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Effects of water content on the strength and deformation characteristics of a heavily compacted lateritic soil

Effet de la teneur en eau sur les caractéristiques de résistance et de déformation d'un sol latéritique fortement compacté

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ABSTRACT: Earth structures require embankment fills. Lateritic soils are often used for embankment fills in the tropical region of the world. The embankment fills are placed by compaction at the optimum moisture content in order to achieve the maximum dry density as per project specifications. However, their behaviour during compaction is not well understood. In the field the moisture content can deviate from the optimum value as a result of improper supervision or weather conditions. This study looks at the effects varied moisture contents have on the shear and deformation properties of a heavily compacted lateritic soil. The effects of effective confining stress were also considered. Lateritic soils were prepared at 85%, 100% and 110% of optimum moisture content. Consolidated undrained triaxial compression test were carried out on the samples. The effective confining stresses applied were varied from 20kPa to 200kPa. The data obtained were analysed to determine the stress-strain behaviour, the excess pore pressure, effective apparent cohesion (c'), and effective friction angle (ϕ'). Stress paths and critical state analysis were carried out and discussed.

RÉSUMÉ : Les structures en terre nécessitent des remblais. Les sols latéritiques sont souvent utilisés pour les remblais dans les régions tropicales du monde. Les remblais sont placés par compactage à la teneur en humidité optimale afin d'atteindre la densité sèche maximale selon les spécifications du projet. Cependant, leur comportement lors du compactage n'est pas bien compris. Sur le terrain, la teneur en humidité peut s'écarter de la valeur optimale en raison d'une mauvaise surveillance ou de conditions météorologiques. Cette étude a examiné l'effet de diverses teneurs en humidité sur les propriétés de cisaillement et de déformation d'un sol latéritique fortement compacté ainsi que l'effet d'une contrainte de confinement efficace. Des sols latéritiques ont été préparés à 85 %, 100 % et 110 % d'humidité optimale. Des essais de compression triaxiale consolidée non drainée ont été effectués sur les échantillons. Les contraintes de confinement effectives appliquées variaient de 20 kPa à 200 kPa. Les données obtenues ont été analysées pour déterminer le comportement contrainte-déformation, la surpression interstitielle, la cohésion apparente effective (c') et l'angle de frottement effectif (ϕ'). Les chemins de contraintes et l'analyse des états critiques ont été effectués et discutés

KEYWORDS: lateritic soil, compressibility, shear strength, triaxial compression, heavy compaction

1 INTRODUCTION

Ghana, just like other developing countries has seen the need for resilient civil engineering infrastructures to facilitate economic development growth. Such infrastructures include roads and earth dams that require embankments. Lateritic soils are the most abundant soils found in this part of the world and are used for embankment fills. Lateritic soils are defined as highly weathered materials that are rich in iron and aluminum oxides or sesquioxides (Alexander & Cady 1963). Formation of laterites and lateritic soils start with the chemical weathering of the parent rock in- situ followed by the leaching out of silica and bases (Lyon, 1971, Gidigasu 1972, Gidigasu, 1976). Laterites and lateritic soilsdevelops a bonded structure (Kemp and Pierce, 1995).

The embankment fills are placed by compaction at optimum moisture content in order to achieve the maximum dry density according to project specifications. A well compaction improves the strength and compressibility properties of the soil. On the field, there may be moisture content variations as a result of improper supervision or weather conditions although the maximum dry density may have been achieved. The dry density and moisture content of soils can influence the mode of failure of soils to an extent in terms of critical state (Stafford 1981). The shear parameters at peak are affected by the initial density and the fabric of the soil (Wood 1990). Interestingly, a lot of research has been conducted to understand the strength behavior of lateritic soils (Lohnes & Demirel 1973, Ogunsanwo 1989, Futai 2004, Ng et al. 2019) but research on the structure induced by compaction water content influences the compressibility behavior of lateritic soil has not received much attention.

This paper seeks to understand the compressibility and shear behavior of lateritic soils prepared at a constant dry density when compacted at the wet side of optimum moisture content, the optimum moisture content and the dry side of optimum moisture content. The critical state framework (Roscoe et al, 1958, Roscoe & Burland 1968) can be used to understand the behavior of lateritic soils. Also, critical state characteristics of soils have been reliable in predicting the drained and undrained behaviour of some soils (Phan et al, 2016)

2 MATERIALS AND METHODS

2.1 *Soil sampling and characterization*

The soil used in the study were obtained from KNUST Campus, latitude, 6.66960693 and longitude, -1.56533553 in the Ashanti region, Ghana. The aerial view showing the location of soil sampling (yellow pin) is shown in Figure 1.

The physical properties of soil samples were determined according to the BSI 1377 (BSI 1990). Figure *2* shows the particle size distribution curve of the studied soil. The soil properties are summarized in Table 1. According to the unified soil classification system the soil is classified as sandy clay of high plasticity (CH).

Figure 1. Aerial view of the location where samples were taken from.

Table 1. Soil Properties

Properties	Lateritic soil
Grain size distribution	
Percentage of gravel: %	7
Percentage of sand: %	38
Percentage of silt: %	12
Percentage of clay: %	43
Atterberg limits	
Liquid limit: %	53
Plastic limit: %	19
Plasticity index: %	34
Specific gravity	2.65
Proctor Compaction	
Maximum dry density: Mg/cc	1.72
Optimum water content: %	18.29

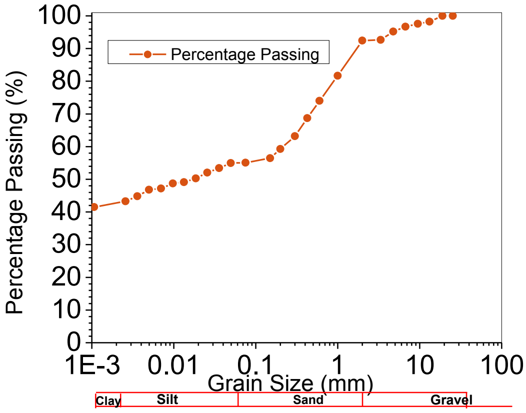

Figure 2. Particle size distribution curve

2.2 *Sample Preparation*

For each moisture content, 6 soil specimens were prepared including; adding the required moisture content and then curing them for isotropic compression and undrained (triaxial shear) tests. The soil specimen were recompacted in the standard proctor compaction mould with dimensions 101.6mm diameter and a height of 127mm, with a rammer weight of 2.5kg. Compaction iteration using the three-point compaction method was done for each moisture content in order to determine the number of blows needed to achieve the target dry density of 1.72Mg/cc; 85 number of blows for 85% of OMC (dry side of optimum), 25 number of blows for 100% of OMC (optimum) and 34 number of blows for 110% of OMC (wet side of optimum).

2.3 *Test Program*

The triaxial equipment was used to carry out the studies. At each point of moisture content, effective confining pressures of 20kPa, 50kPa, 75kPa, 100kPa, 150kPa and 200kPa were applied on the 18 individual specimen saturated to a minimum B-value of 95% at rate of 0.07mm/min. This was done to study the deformation and the strength characteristics of the soil at the varied compaction moisture content and hence compared.

3 DISCUSSION OF RESULTS

3.1 *Effect of water content variation on the compressibility.*

Figure 3 shows the isotropic compression behavior of the recompacted lateritic soil at 85% of OMC, 100% of OMC and 110% of OMC respectively. Linear regression at higher confidence interval were used to obtain the slope (λ) of the NCL.

The slope (λ) obtained were, 0.09, 0.10, and 0.13 at 85%, 100% and 110% of OMC respectively as shown in Figure 4. This indicates that the soil is more compressible at the wet side of optimum (110% of OMC) than at the dry of optimum (85 of OMC). The high compressibility behavior at the 110% of OMC may be attributed to the fact that the soil matrix had more moisture content and hence more excess pore pressure dissipating. The lowest compressibility at 85% of OMC may be attributed to the fact that the soil matrix had the least moisture content and therefore less excess pore pressure dissipating from the soil.

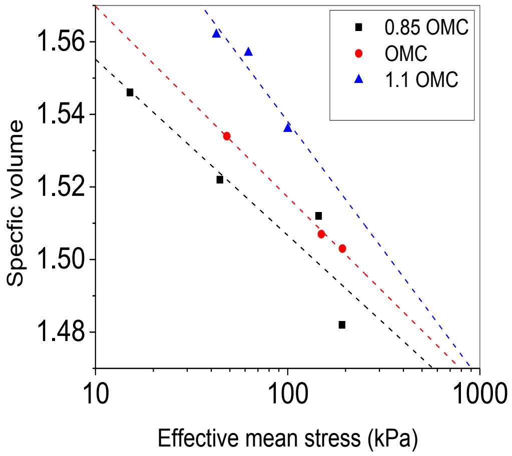

Figure 3. Isotropic compression behavior

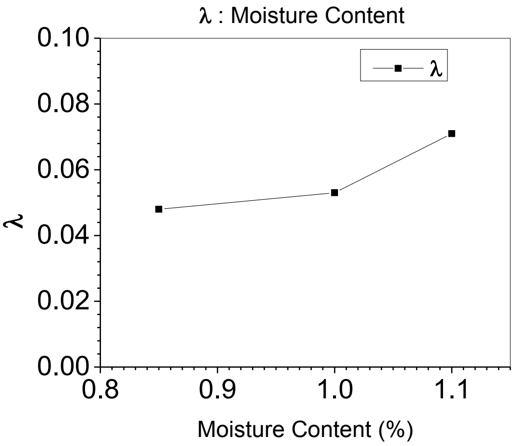

Figure 4. Effect of moisture content variation on the λ of the NCL

3.2 *Effect of water content variation on the stress-strain and excess pore pressure response*

Figure 5(a) illustrates the typical stress-strain behavior obtained of the lateritic soils specimen recompacted at 85% of OMC, 100% of OMC and 110% of OMC. The result for 85% of OMC and

100% of OMC show a strain hardening behavior at high confining stresses and strain softening behavior at low confining stresses. However at the 110% of OMC both high and low effective confining stresses exhibited strain softening behavior. Each soil specimen did not have well defined peak deviator stress and loading was up to 25% strain. The deviator stresses were highest at 85% of OMC and lowest at 110% of OMC.

In the Figure 5(b) the excess pressures response showed that the soil specimen contracts till it reaches a peak value at smaller strains and tries to dilate but it is not allowed so the pore pressures becomes negative. Based on this phenomenon all the soil specimen can be termed as overconsolidated soils. Also from Figure 5(b) the excess pore pressures generated are with increasing moisture content and increasing effective confining stress.

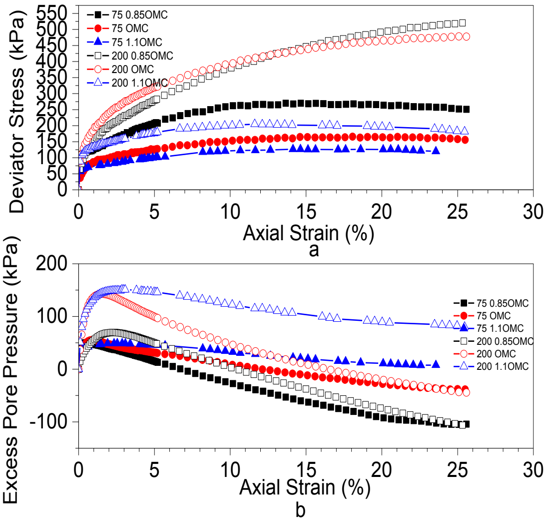

Figure 5. Undrained tests at confining stress of 75kPa and 200kPa for varying moisture content. a) The deviator stress curve b) The pore pressure curve.

3.3 *Effect of water content variation on the stress paths*

The Figure 6 shows the stress path on the q':p' plane for the varying moisture content. There were two phase transformations for soil specimen. The face transformation can be explained that the soil specimen initially contracts or the effective mean pressures reduces and then eventually start increasing or dilating. The results obtained are similar to the lateritic soil reported by Ng et al. (2019). They attributed the initial contraction behavior to the collapse of inter-aggregate pores and the dilative behavior due to the rearrangement and interlocking of large size aggregates. The recompacted soils at 85% of OMC had higher than the soils recompacted at 100% of OMC and those recompacted at 110% of OMC.

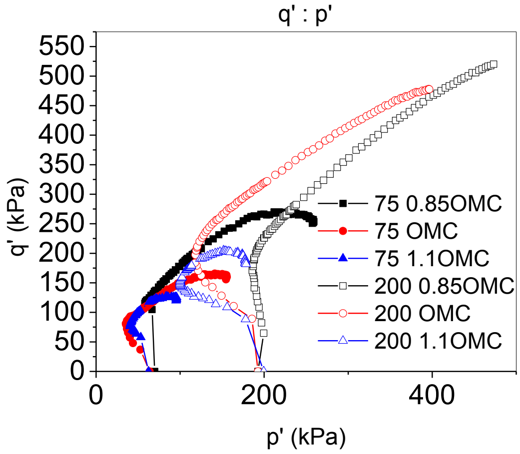

Figure 6. Stress paths at varying moisture content for 75kPa and 200kPa

3.4 *Effect of water content variation on the strength parameters, c' & ϕ'*

The strength parameters c' and ϕ' were determined according to low effective confining stresses (20kPa, 50kPa, 75kPa) and high effective confining stresses (100kPa, 150kPa, 200kPa). The effect of cohesion and friction angle at low effective confining stresses was not well-defined with increasing moisture content as shown in Figure 7. However, at high effective confining stresses the friction angle increased with an increase in moisture content and the cohesion decreased with an increase in moisture content as shown in Figure 8.

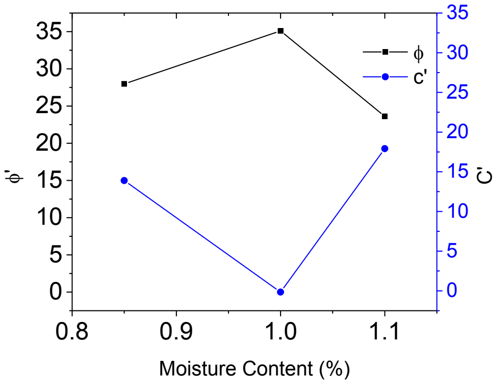

Figure 7. Effect of moisture content variation on the c' & ϕ' at low effective confining stress

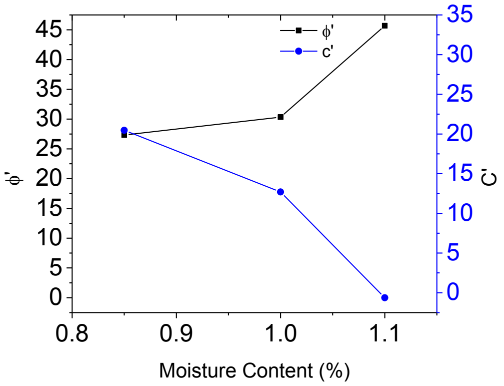

Figure 8. Effect of moisture content variation on the c' & ϕ at high effective confining stress

3.5 *Effect of water content variation on the critical state line*

The critical state stress state at each moisture content point were determined in the q':p' plane as shown in the Figure 9. The slope of the critical state line was,1.20, 1.25, 1.28 at 85% of OMC, 100% of OMC and 110% of OMC respectively and shown in Figure 10. The critical state internal angle of friction, ϕ_{cs}' that corresponds to the M values obtained are 30° at 85% of OMC, 31° at 100% of OMC and 32° at 110% of OMC as seen in Figure 11. The behavior can be explained by the stress paths obtained in Figure 6. From Figure *6*, it can be seen that at 110% of OMC the soil specimen exhibited dilation for all soil specimen and at 85% of OMC at high effective confining stress they were least dilative.

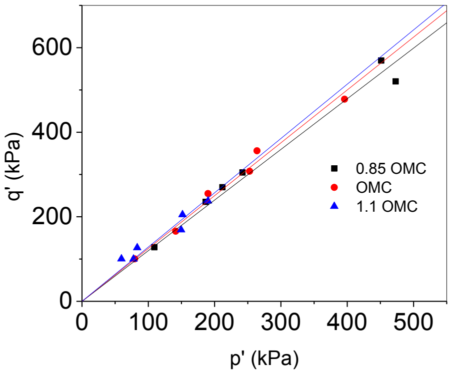

Figure 9. Critical state lines at 85% of OMC, 100% of OMC and 110% of OMC

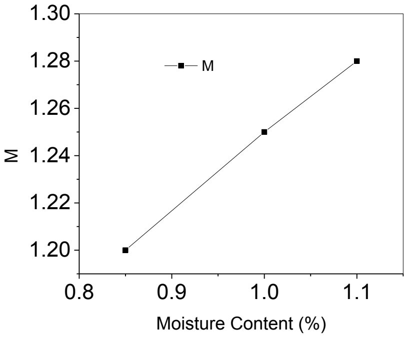

Figure 10. Effect of moisture content variation on the M

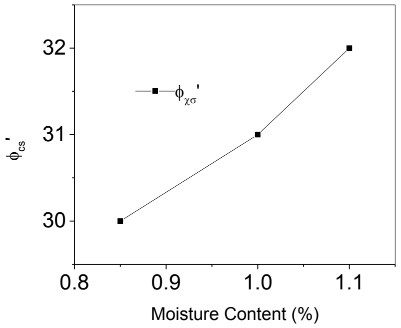

Figure 11. Effect of moisture content variation on the ϕ_{cs}'

4 CONCLUSIONS

The research program looked at the effect of varying moisture content on the compressibility and shear behavior of a heavily compacted lateritic soil. Based on the results obtained, the lateritic soil recompacted at the dry side of optimum moisture content exhibited the least compressible behavior. This was due to the fact that its soil matrix had the least moisture and therefore not much excess pore pressure dissipated. On the wet side of optimum moisture content, the soil was most compressible because the soil matrix had more moisture content and hence more excess pore pressure was dissipated.

All the soil specimen developed negative excess pore pressures during shearing. The stress paths for each soil had a two phase transformation where the soil initially contracts and then eventually starts dilating. The recompacted soil specimen at the wet side of optimum exhibited a more dilating behavior whereas at the dry of optimum and optimum moisture this behavior was exhibited only at low effective confining stresses. Therefore critical state internal angle of friction ,ϕ_{cs} increased with an increasing moisture content and similarly the angle of internal friction ϕ' behaved the same way when the recompacted soil specimen were subjected to high effective confining stresses. The cohesion, c at high effective confining pressure decreased with an increasing moisture content however no clear trend was observed at low effective confining pressure

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6 REFERENCES

Alexander LT, Cady JG (1962) Genesis and hardening of laterite in soils, vol 128. U.S. Department of Agriculture Technical Bulletin, New York.

BSI (1990) BS 1377: Methods of test for soils for civil engineering purposes. BSI, London, UK.

Futai M.M, Almeida MSS, Lacerda WA (2004) Yield, strength, and critical state behavior of a tropical saturated soil. J Geotech Geoenviron Eng 130(11):1169–1179.

Gidigasu MD. In: Laterite Soil Engineering: Pedogenesis and Engineering Principles. Developments in Geotechnical Engineering 1976;vol. 9. Amsterdam: Elsevier; 1976.

Gidigasu, M. D. (1972) 'Mode of formation and geotechnical characteristics of laterite materials of Ghana in relation to soil forming factors', *Engineering Geology*, 6(2), pp. 79-150. doi: 10.1016/0013-7952(72)90034-8.

Kemp S. J. and Pierce J. M. 1995, Mineralogical and petrographic analysis of tropical red clay soils British Geological Survey Technical Report No, WG/95/2R.

Lohnes, R.A. and Demirel, T., 1973. Strength and structure of laterites and lateritic soils. *Engineering Geology*. 7:13 33

Lyon Associates Inc. and BRRI, 1971, Laterite and lateritic soils and other problem soils of Africa, An Engineering Study for Agency for International Development AID/esd-2164, Kumasi Ghana

Ng C. W. W., Akinniyi DB, Zhou C, Chiu CF (2019) 'Comparisons of weathered lateritic, granitic and volcanic soils: compressibility and shear strength', *Engineering Geol*ogy, 249(December 2018), pp. 235-240. doi: 10.1016/j.engge.2018.12.029.

Ogunsanwo, O. (1989) 'Some geotechnical properties of two laterite soils compacted at different energies', *Engineering Geology*, 26(3), pp. 261–269. doi: 10.1016/0013-7952(89)90013-6.

Phan VT, Hsiab D and Nguyen PT (2016) Critical state line and state parameter of sand fines mixtures. Procedia Engineering 142: 299–306, https//doi.org/10.1016/ j.proeng.2016.02.045.

Roscoe, K.H., Burland, J.B., 1968. On the generalized stress-strain behavior of wet clay. In: Engineering Plasticity. Cambridge University press, pp. 535–609

Roscoe, K.H., Schofield, A.N., Wroth, C.P., 1958. On the yielding of soils. Géotechnique 8 (4), 22–53..

Stafford JV (1981) An application of critical state soil mechanics: the performance of rigid times. Journal of Agricultural Engineering Research 26(5): 387–401, https://doi.org/10.1016/0021-8634(81) 90115-3.

Wood, D.M., 1990. Soil Behavior and Critical State Soil Mechanics. Cambridge University Press.