Technoscience Journal for Community Development in Africa 2:1 (2021) 109–120
ISSN 2659-0573

Research Article

Mineralogy and collapse behaviour of compacted lateritic soils from North-central Nigeria

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Abstract: There is limited knowledge about the collapse behaviour of lateritic residual soils, particularly those from humid tropical climates like Nigeria. This work investigates the collapse potential (CP), at 200 kPa, of compacted lateritic soil specimens prepared from two lateritic soils of different mineralogy. The soils were compacted both at standard Proctor and modified Proctor energy levels. The soils consist mainly of silica, aluminium oxide and iron (iii) oxide. Both soils classify as silty sand (Unified Soil Classification System). However, sandstone derived lateritic soil from Gidansani (G sample) has lower liquid limit and plasticity index than the migmatite derived soil from Ilorin (R sample). CP varies from 5.3 % to 18.9 % for G soil and from 5.7 % to 16.6 % in the R specimens. This range of CP indicates that both G and R soils have moderately severe degrees of collapse. Specimens compacted dry of optimum exhibit a positive linear relationship with CP while specimens compacted wet of optimum exhibit reduced CP with increasing dry density. CP increased with moisture content and degree of saturation irrespective of the energy of compaction and soil type. Compaction at higher energy level reduces the tendency for large collapse.

Keywords: Lateritic soil; compaction; collapsible soils; soil suction; collapse potential

1. Introduction

Lateritic soils are reddish coloured, hard residual soils, formed by mechanical and chemical weathering of iron-rich rocks. In subtropical and tropical parts of the world, lateritic soils are the most prominent weathered pedogenic surface deposits. In Nigeria, the abundance and cheap availability make the use of lateritic soils attractive as compacted fills in landfill liners, highway embankments, artificial backfills and slopes (Adeyemi et al., 2015). The effects of evapotranspiration coupled with low water table often make residual soil, such as lateritic soils, unsaturated (Rao, 2012). In addition, compacted soils at the time of placement, are always unsaturated and possess negative pore-water pressure suction (Elgabu, 2013). Consequently, natural deposit and compacted lateritic soils are liable to volumetric instability when there is a change in water content leading to failure of engineering structures due to differential settlements, piping and cracks in walls or floors. Hence, proper understanding of the volumetric instability behaviour of compacted lateritic soil is important.

Phenomenon such as swelling, shrinkage and collapse are behaviour that moisture induced volumetric instability can cause in residual soils. However, the rate of collapse of unsaturated soils is faster compared to rates of swelling and shrinkage (Rao, 2012). In addition, according to Culshaw and Jefferson (2018) collapse generally takes place rapidly as the soil changes from a metastable condition to a normally consolidated one. Moisture induced collapse in soils is influenced by factors such as matric suction, dry unit weight, initial moisture content and vertical stress (Lawton et al., 1992; Tadepalli & Fredlund, 1991). In compacted soils, previous works have shown that the collapse potential

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(CP) decreases with increase in dry unit weight and moisture content (Das and Thyagaraj, 2018; Kholghifard et al*.,* 2014). In addition, CP increases with increase in applied vertical stress. But with further in the vertical stress it decreases (Lawton et al., 1992; Silveira and Rodrigues (2020). Pandya & Sachan (2020) observed that specimens having higher matric suctions have higher CP irrespective of their moisture content and unit weight.

In the recent time, construction and developmental activities have been carried out on this problematic residual soil. However, despite these developments, the subject of collapsible soils has not received much attention in Nigeria in recent years. There are very few reports on the collapse behaviour of lateritic residual soils, particularly those occurring in humid tropical climates characterized by distinct wet and dry seasons. This work therefore investigates the collapse phenomenon in some residual lateritic soils, with focus on the collapse mechanism of dry or partially saturated compacted lateritic soils during incremental soil moisture contents under constant load and subsequently evaluates the influence of the soil moisture content and unit weight on the collapse process. In the process, the influence of the increase in soil moisture on the soil suction of the compacted lateritic soil is investigated to determine the relationship between the soil suction and collapse behaviour of the compacted soil.

2. Study area and methods

2.1. Location of study area

Two samples were taken from road cut lateritic exposures which have been actively excavated for road construction and brick making. Fig. 1 shows the locations of the sampling burrow pits on a geologic map of the area. One of the locations lies on Latitude 8° 20’ 25’’ and Longitude 4° 30’15’’ within Ilorin metropolis. The other location is on Latitude 8° 50’ and Longitude 5° 0’ 40’’ at Gidansani, a settlement close to Yikpata along the Share - Shonga highway. The geologic map shown in Fig. 1 shows that the lateritic soil at Gidansani is developed over Nupe Sandstone Formation of the Northern Bida Basin which lies unconformably over the weathered Basement Complex. The map also shows that the lateritic soil sampled at Ilorin was developed over migmatites of the Basement complex. The geology of Nigeria consists of three major litho-petrological components; namely, the Basement Complex, Younger Granites, and Sedimentary Basins. Gidansani sample location belongs to the sedimentary basins while the Ilorin sample location belongs to the Basement complex terrain. Although Nigeria falls wholly within the tropics, there is variation in local climate from region to region. Both sampling locations are in Kwara State, North-central, Nigeria, and belong to the hot humid sub climate with an average annual rainfall between 1183 and 1787 mm (FMW, 2013). There are two marked seasons: the rainy season from April to October and the dry season from November to March (Obaje 2009).

2.2. Materials and methods

Index tests including natural moisture content, liquid limit, plastic limit, linear shrinkage, specific gravity and sieve analysis were carried out on the two soil samples. These tests were carried out in accordance with British Standard 1377 (1990). The soil samples were analysed for mineral content using X-ray diffraction (XRD), while XRF spectroscopy was used to quantitatively determine the major elements in the soil samples. The samples were pulverized with an iron mill to grain size of approximately 10 µm. Soil major elements were analysed on a fused bead, except Na_2O which is analysed on a pressed pellet. The results were determined quantitatively. XRD analysis was completed using a PANalytical Empyrical with a Cu-anode X-ray tube and Highscore was used for interpretation. Soil samples already air-dried to constant weights were compacted both at standard and modified Proctor levels. Twenty compacted specimens at different moisture contents and dry densities were obtained from four compaction processes; ten from each sample compacted at both standard and modified Proctor levels. These specimens were trimmed and their heights were determined. Then they were placed in the oedometer loading device immediately after determining their initial wet masses. A seating stress of 5 kPa was applied. Within 5 min of applying the seating stress, increasing load (12, 25, 50, 100, up to 200 kPa) was added each hour at natural water content. Record of deformation before applying each load increment was taken. The soil specimen is then inundated with distilled water and further deformation is recorded. Record deformation versus time at approximately 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, 30 min and 1, 2, 4, 8, and 24 h was taken. Collapse index, I_e (percent—relative magnitude of collapse determined at 200 kPa) was calculated based on ASTM D 5333 – 03 using Equation 1.

$$\text{Collapse index } (I_e) = \frac{\Delta h}{h_o} . 100 \qquad (1)$$

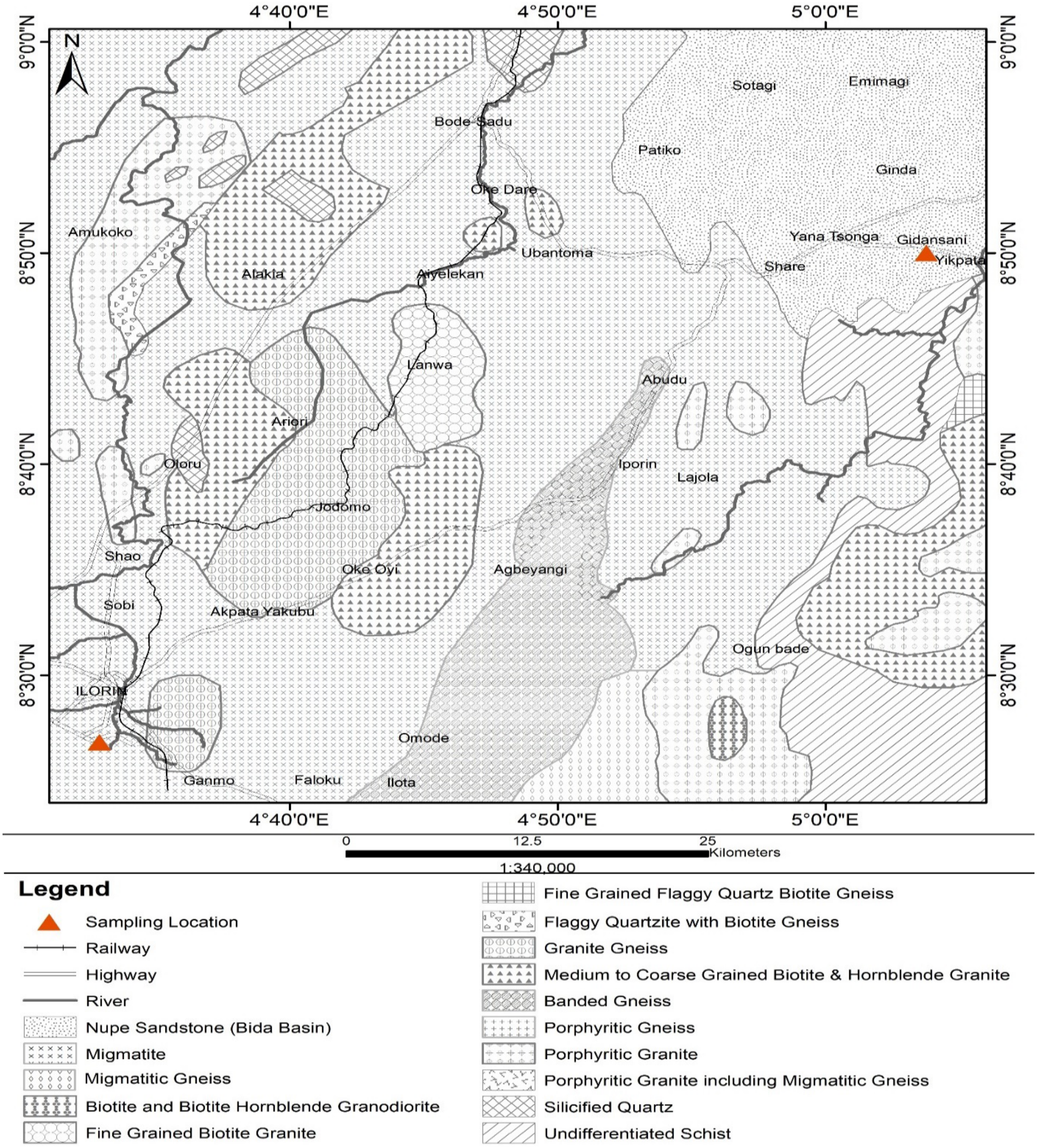

Figure 1: Geologic map showing location of sampling site

where:
Δh= Change in specimen height resulting from wetting, (mm); and
h_o = initial specimen height, (mm)

A portion of each specimen was also enclosed in filter paper (Whatman Grade 42) and enclosed in a plastic bag for matric suction determination following ASTM D 5298 – 03. This property is expressed (kPa), was determined from the amount of water absorbed after seven days from standard calibration curve for Whatman Grade 42 paper based on the wetting testing procedure modified after ASTM D5298-10 cited in Kim et al., (2017). This calibration curve was originally proposed by Greacen et al., (1987) and it has a correlation coefficient greater than 0.99 for filter paper moisture content and suction in kPa.

3. Results and discussion

3.1. Mineralogical and chemical properties of the soils

The sandstone derived lateritic soil sample from Gidansani (G) is mainly 83.9 % silica, 9.1 % aluminum oxide and 2.6 % iron (iii) oxide (Table 1). The sample derived from lateritic soil at Ilorin (R) consists of 54 % silica, 23.9 % aluminum oxide, 11.8 % iron (iii) oxide and 1.4 % titanium oxide (Table 1) XRD results show that both the sandstone derived soil at Gidansani and the migmatite derived soil at Ilorin consist of quartz, kaolinite, mica, K-feldspar and Goethite in varying proportions (Table 2). The G sample has higher quartz and goethite content while the Ilorin sample has higher kaolinite and K-feldspar content than the G sample. Figs. 2 and 3 show the X-ray diffractograms of the two soils.

Table 1: Chemical composition of the soils

XRF major elements (%)	Ilorin (R)	Gidansani (G)
SiO_2	54.04	83.85
TiO_2	1.37	0.56
Al_2O_3	23.9	9.13
Fe_2O_3	11.79	2.6
MgO	0.23	0
MnO	0.04	0.02
CaO	0.17	0.09
Na_2O	0	0.01
K_2O	0.56	0.35
P_2O_5	0.05	0.03
LOI	9.54	3.98
Total	101.69	100.62

Table 2: Mineralogical composition of the soils

Mineral constituent (%)	Quartz	Kaolinite	Mica	K-feldspar	Goethite
Ilorin (R)	29	43	15	8	5
Gidansani (G)	52	23	14	2	7

3.2. Physical properties of the soils

Table 3 presents the index properties of the soils and their engineering classification. Both soils classify as silty sand (Unified Soil Classification System) and they both belong to group A-2 of the American Association for State and Highway Transportation Officials (AASHTO) classification. According to these classifications, both soils are expected to have good engineering properties. However, the G soil has lower plasticity and shrinkage properties than the R sample. The G sample has lower liquid limit and plasticity index than the R sample (Fig. 4). High liquid limit normally indicates high compressibility and shrinkage/ swelling potential. A high plasticity index also indicates lower shear strength and it's expected to experience significant change in consistency with a small change in water content. This result is expected since the G soil has more quartz content and lower kaolinite content as revealed by the mineralogy. Kaolinite is plastic and hydrophilic while quartz is non-plastic. Fig. 5 shows the grading curves of the two soils. Both soils are well graded but the R soil has more fine sand than the G sample.

Table 3: Physical properties and engineering classification of the soil samples

Property	Value	
	R	G
Natural moisture content (%)	12.63	9.25
Linear shrinkage (%)	10.0	7.5
Moisture content (%)	12.6	9.3
Liquid Limit (%)	43.0	38.5
Plastic Limit (%)	30.3	36.6
Plasticity Index (%)	12.7	1.9
Specific gravity	2.53	2.63
Gravel (<4.75 mm)	6.0	4.0
% sand (4.75 mm – 2 mm)	66.0	67.0
% fines (< 75 mm)	28.0	29.0
USCS	SM (silty sand)	SM (silty sand)
AASHTO	A-2-7	A-2-4
MDD - Standard Proctor (kN/m^3)	16.27	15.8
MDD - Modified Proctor (kN/m^3)	17.06	16.8
OMC- Standard Proctor (%)	23.5	20.8
OMC - Modified Proctor (%)	23.1	25.9

3.3. Collapse indices of the soils

Table 4 and Table 5 present the CP under a load of 200 kPa of soil specimens from the two soil samples (R and G) compacted soils compacted at standard proctor and modified Proctor levels. For the G soil, CP varies from 5.3 % to 18.9 %, while CP varies from 5.7 % to 16. 6 % in the R specimens. This range of CP indicates that both R and G soils have moderately severe degree of collapse (D 5333 – 03). Jennings

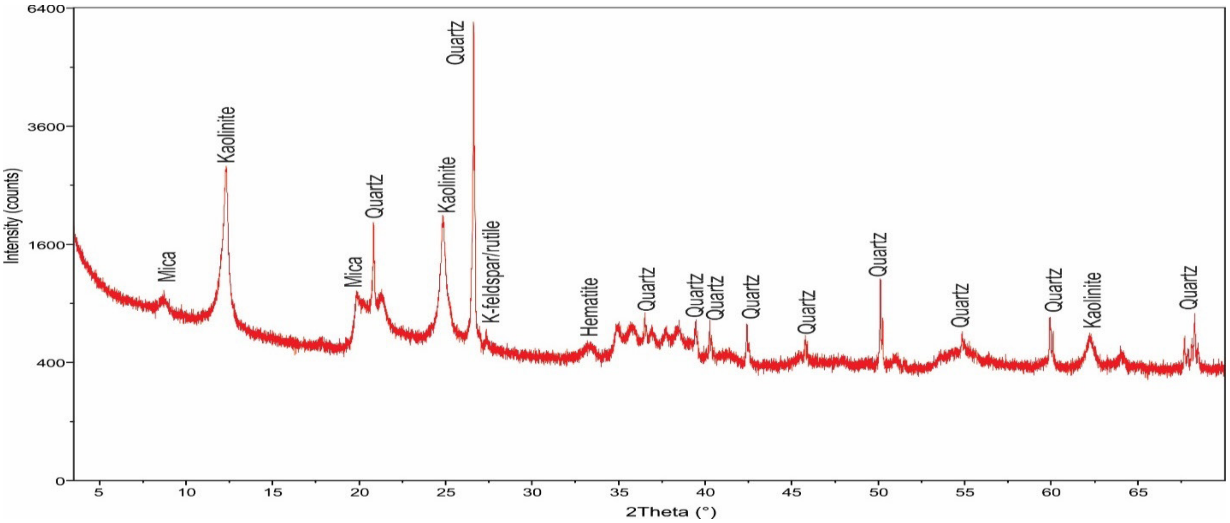

Figure 2: X-ray diffractogram of soil from Ilorin

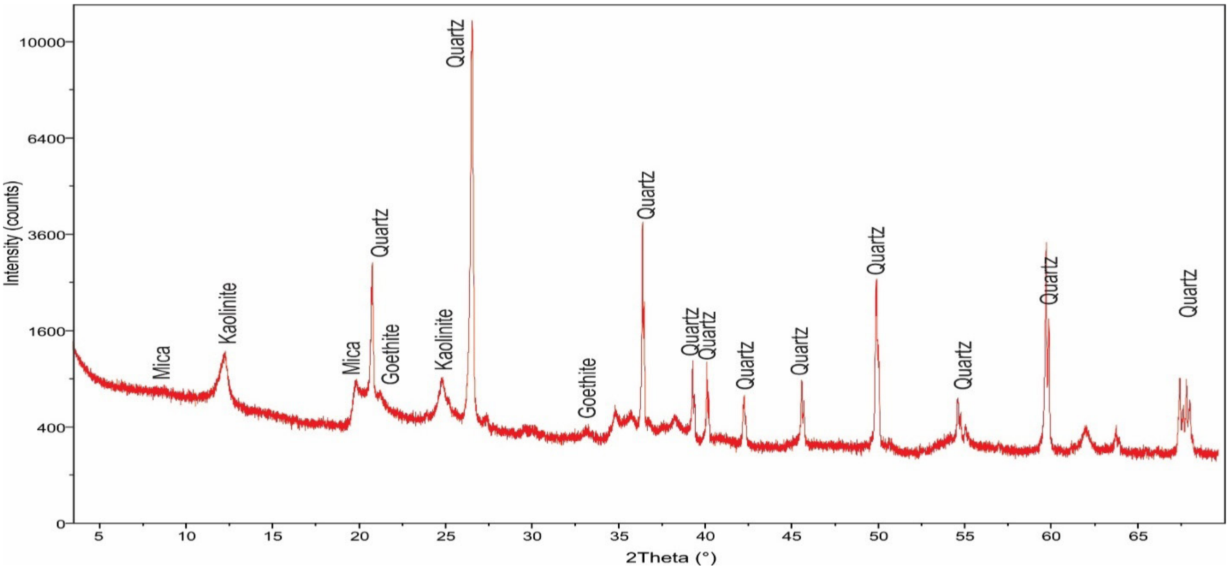

Figure 3: X-ray diffractogram of soil from Gidansani

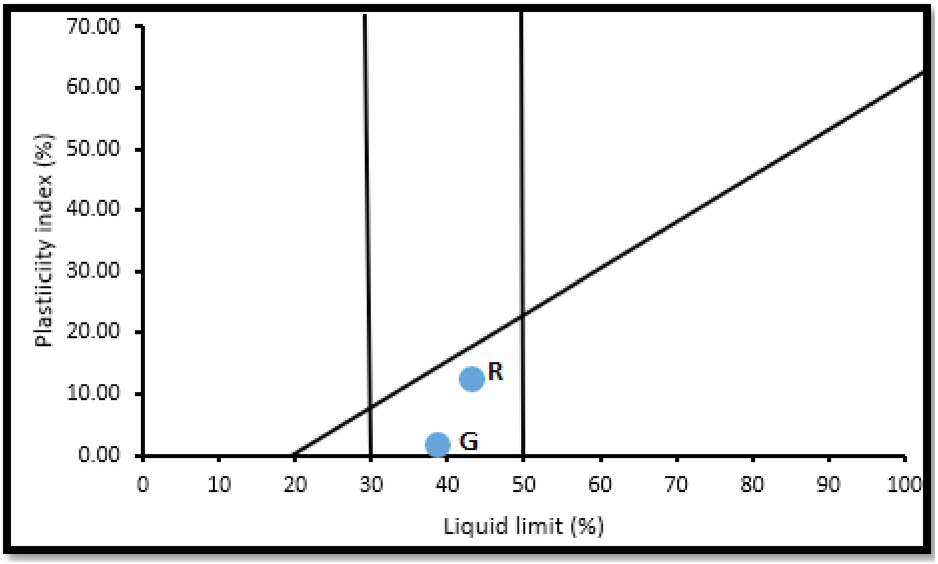

Figure 4: Plasticity chart of the soil samples

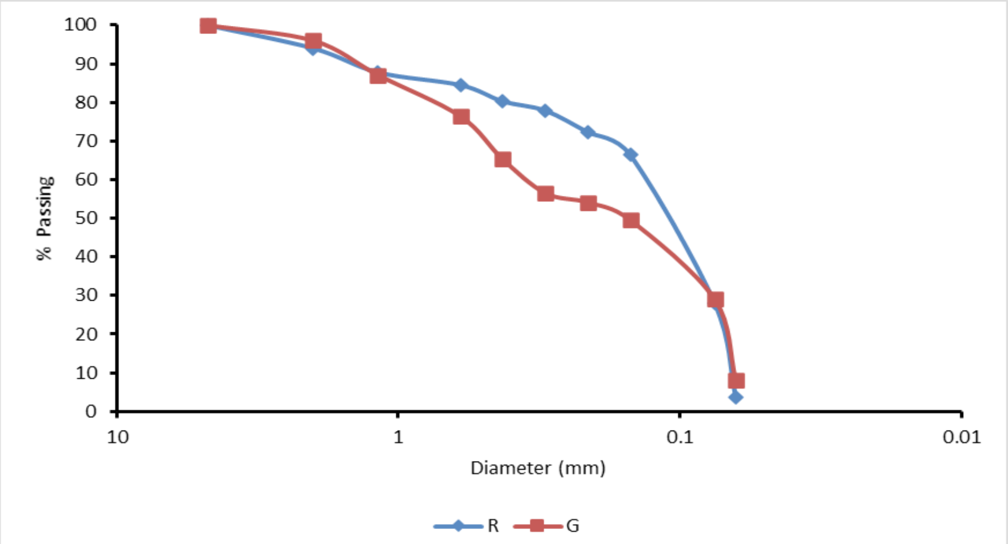

Figure 5: Grading curves of the soil samples

Table 4: CP of G soil specimens compacted at standard and modified Proctor. (* SP- standard Proctor, * MP- Modified Proctor)

Specimen no	CP (%)	Matric Suction (kPa)	Water content (%)	Dry density (kN/m^3)	Void ratio	Degree of saturation (%)
SPAG	6.7	501.2	16.7	12.3	1.11	43.8
SPBG	9.2	3162.3	17.4	13.7	0.88	45.7
SPCG	13.2	5623.4	20.8	15.8	0.63	54.8
SPDG	15.6	1778.3	26.7	12.7	1.04	70.1
SPEG	18.6	6309.6	31.6	11.4	1.26	83.1
MPAG	5.3	1584.9	12.5	11.7	1.20	32.9
MPBG	8.2	3162.3	19.2	13.2	0.95	50.6
MPCG	14.6	6309.6	23.1	15.2	0.70	60.7
MPDG	16.1	501.2	25.9	16.8	0.53	68.2
MPEG	18.9	3981.1	29.4	12.2	1.12	77.4
Range	5.3 - 18.9	501.2 - 6309.6	12.2 - 31.6	11.4 - 16.8	0.53 - 1.26	32.9 - 83.1

Table 5: CP of R soil specimens compacted at standard and modified Proctor. (* SP- standard Proctor, * MP- Modified Proctor)

Sample	CP (%)	Matric Suction (kPa)	water content (%)	Dry density (kN/m^3)	Void ratio	Degree of saturation (%)
SPAR	9.2	5011.9	13.0	13.4	0.86	33.0
SPBR	10.2	1778.3	16.1	14.5	0.72	40.8
SPCR	13.6	125.9	22.2	15.2	0.63	56.2
SPDR	15.6	6309.6	23.5	16.3	0.53	59.5
SPER	16.6	25118.9	31.8	13.3	0.86	80.5
MPAR	5.7	39810.7	17.4	12.6	0.96	44.0
MPBR	8.2	25118.9	18.8	15.1	0.64	47.4
MPCR	10.7	1258.9	23.1	17.1	0.45	58.4
MPDR	12.4	1778.3	27.6	14.3	0.73	69.8
MPER	14.9	5011.9	34.6	12.5	0.98	87.6
Range	5.7 – 16.6	125.9 – 39810.7	13 – 34.6	12.6-17.1	0.53-0.98	33- 87.6

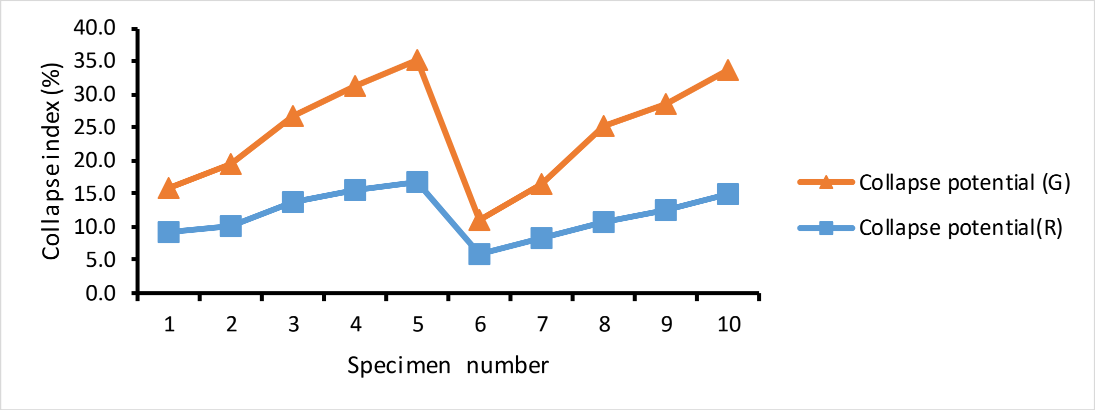

Figure 6: Comparison of the collapse potentials of the soils

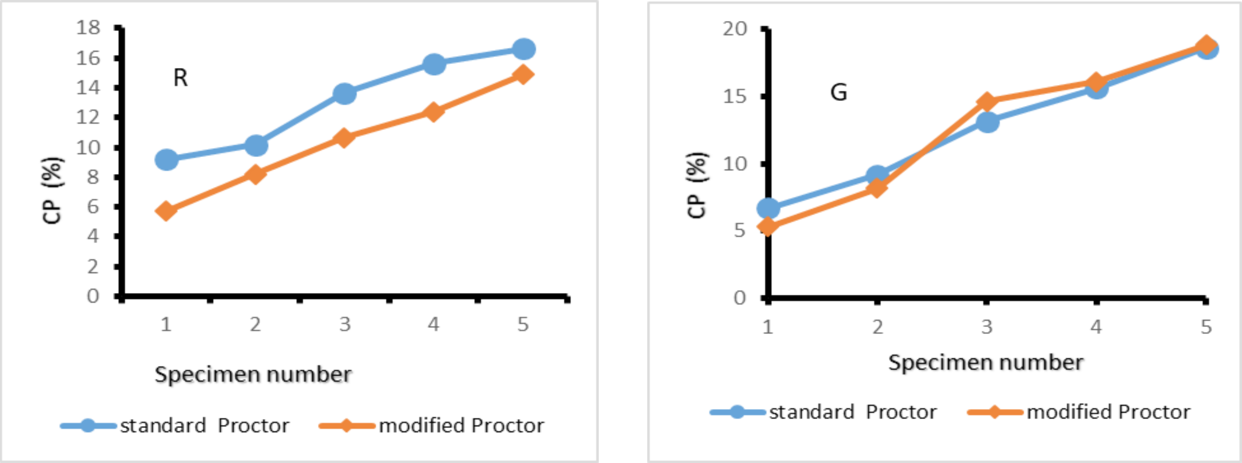

Figure 7: Comparison of CP values of soil specimens compacted at standard Proctor and modified Proctor levels

Table 6: Coefficient of volume compressibility (mv) of the compacted specimens at a pressure range of 0 -200kPa

S/N	Specimen no	$m_v \times 10^{-2}$(R)	Specimen no	$m_v \times 10^{-2}$ (G)
1.	SPAR	4.18	SPAG	4.18
2.	SPBR	4.31	SPBG	4.31
3.	SPCR	4.16	SPCG	4.16
4.	SPDR	4.16	SPDG	4.16
5.	SPER	4.15	SPEG	4.16
6.	MPAR	4.20	MPAG	4.20
7.	MPBR	4.20	MPBG	4.16
8.	MPCR	4.30	MPCG	4.16
9.	MPDR	4.51	MPDG	4.25
10.	MPER	4.16	MPEG	4.16

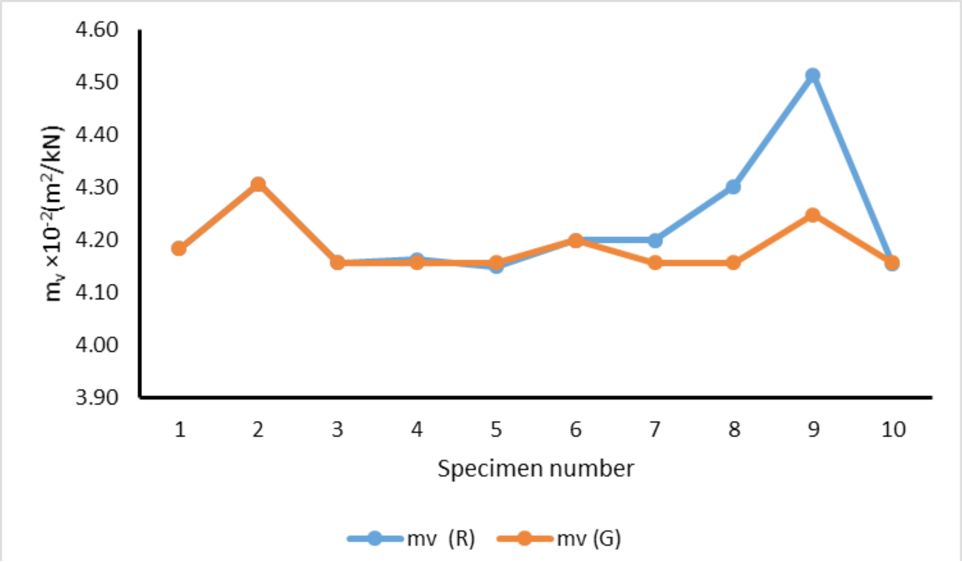

Figure 8: Comparison of m_v for specimens from R and G soils

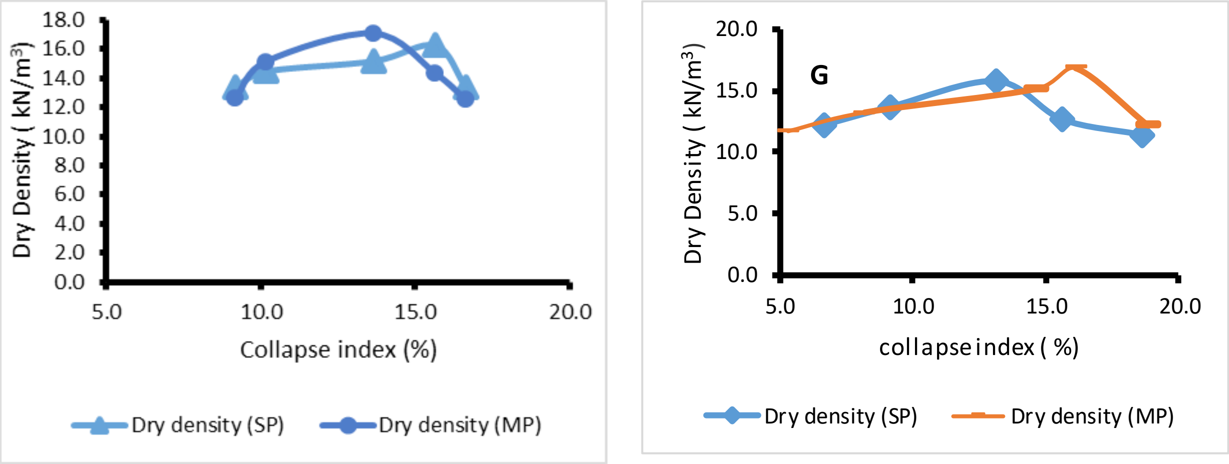

Figure 9: Variation of collapse index with dry density. *SP – Standard Proctor, *MP- Modified Proctor

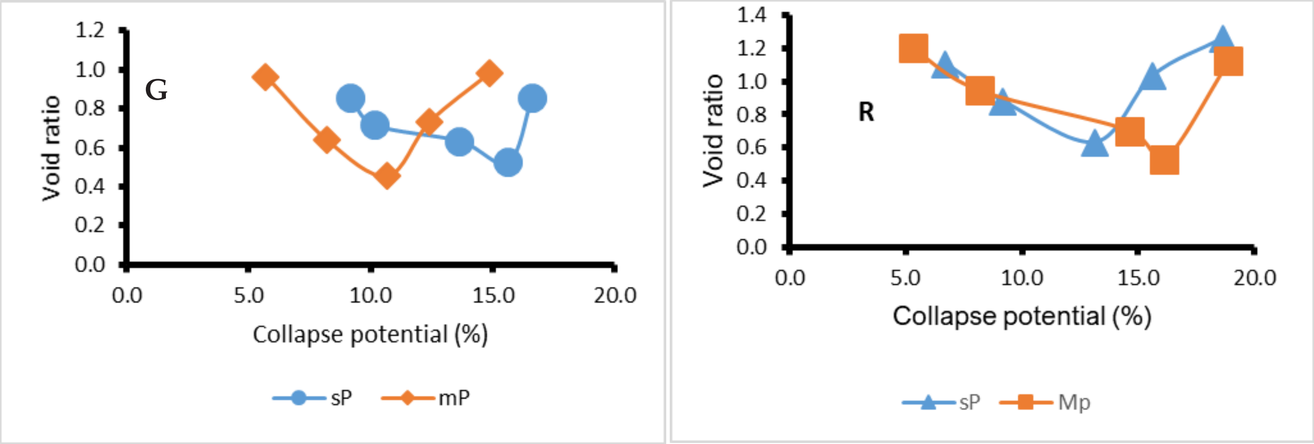

Figure 10: Variation of collapse potential with void ratio.

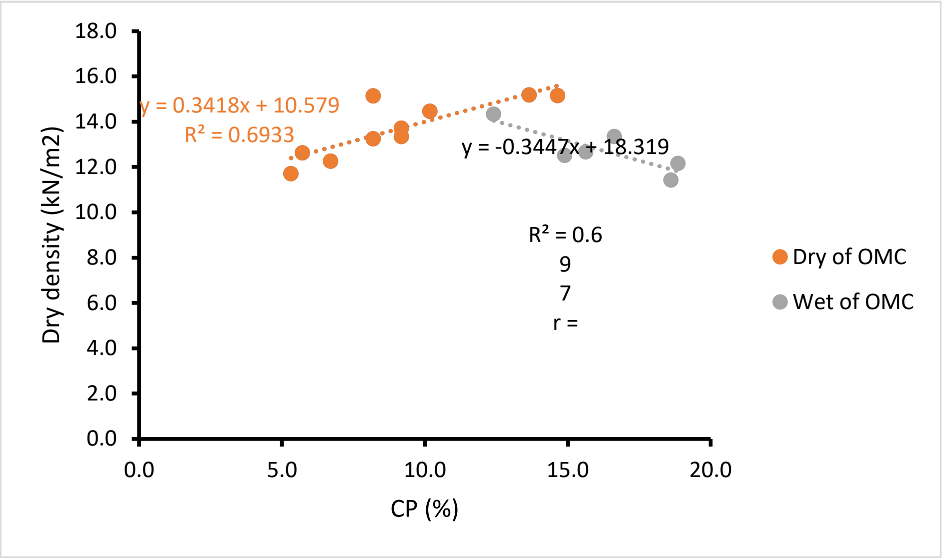

Figure 11: Regression plots of dry density and CP at 200k

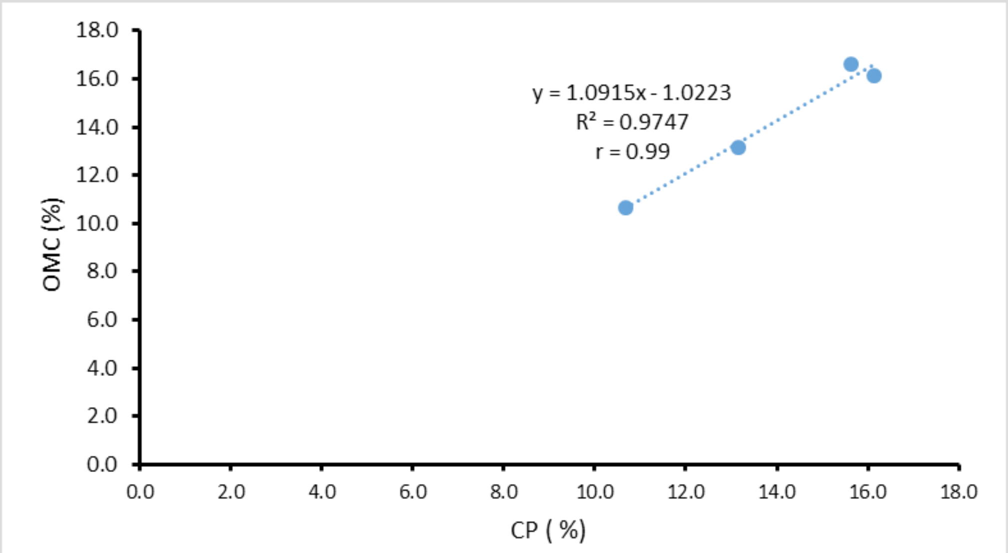

Figure 12: Regression plot of relationship between OMC and CP (%)

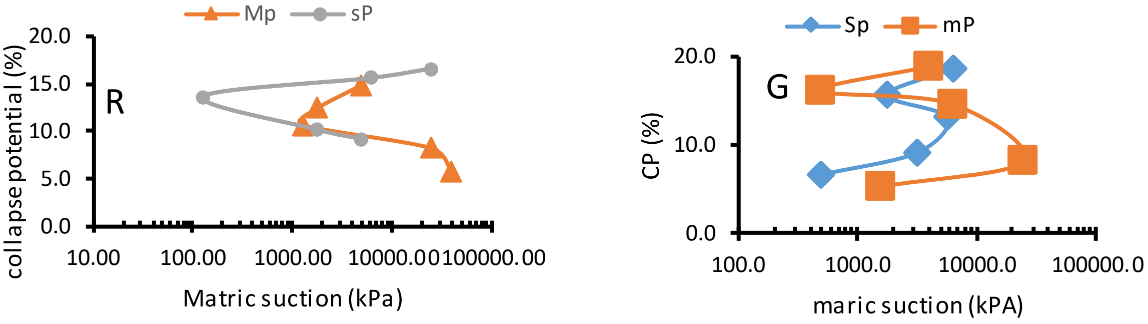

Figure 13: Variation of CP with matric suction. *SP – Standard Proctor, *MP- Modified Proctor.

and Knight (1975) categorize soils with this range of collapse indices as those that are capable of posing up to severe collapse trouble. Specimen prepared from G soil has higher CP than those prepared from R soil (Fig. 6). This supports the hypothesis that soils with low clay content collapse less (Rogers, 1994). The R soils have clay mineral content above 40 % as revealed by the mineralogy test. Specimen compacted at modified Proctor level of compaction has lower CP than those compacted at the standard Proctor especially in the R sample (Fig. 7). This implies that compaction at higher energy level reduces the tendency for large collapse.

The coefficient of volume compressibility of both soils without wetting were compared at pressure range of 0 – 200 kPa (Table 6 and Fig. 8). The specimens from both R and G soils compacted with low energy (Serial Numbers 1 - 5) exhibit similar compressibility while those compacted at higher energy (Serial Numbers 6 - 10) exhibit different compressibility values. The R soil specimens have higher compressibility than the G soil.

3.4. Effect of dry density and void ratio on the collapse behaviour of the soils

Collapse index varried with dry density as shown in Fig. 9. For both soil samples, CP increased with dry density up to a maximum value corresponding to the maximum dry densities and optimum moisture contents (OMC) of the samples compacted at both standard Proctor and modfied Proctor level. Void ratio decreased to minimum at maximum dry density (MDD) and increased with further compaction and addition of water. Fig. 10 shows how void ratio varied with CP. It is shown that that lower CP can be achieved at OMC and MDD by compacting using higher energy like modified Proctor. For both soil types, specimen compacted dry of optimum exhibit a positive linear relationship with CP while specimens compacted on wet of optimum exhibit reduced CP with increasing dry density (Fig. 11). This can be attributed to the floculated nature of soils compacted dry of optimum which favours collapse. There is also an increase in CP with increase in OMC as shown in Fig. 12. Since soils compacted at high energy tend to have lower OMC and higher MDD, it is implies that compacting at high energy, wet of optimum favours lower collapse tendency.

3.5. Relationship between matric suction and collapse index

Matric suction, being one of the determinants of soil shear strength (Pujiastuti et al. 2018), was plotted against CP at 200 kPa (Fig. 13). The graphs show that for the R soil compacted at modified level of compaction, strong negative correlation exists between CP and matric suction CP reduced with increase in matric suction. For other R specimen compared at standard Proctor and the G specimen, CP and matric suction do not show distinct relationships. It can be observed from Fig. 13 that at higher matric suction, CP tend to be low for specimen compacted at the higher energy level while for the ones compacted with lower energy, CP tend to increase with matric suction. High compactive energy seems to reduce the tendency for collapse while soil type also plays a major role in CP behaviour of the soils. The indistinct relationship between CP and matric suction of specimens indicate that other factors aside soil type and compactive energy play a major role in the CP behaviour of the soils. The higher initial matric suction tries to maintain the meta-stable bond between soil particles without significant collapse but eventually collapse.

3.6 Effect of placement moisture content and degree of saturation

Positive linear relationship exists between CP and initial moisture contents and degree of saturation as shown in Figs. 14 and 15 respectively. CP increased with placement moisture content and degree of saturation irrespective of the energy of compaction and soil type. This implies that placement moisture content and degree of saturation affect amount of collapse irrespective of soil type and the degree and amount of compaction the soil has been subjected to.

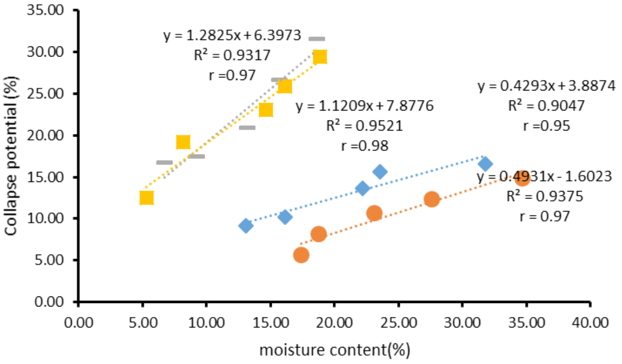

Figure 14: Relationship between CP and moisture content for both samples

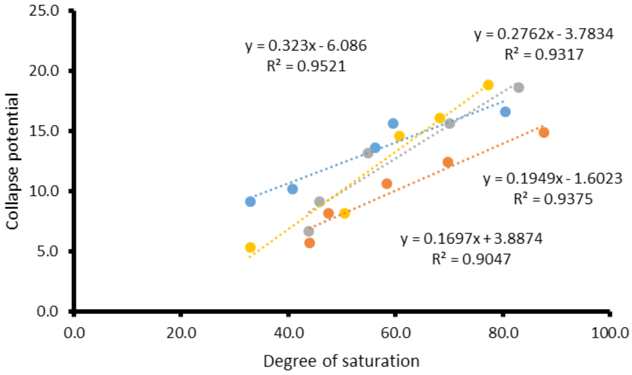

Figure 15: Relationships between CP and degree of saturation for both samples

4. Conclusion

Soil specimens from two lateritic soils of different mineralogy were compacted at both standard Proctor and modified Proctor energy levels. Five specimens each were obtained from 4 compaction processes; 10 for each soil. These compacted specimens at varying initial moisture contents and dry densities were subjected to single oedometer tests with and without inundation under a stress load of 200 kPa and their CP and matric suction were determined. The silica rich G soil specimen exhibits higher CP, while the kaolinite rich R soil exhibits lower CP. CP values for both soils classify them as soils with moderate severe degree of collapse. Specimens compacted with high energy possessed lower CP than those compacted at low energy. Both R and G soil possessed similar compressibility properties without change in moisture content at low energy of compaction why disparity occurred at higher energy. Specimen compacted dry of optimum exhibits lower CP. Lower CP was achieved at OMC and MDD by compacting using higher energy like modified Proctor. CP increased with placement moisture content and degree of saturation irrespective of the energy of compaction and soil type. CP increased with soils compacted at high energy, wet of optimum have lower collapse tendency. High compactive energy reduced the tendency for collapse while soil type also plays a major role in CP behaviour of the soils.

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