404.7 1580.54 1775.54 1823.81 1702.23 1530.8	MCM	recompacted
TP-5	1	15.3 21.87 28.3 31.8 35.9 39.7	1002.5 1296.45 1456.28 1536.43 1445.3 1256.2	SCM	fresh
	1	15.65 21.23 28.96 32.56	1269 1406.85 1599.87 1698.28	SCM	recompacted

		-	-		
		35.64	1689.36		
		40.1	1489.7		
	1	16.52	1185.6	MCM	fresh
		22.63	1345		
		27.5	1530.7		
		34.1	1550.4		
		37.8	1435.9		
		42.5	1376.2		
	1	17.19	1453.28		
		23.01	1570.54		
		27.9	1685.37	MCM	recompacted
		34.56	1786.46		
		40.95	1586.32		
		43.89	1423.01		

The above table indicates how compaction energy affects the maximum dry density and the optimum moisture content. Accordingly, the result indicate that the more the compaction energy, the higher the value of the OMC and MDD of the samples because the energy reduces the void space for further increase in MDD and the energy also leads to an increase in the holding capacity of water due to breaking of the soil cementation.

The type of compaction energy used are the standard mould (25 blows) and the modified compaction mould (56 blows) by using fresh and recompacting the soil samples in order to see the variation of the OMC and MDD.

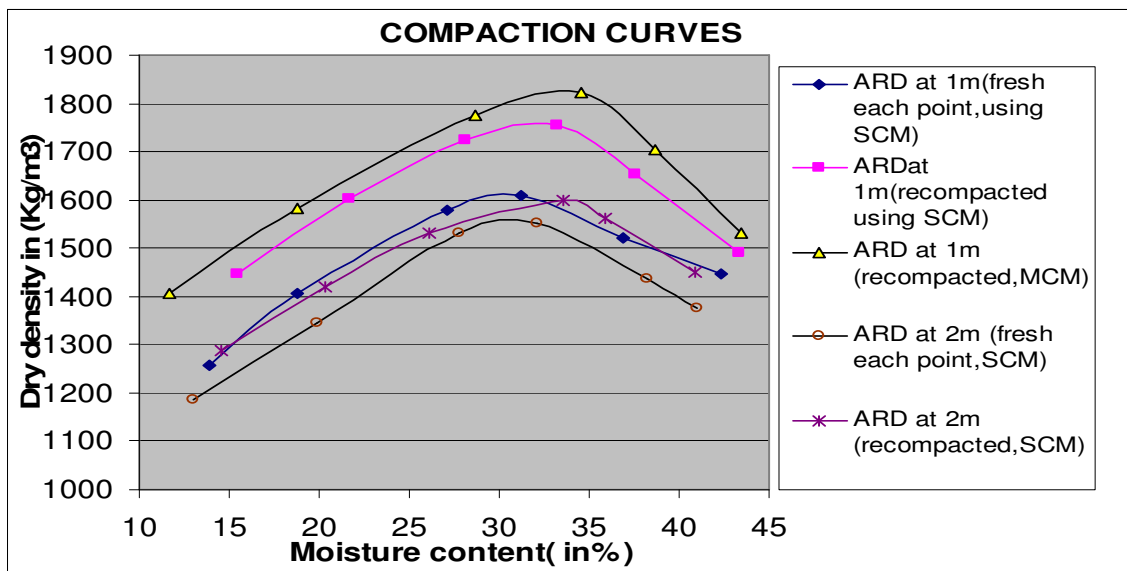


Fig. 4.1.2.3/1; The influence of compaction energy on compaction characteristics of lateritic soil , TP-4.

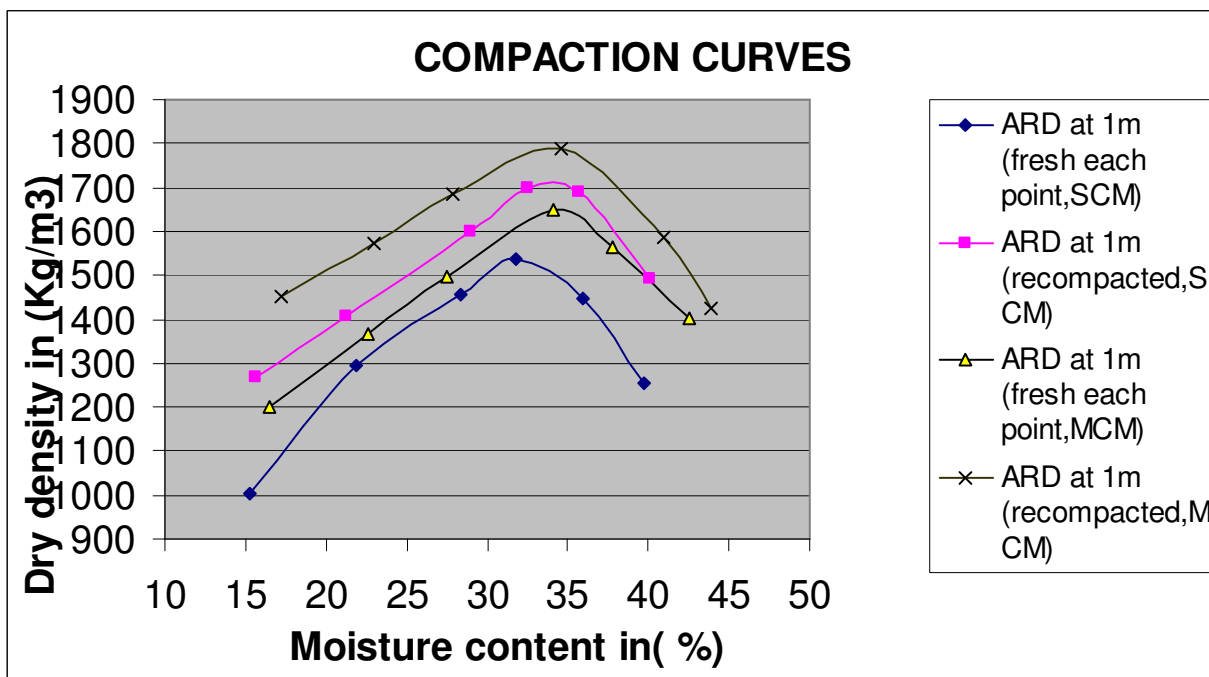


Fig 4.1.2.3/2; the influence of compaction energy on compaction characteristics of lateritic soil , TP-5

From Fig.4.1.2.3/1 and 2, the compaction characteristics of lateritic soils are very much dependent on the method of applying the compaction energy. From the same figures one can see that, as the applied energy increases, the maximum dry density (MDD) increases significantly but the optimum moisture content (OMC) is not that much affected. Further, as the degree of cementation increases, the OMC and MDD will have higher values.

In this case, it becomes imperative to use a fresh soil sample to establish each point on the compaction curves, otherwise the compaction characteristics of the soil will change progressively as the compaction test proceeds, and the test result may be meaningless

The following table represents the effect of both drying and compaction energy of TP-1 at a depth of 1m. Each point on the next curves represents fresh soil sample and hence the effect on the maximum dry density was clearly observed but on the optimum moisture content was not much.

Table 4.1.2.3/2; Compaction test data (for ARS, ARD and OVD).

Location of sample	Depth (m)	ARS of Dry density (Kg/m3)			Dry ARD of density (Kg/m3)				OVD of Dry Density			
		Moisture content (%)	using SCM	using MCM	Moisture content (%)	using SCM	using MCM	Moisture content (%)	(Kg/m3) using SCM	Moisture content (%)	(Kg/m3) using MCM	Moisture content (%)
TP-1	1	26.5	1120.54	1145.84	15.65	1186.09	1245.19	14.67	1450.4	13.4	1550.67	12.34
		31.26	1232.32	1275.6	21.23	1289.78	1435.38	22.43	1701.03	21.45	1934.06	23.56
		35.95	1312.56	1345.05	28.96	1465.8	1589.56	30.2	1845.99	25.67	2010.79	29.67
		40.1	1220.21	1249.79	32.56	1506.85	1623.01	34.78	1710.02	34.61	1875.68	35.9
		-	-	-	35.85	1456.02	1401.56	43.8	-	-	-	-
		-	-	-	38.86	1353.26	-	-	-	-	-	-

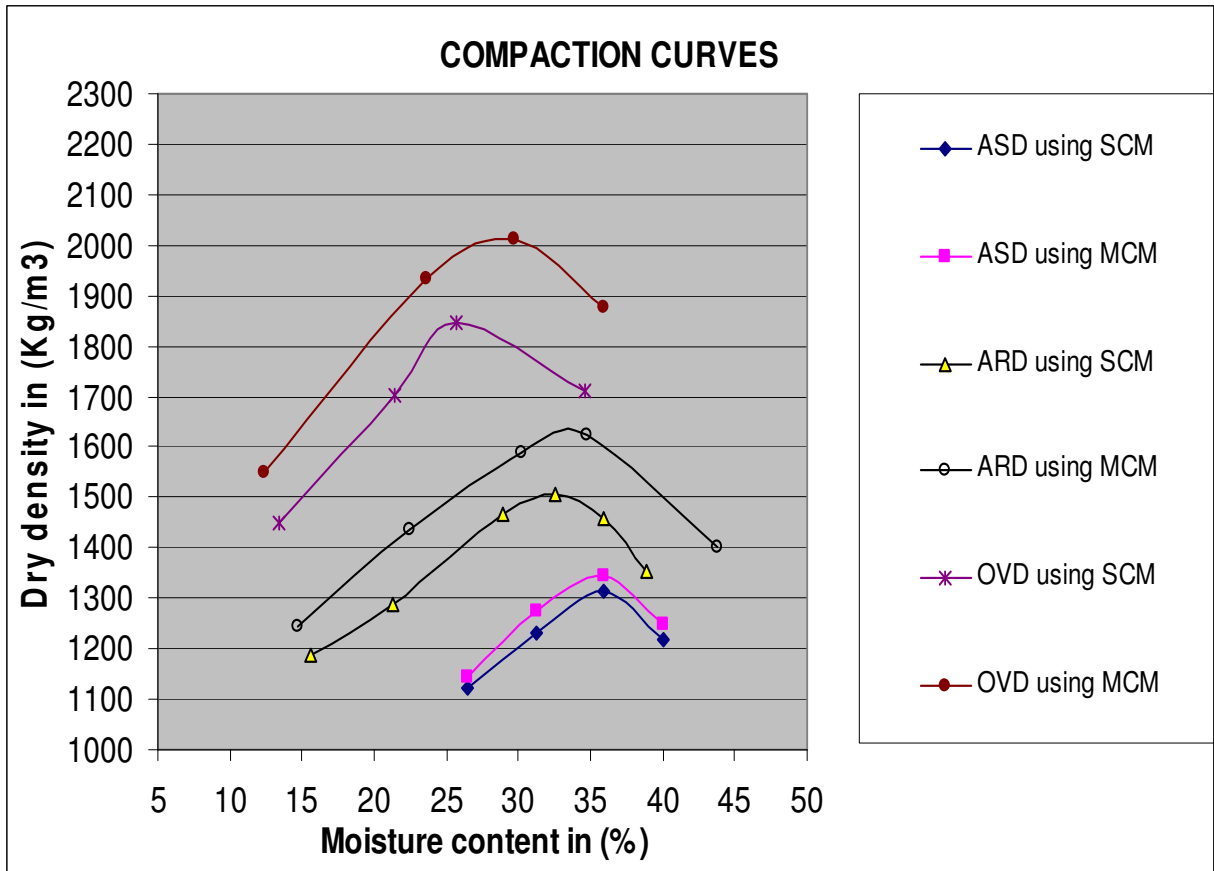


Fig. 4.1.2.3/3; The influence of compaction energy and drying on compaction characteristics of Lateritic soil, TP-1, (each point represents fresh sample).

4.2 Permeability of compacted soils

Permeability test using the variable head method has been done for the soil after compacting the soil sample using the MCM at varying moisture content and at the OMC .Different time after compacting the soil was used for testing. The tests have been done after saturating the samples.

4.2.1 Different moisture content

Permeability tests have been done at the drier (3%) of the optimum moisture content, at the wetter (3%) of the optimum moisture and at the optimum moisture content as indicated in Table 4.2.2/1. The test was done immediately after compaction.

4.2.2 Time effect after compaction

Permeability tests have been done after compacting the soil samples at optimum moisture content of each fresh samples and leaving the compacted soils, and permeability tests have been done after the indicated days shown in Table 4.2.2/1.

Table 4.2.2/1; Effect of time after compaction and moisture contents on permeability.

Location of sample	Depth (m)	Compacting Moisture content (%)	Average Coefficient of Permeability (cm/sec)	Time of testing after compacting (days)
TP-1	1	32.95	7.75E-05	0
		35.95	5.90E-06	0
		38.95	5.80E-05	0
		35.95	5.90E-06	0
		35.95	5.20E-06	7

		35.95	4.60E-06	15
		35.95	4.10E-06	29
		35.95	3.20E-06	55
	2	33.31	8.05E-05	0
		36.31	8.21E-06	0
		39.31	6.14E-05	0
	3	33.94	8.78 E-05	0
		36.94	1.14E-05	0
			7.14E-05	0

The test result has indicated that the soil compacted on the drier (of 3%) and wetter (of 3%) sides of the optimum moisture contents are more permeable than the soil compacted at optimum moisture content because the void space becomes more closer at the OMC. In addition to this, the permeability coefficient for wet compaction has been obtained to be slightly lower than that for dry compaction as shown in Figure 4.2.1/1 since the soil particles are more lubricated at the wetter side than the drier side of the OMC which leads to become closer and closer. Moreover, as the depth increases, the coefficient of permeability increases which indicates the cementation of the soil particles are not strong enough to overcome the passage of water through the soil particles as indicated in Fig.4.2.1/1.

Further, keeping the soil samples for a longer time after compaction decreases the permeability of the soil due to the binding nature of the soils and hence it hinders the passage of water through the particles of the soil as indicated in Fig.4.2.2/1.

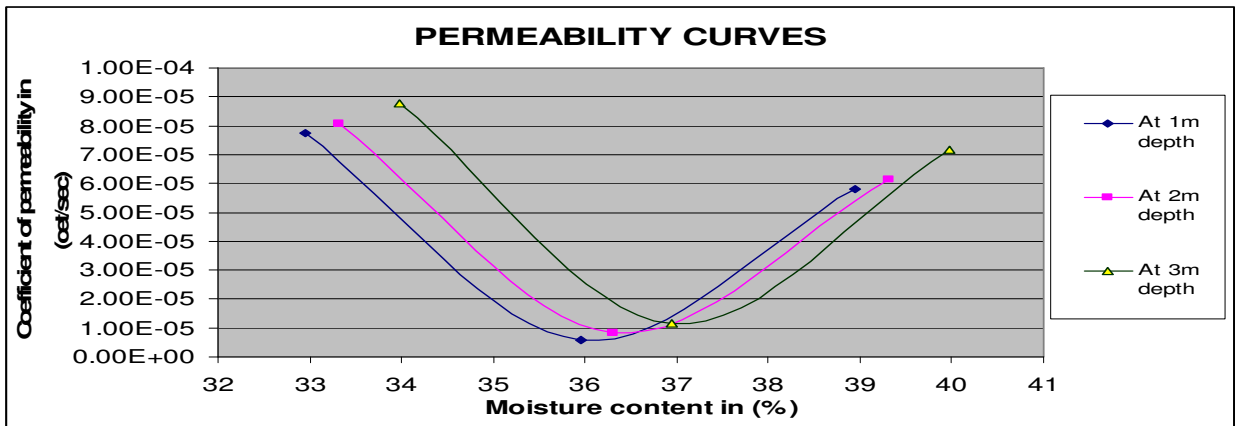


Fig.4.2.1/1;The influence of compaction moisture on the coefficient of permeability of compacted of lateritic soil, TP-1, each point represents fresh sample (ARS).

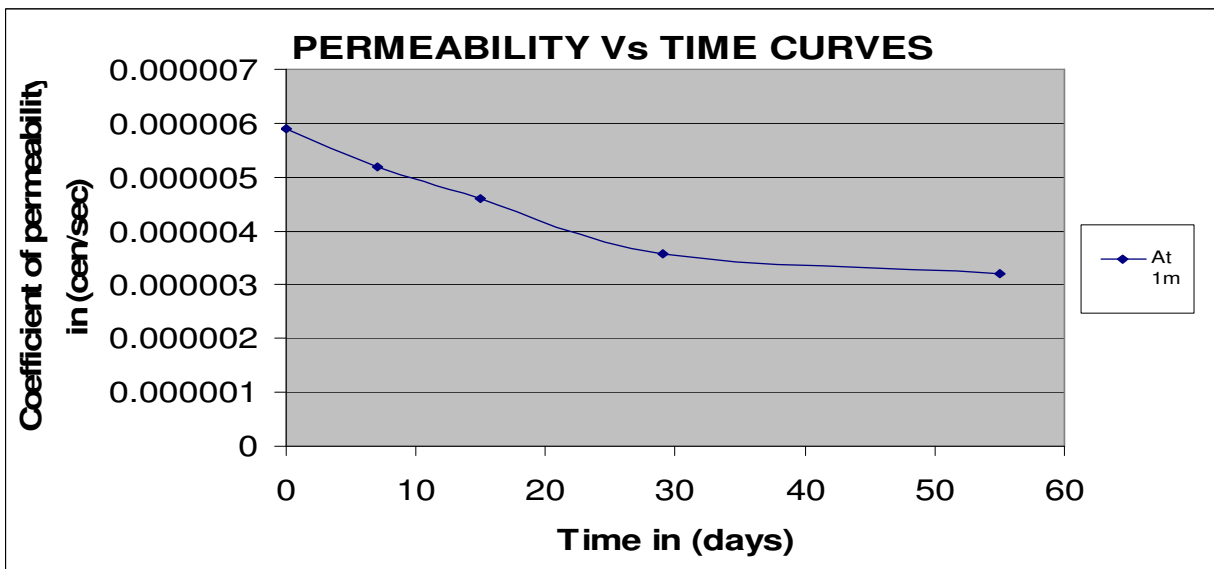


Fig.4.2.2/1;The influence of time after compaction (at OMC) on the coefficient of permeability of compacted lateritic soil , TP-1, each point represents fresh sample (ARS).

4.3 Unconfined compression strength tests

Unconfined compression strength (UCS) tests were carried out by compacting the soil using standard proctor compaction apparatus at different moisture contents and at different time after compacting the soil samples (at OMC).

The tests were carried out on cylindrical soil samples gradually loaded at its two ends until it was destroyed by brittle or plastic failure. The vertical compression of the sample was measured throughout the loading process, while the sample may deform laterally without confinement.

4.3.1 Different moisture content

Compaction tests have been made on samples compacted at optimum moisture content, at the drier (3% of OMC), and wetter (3% of OMC) sides of the optimum moisture content and results of the conducted tests are indicated in Table 4.3.1/1.

Table 4.3.1/1; Effect of compaction moisture on the unconfined compressive strength for fresh of ARD soil.

Location of sample	Depth (m)	Pre-treatment	Moisture content in (%)	UCS values in (Kpa)
TP-3	1	ARD	31.5	240.8
			34.5	332.75
			37.5	221
	3	ARD	28.05	326.9
			31.05	496.2
			34.05	301.52

TP-4	1	ARD	28.75	217.85
			31.75	295.41
			34.75	189.61
	1	ARS	29.84	198.53
			32.84	255.75
			35.84	187.5
	3	ARD	30.91	185.12
			33.91	235.09
			36.91	164.87
	3	ARS	31.05	174.4
			34.05	224.67
			37.05	154.9

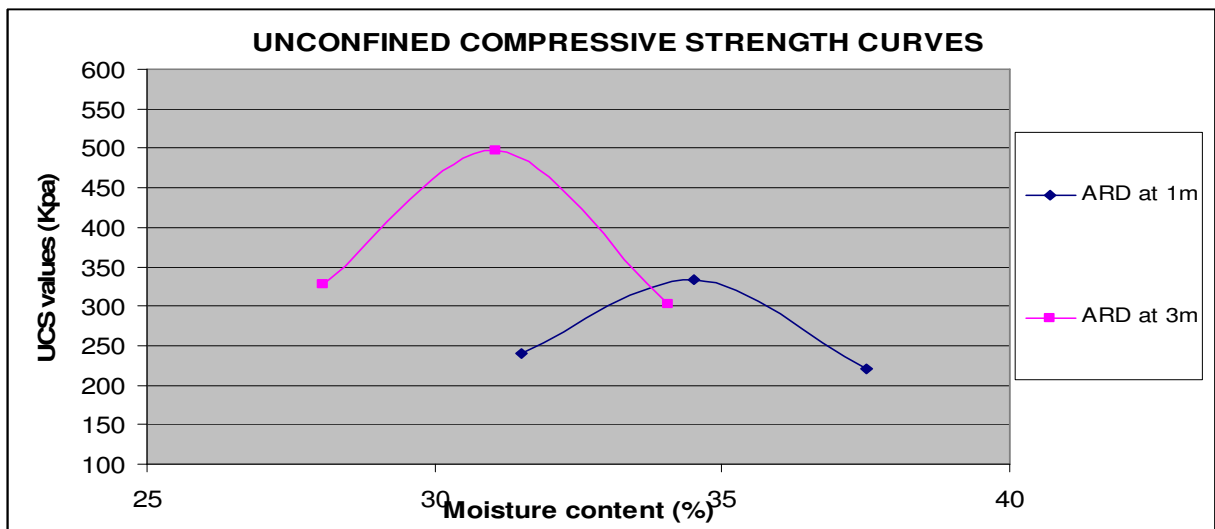


Fig. 4.3.1/1; The influence of moisture content on the UCS values of compacted soils of TP-3.

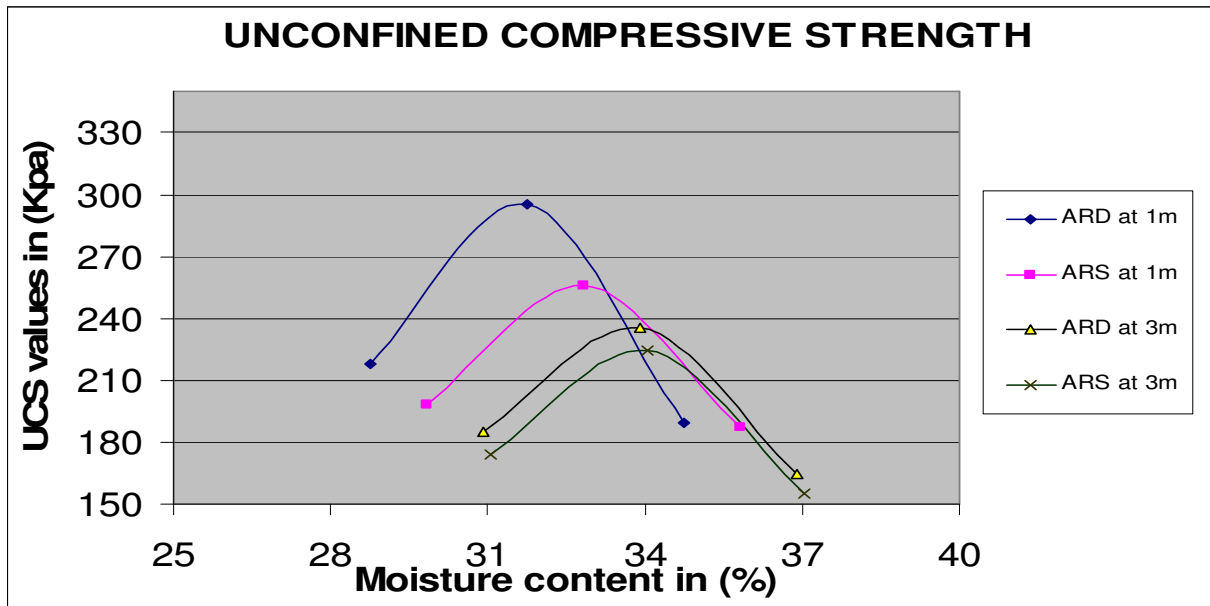


Fig. 4.3.1/2;The influence of moisture content on the UCS values of compacted lateritic soils, TP-4

From the above curves, we can see clearly the effect of degree of laterization at different depths on the value of the unconfined compressive strength of the lateritic soils. Accordingly, increases in UCS values are observed as the sample drying increases due to cementation of the soil particles.

The effect of UCS value at 1m is higher than that of 3m which indicates the existence of more cementation at 1m than 3m for TP-4 but the reverse is true for TP-3. In addition to this, the optimum moisture content shifts to the right for the soil which is less cemented.

4.3.2 Time effect after compaction

Tests have been conducted after compacting the soil samples at optimum moisture content of 35.95% for ARS and 32.56% for ARD. The soil samples were left for some time after compacting, and then unconfined compression strength tests have been done after the indicated days as shown in Table 4.3.2/1.

Table 4.3.2/1; the effect of time after compaction (at OMC using SCM) on the Unconfined Compressive Strength (UCS).

Axial deformation in (%)	Axial Stress in (Kpa)			
	ARS		ARD	
	at t=0	after t=20 days	t=0	after t=20 days
0	0	0	0	0
0.5	34.56	71.58	84.92	90.99
1	50.09	100.03	113.29	138.59
1.5	65.4	120.91	135.28	177.18
2	83.76	139.12	155.77	200.96
2.5	96.21	141.73	170.07	210.23
3	109.67	99.71	181.82	199.42
3.5	120.89	58.25	189.89	186.4
4	138.04	35.87	190.9	166.6
4.5	143.48	-	175.79	-
5	134.97	-	132.74	-
5.5	126.01	-		-

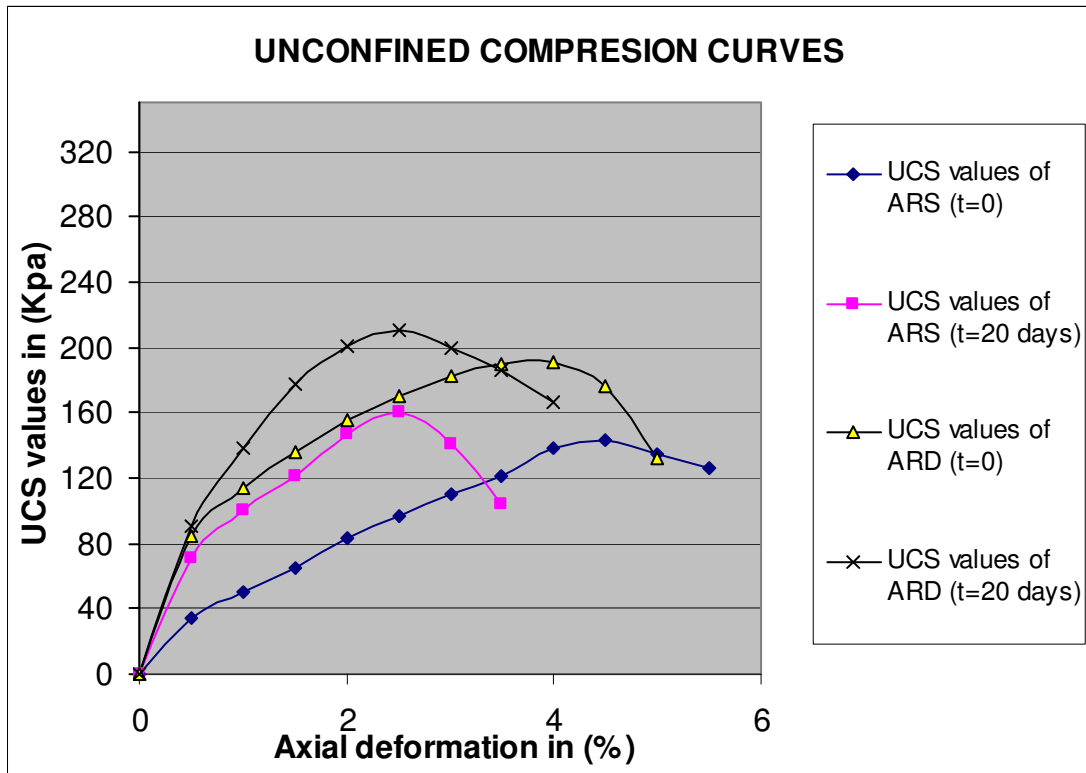


Fig.4.3.2/1;The influence of disturbance of samples and time after compaction keeping the compacting moisture content constant (at OMC) on the UCS values of compacted lateritic soil, TP-1 (in all cases fresh samples is used).

The test results indicated that moisture contents and time after compacting of the soil affects on the results of unconfined compressive strength of the lateritic soils of Assossa. In addition to this, Figure 4.3.2/1 showed that drying of the soil samples gave less strain (i.e. the soil becomes more brittle) due to loss of water and drying effect of lateritic soils.

4.3.3 Degree of sensitivity

Evidence of the effects of disturbance is manifested clearly in the results from Unconfined Compression Test (ASTM D-2166-72). The strength of an undisturbed soil is higher than that of the remolded clay.

Degree of sensitivity is the ratio of the compression strength of an undisturbed sample to that of the remolded sample.

Table 4.3.3/1; value of UCS and strain for both disturbed and undisturbed samples.

UCS values (KPa) of ARS compacted at 26.5%	0	33.41	54.34	70.67	85.96	100.8	113.1	119.45	101.1	87.11
UCS values(KPa) of undisturbed sample	0	92.84	145.21	198.7	243.98	289.76	305.82	270.5	231.1	
strain in (%)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5

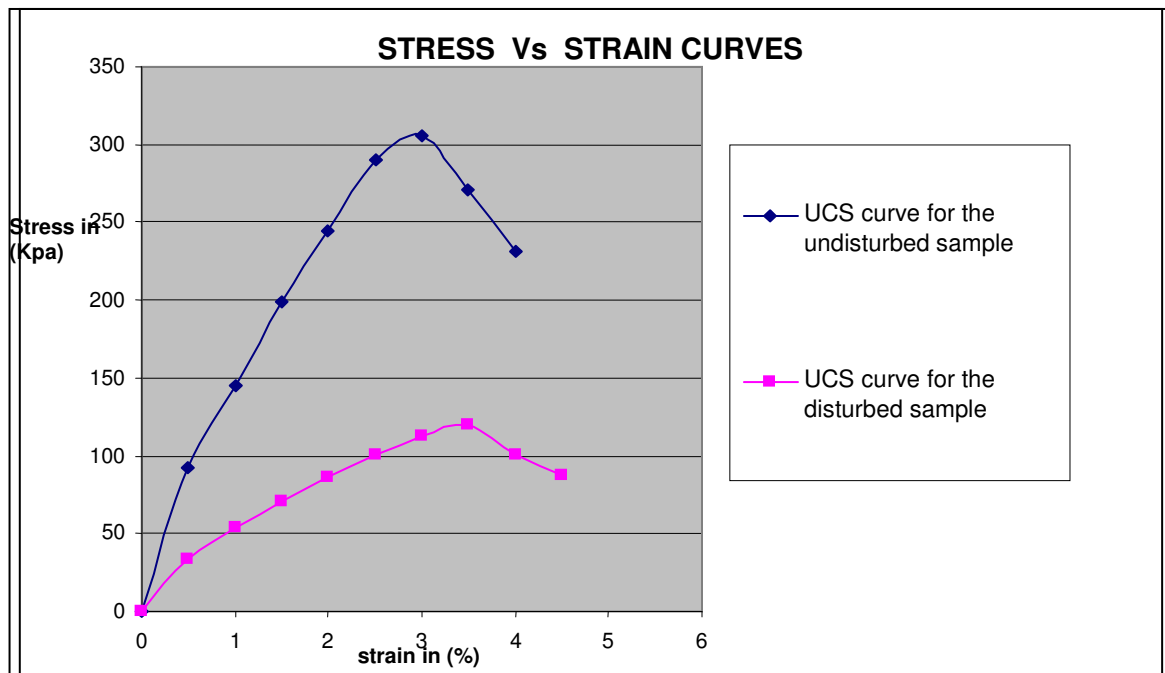


Fig.4.3.3/1; shows the influence of sample disturbance at a depth of 1m of TP-1.

Table 4.3.3/2: field and labalotory properties of dry density and UCS values. The

UCS values are taken from figure 4.3.3/1.

Items	Moisture content (%)	Dry density (Kg/m ³)	UCS values (Kpa)
Field test	26.5	1118.84	306
Laboratory test	26.5	1120.54	120

Then the sensitivity of the clay= $306/120 = 2.55$, from this, as the bondage increases, the sensitivity also increases.

4.4 Mineralogical and geochemical tests

4.4.1 Mineralogical tests

Mineralogy is the primary factor controlling the size, shape, and physical and chemical properties of soil mechanics. The most widely used technique to determine mineralogical composition is x-ray diffraction (XRD) (Mitchell, 1979). This test was done at the Geological Survey of Ethiopia.

Kaolinites formed of units consisting of single tetrahedral silica and a single octahedral alumina sheet. These units may repeat themselves indefinitely to form a lattice of the mineral (John N.Cernica, 1995).

Variation under the group is due to:

- The way layers are stacked above each other
- The position of Aluminum ions within the available sizes in the octahedral sheet.

The general chemical composition is expressed by the formula:



Kaolinite is the most abundant constituent of residual clay deposits. They are very stable, possess a tight cohesive structure that resists the penetration of water in to the lattices and hence are not subjected to expansion when saturated. Furthermore, the coefficient of internal friction is somewhat higher than that of most other clay minerals (as shown by Skempton, and Hunde).

Mineralogical test:

- General chemical composition:
- kaolinite= $(\text{OH})_8\text{Al}_4\text{Si}_4\text{O}_{10}$
 - Hallosites= $(\text{OH})_8\text{Al}_4\text{Si}_4\text{O}_{10}.4\text{H}_2\text{O}$
 - Ellite= $(\text{OH})_4\text{Ky}(\text{Al}_4\text{FeMg}_4)(\text{Si}_{8-y}\text{Al}_y)\text{O}_{20}$
 - Montmorillonite= $(\text{OH})_4\text{Al}_4\text{Si}_8\text{O}_{20}.n\text{H}_2\text{O}$

- Identified minerals

TP-1-1:	-Quartz low	(SiO ₂).....	(71.7%)
	-Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	(9.0%)
	-Dickite	Al ₂ Si ₂ O ₅ (OH) ₄	(10.1%)
	-Nacrite	Al ₂ Si ₂ O ₅ (OH) ₄	(10.1%)

TP-1-3:	- Quartz low	(SiO ₂).....	(61.1%)
---------	--------------	--------------------------	---------

	- Kaolinite	$\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$	(13.2%)
	- Dickite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	(9.6%)
	- Hematite	Fe_2O_3	(10.1%)
TP-3-1:	- Quartz low	(SiO_2)	(15.2%)
	- Dickite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	(45.2%)
	- Nacrite	$\text{Al}_2\text{Si}_2\text{O}_7(\text{H}_2\text{O})_2$	(39.5%)
TP-3-3:	- Quartz low	(SiO_2)	(17.5%)
	- Kaolinite	$\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$	(62.5%)
	- Hematite	Fe_2O_3	(16.5%)
	- Feldspar& others	$\text{Na}(\text{AlSiGe}_2\text{O}_8)$	(3.50%)
TP-4-1:	- Quartz low	(SiO_2)	(18.2%)
	- Kaolinite	$\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$	(64.7%)
	- Hematite	Fe_2O_3	(17.1%)
TP-4-3:	- Quartz low	(SiO_2)	(18.2%)
	- Kaolinite	$\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$	(64.7%)
	- Hematite	Fe_2O_3	(17.1%)

The three lower minerals are the dominant minerals as the X-ray diffraction test showed but there is a small amount of Feldspar. In general, the samples are clay minerals with the dominant of the Kaolinite mineral as the laboratory test indicated. Further, the red color of the soil is due to the presence of Hematite.

Furthermore, the activity of the clay sample is less than 0.5 as shown in section 3.2.1 of Table 3.2.1/1(this is similar to Skempton's analysis of kaolinite which their activity is less than 0.5) as shown by John N.Cernica (1995).

4.4.2 Geochemical tests

Geochemical (Oxide) Tests are carried out to know quantitatively main Oxides of the soil material. The Oxides and Hydroxides of Aluminum, Iron and Silicon are of greatest interest

since they are the ones most frequently encountered. Iron and Aluminum Oxides coat mineral particles, or cement particles of soils together. They may also occur as distinct crystalline units, such as Hematite, Gibbsite and Magnetite (Mitchell, 1976). Geochemical tests were carried out at Geological Survey of Ethiopia Geochemical Laboratory. To obtain the percentage Oxide composition of the soils under investigation Atomic Absorption Spectrometer and Colorometer Analysis methods were used. The test results are shown in Table 4.4.2/1.

The degree of laterization of the soil samples can be evaluated based on silica-sesquioxides ($\text{SiO}_2/\text{R}_2\text{O}_3$) ratio. The Sesquioxide, designated as R_2O_3 , is the combination of Aluminum Oxide (Al_2O_3) and Iron oxide (Fe_2O_3). The chemical formula SiO_2 designates the Silica. Accordingly unlaterized soils have ($\text{SiO}_2/\text{R}_2\text{O}_3$) ratio greater than 2. For lateritic soils ($\text{SiO}_2/\text{R}_2\text{O}_3$) ratio lie between 1.33 and 2 and for true laterites the ratio is less than 1.33 except for the 3m depth of TP-2.

The test results shown in Table 4.4.2/1 shows that the soils under investigation have ($\text{SiO}_2/\text{R}_2\text{O}_3$) ratio below 1.33. This indicates that the soils are true laterites. True laterites are simply referred as laterites, which are highly laterized as shown by Blight (1997).

Table 4.4.2/1; Oxide Composition in Percent

designation	depth (m)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	caO	MgO	Na ₂ O	K ₂ O	MnO	H ₂ O	LOI	TiO ₂	P ₂ O ₅	SiO ₂ /R ₂ O ₃
TP-2	1m	48.57	25.00	11.44	0.25	0.18	< 0.01	0.19	0.03	0.68	11.02	1.16	0.10	1.33
	3m	50.30	24.18	12.28	< 0.01	0.10	< 0.01	0.19	0.05	0.54	10.20	0.91	0.04	1.38
TP-3	1m	42.89	26.62	13.49	< 0.01	0.36	< 0.01	0.21	0.05	0.83	12.13	1.87	0.10	1.07
	3m	28.26	29.41	25.30	< 0.01	0.05	< 0.01	0.08	0.06	0.30	14.96	0.96	0.07	0.52
TP-5	1m	46.17	25.32	11.21	0.08	0.43	< 0.01	0.38	0.04	1.03	11.99	1.76	0.10	1.26
	3m	46.97	25.72	10.98	< 0.01	0.30	< 0.01	0.38	0.04	0.52	11.53	1.95	0.12	1.28

5. Discussions

The results in this thesis work are reanalyzed and discussed as follows:

The observed soil is a red clay soil due to the presence of iron oxide, which is one of the sesquioxides, and it is insoluble in water. The geochemical tests (oxide analysis) indicated that the observed soil samples are true lateritic soils except TP-2 at a depth of 3m. Furthermore, the X-ray diffraction shows the minerals are Quartz (low), Nacrite and Dickite. The classification methods for the soils should be supported by Wesley Mineralogical classification for such tropical soils. The activity of the soils is less than 0.7, which indicates that the sample is inactive to swelling whenever there is fluctuation of moisture. Furthermore, the test result indicated that the free swell is less than 30 %, which is less sensitive to expansion (Teffer A. and Leikun M.). In general, the soil has strong mineralogical influence derived from residual soils having the nature of cementation due to the presence of Iron and Aluminium Oxides (group C sub-group c, based on Wesley Mineralogical Classification).

Based on Atterberg Limit and grain size distribution test results, the soil under investigation has been classified as clay as the percent finer of the soil is greater than 50%. Results indicated that the higher the dryness of the soil, the higher the effect on the dry density and the optimum moisture content would be. This statement has a direct relation with the geochemical test results (oxide analysis). This behaviour is due to the cementation nature of the Sesquioxides in the soil. The Sesquioxides cement the soil particles together resulting in stiff soil aggregation and reduce the permeability due to the cementation of the soil particles. Further, the shear strength and UCS values increased as indicated in the literature and as confirmed in the tests. It has been observed that the geotechnical properties of such soils can be properly described if mineralogical classification is used to support the conventional classification systems.

Compaction tests were done at different depths of the soil profile (i.e. at a depth of 1m, 2m, and 3m). The result indicated that as the depth of the soil profile increases, the maximum dry density decreases except for TP-3 and TP-4 due to the mineralogical content of the soil, which leads to the concept of degree of laterization. In addition to this, the optimum moisture content shifts to the right as cementation decreases for TP-1, 2 & 5. The changes of the above result depend on the amount of the cementing agents (Sesquioxids) and this is internally affected by drying and compaction efforts. The result indicated that an increase in compaction energy, increase the maximum dry density for a given borrow test pit as shown in Fig. 4.1.2.3/1,2 and 3; hence the compaction characteristics of lateritic soils will be very dependent on the method of applying the compactive energy. It is impossible to attain maximum dry density and optimum moisture content for soils which have higher in-situ moisture content than the optimum moisture content of the soil as shown in Fig. 4.1.2.1/2 and 5.

Method of sample preparation (pre-treatment conditions) during compaction has been obtained to have an influence on the maximum dry density and optimum moisture content of the lateritic soil (as received, dry and oven dry soils). In general, sample preparation for laboratory compaction tests should resemble the conditions prevailing in the field. The observation from the tests indicated that different pre-treatment conditions of the soil samples before testing have different values. For example, test results of the optimum moisture content (OMC) and the maximum dry density (MDD) have different values when the sample is as received (ARS), air dried (ARD) and oven dried (OVD) (i.e. as drying of the soil sample increases, a significant increase in MDD and a decrease in the OMC due to the cementation nature of the soils). Further, recompacting the soil increases both the MDD and OMC by rearranging the soil particles and breaking the bonds of cementation which further allow the entrance of water into the soil particles to have more water in the soil particles. Hence, the tests in the laboratory should prevail the conditions in the field in order to minimize the error of prediction on the engineering properties of the soils from these test results.

In the UCS tests, the varying moisture contents and the time effect after compaction has got an influence on the strength of the soils. The conducted test results showed that a decrease in the UCS values on the drier and wetter side of the OMC as the void ratio is minimum at the OMC, which leads to high contact between soil grains. In addition to this, values of UCS has been observed to increase as the time after compaction increases due to the cementation nature of the soil particles which leads to an increase in internal friction. Further, the brittleness of the soil gets more and more as the soil becomes drier and drier; hence the soil will be more sensitive to changes on their properties (i.e. the more brittle (in the pre-treatment condition) the soil, the higher the effect on breaking of the bonded particles due to the compaction energy). Furthermore, the clays are more sensitive to disturbance as shown in Table 4.3.3/1 as compaction affects the cementation of the soil particles.

As the time increases after compaction, the coefficient of permeability decreases because of the cementation nature of the soils due to the presence of Sesquioxids (cementing agents). Furthermore, the conducted test indicated that the coefficient of permeability was higher at the OMC as there minimum void ratio at the optimum moisture content.

XRD analysis shows, the soil is highly composed of the Kaolinite mineral group, which is responsible for less expansiveness of the soil. Further, it contains the Hematite mineral, which gives rise to the red colour of the soil.

According to Wesley's Mineralogical Classification, the soil samples fit in to group C subgroup c , that is, residual soil with a strong mineralogical influence driving from special clay minerals only found in residual soils, namely Sesquioxides. The Aluminium and Iron Oxide content of these soils is of a considerable magnitude and hence can influence the property of these soils.

6. Conclusions and Recommendations

6.1 Conclusions

Based on the test results carried out the following conclusions are drawn.

1. Geochemical test result reviewed that soil under investigation is a true lateritic soil except TP-2 at a depth of 3m. Wesley Mineralogical Classification should support the conventional classification methods for such tropical soils. As per to this classification, the soil has strong mineralogical influence derived from residual soils having the nature of cementation due to the presence of Iron and Aluminium Oxides (group C sub-group c).
2. The activity of the soil is less than 0.7; hence, the soil is less sensitive to swelling. Further the free swell test results shows less than 30% which indicates the soil is less sensitive to expansion as fluctuation of water exists.
3. Regardless of their position on the plasticity chart, the soils do have high strength and good as fill materials even if their clay content is above 50%. Therefore, such materials should not be discarded based on their position on the plasticity chart.
4. Methods of sample preparation during compaction have been obtained to have an influence on the maximum dry densities and optimum moisture contents. Therefore, there must be resemblance of the tests in the laboratory with the conditions prevailing in the field.
5. Compaction energy has strong effect in breaking of the cemented soil particles which are not fully matured like in the case of pre-treatment conditions (ARS, ARD and OVD). This is because, in the pre-treatment conditions, the cementation nature of the Sesquioxides (cementing agents) are too weak enough to be broken by the energy. Further, increasing in

compaction energy increases the effect in breaking of the cementation of the soil particles which have weak cementation like in the pre-matured laterization (in the case of pre-treatment conditions).

6. Drying of the soil before the test has a great influence in the compaction characteristics of these soils. The more drier the soil, the higher the dry densities but the lesser the optimum moisture content since cementation and mineralogy content of the soil affect on these values.
7. Keeping the compacted soil for longer time decreases the permeability of the soil because the cementing agents increase in binding the soil particles; hence, reducing the passage of water through the soil particles. In addition to this, soils compacted on the drier or wetter side of the optimum moisture content would lead to higher values of coefficient of permeability with slight increase on the drier side as compared to the wetter side since the void ratio is minimum at the optimum moisture content. Therefore, immediate contact of water and dry compaction should be avoided to minimize the effect of internal erosion and seepage flows for such soils.
8. For the soils investigated, compaction moisture and time effect after compaction has been obtained to influence the values of the UCS significantly. Accordingly, a decrease in UCS was observed as the moisture content is away from the optimum moisture content in both sides. Further, time after compaction increases, the UCS values have been observed to increase. The soil strain gets smaller and smaller as the soil gets drier and drier; hence more attention has to be given for brittle nature of the soils in the case of compaction effort. Further, the soil is highly sensitive to disturbance during extraction, handling and testing phases.
9. The observations at the site during sampling and the chemical test shows the soil has red in colour.

6.2 Recommendations:

- After compaction of the soils, the time elapsed (taken) to recover their behaviour before compaction has to be investigated.
- The compaction properties of the lateritic soils has to be investigated by lowering the temperature instead of using the oven drying in determining the moisture contents of the soils which are going to compacted.
- Further investigation has to be carried out to consolidate the results obtained in this work by taking a soil of only one generic type with a number of tests and locality at a time, and by deeply focusing on specific aspect of the problem so that definite conclusions can be made for each type of soil. Afterwards, the results may be combined to establish appropriate guidelines.

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APPENDIX

Specifications of Proctor for different compaction energy

Table A/1: shown below is a summary of different compaction energy used during soil grain crushing analysis by different compaction methods and varying number of blows. Note that modified proctors were amended by changing only number of blows from 56 to 10, 30 and 65.

TableA /1: Compaction Efforts of different proctor specifications.

Item	Specifications of Proctor Compaction			
	Standard	Modified	Modified	Modified
Volume of mold, (cm ³)	1000	2325	2325	2325
Mass of hammer, (kg)	2.495	4.535	4.535	4.535
Height of drop of the hammer, (mm)	304.8	457.2	457.2	457.2
Number of hammer blows per layer of soil	25	10	30	65
Number of layers of compaction	3	5	5	5
Energy of compaction, (kilojoules/m ³)	560	437	1312	2843

Table A/2: Adopted standards Related to Optimum Density-Water content Test

Test method			hammer		mould		Blows	energy
	ASTM	AASHTO	Weight (Kg)	Fall (mm)	Volume(m ³)	layers	Per layer	Per test (KJ/m ³)
Standard proctor	D-698-78	T-99	2.49	305	9.44*10 ⁻⁶	3	25	592
Modifid proctor	D1557 -78	T-180	4.54	457	9.44*10 ⁻⁶	5	25	2695

