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# Effect of Moisture on Volumetric Behaviour of Compacted Laterites

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ABSTRACT: A number of studies have been conducted to assess the volumetric stability of compacted soils including lateritic soil when subjected to moisture variations. Whereas it is now recognized that depending on the degree of compaction and initial moisture content most lateritic soils are susceptible to collapse when sufficiently wetted, it is not yet clear whether or not within the densities recommended for flexible road pavement construction the likely collapse is insignificant. Any significant and/or differential collapse is a nuisance to flexible pavement works. This paper presents experimental results of water retention behaviour and collapse of lateritic soil typical of those recommended for construction of improved flexible pavement subgrade and subbase. The contact filter paper method was deployed to measure matric suction while the single oedometer method was used to determine collapse. The results indicate that matric suction is higher for soils compacted dry of optimum regardless of the value of density achieved. Collapse was equally a function of compaction moisture content and hence realized density with its value tending to zero as compaction moisture content approached optimum moisture content. Given the levels of collapse observed, it is risky to rely on specifications based on the degree of compaction alone without specifying moisture content range.

**Key words:** Compacted laterites, water content, matric suction, collapse.

## 1 INTRODUCTION

Lateritic soils are residual soils which are usually reddish to reddish brown in colour (Emeso, 2013). They are the most common reddish colour weathered pedogenic surface deposits occurring in the tropical and subtropical regions of the world (Eberemu, 2011). In tropical regions, lateritic soils are intensively used in road works (Meissa et al, 2011) for construction of flexible pavement layers including the subgrade, subbase and base. Their selection and use in road works is guided by specifications which are employed to ensure a quality road is constructed. However, road pavements and embankments constructed with laterites have experienced structural failures in form of collapse, compression and cracking as a result of variations in moisture (Wen et al., 2015). Of these forms of failure, collapse was of particular interest in this study.

Following periods of especially sustained rainfall, moisture content of the pavement layers may significantly increase depending on drainage conditions of the surface while it may reduce during the dry season. Such soil moisture changes have considerable effect on the volumetric stability of soil (Fredlund & Rahardjo, 1993; Pereira et al., 2000; MdNoor et al., 2009; Adem and Vanapalli, 2015; Jayasree, 2015) including lateritic soils that are susceptible to collapse upon wetting (Kholghifard et al., 2014). The degree of collapse depends on degree of compaction yet the degree of compaction does not guarantee absence of collapse. According to Elgabu (2013), compacted soils are invariably unsaturated at the time of placement and possess negative pore-water pressure or suction. Therefore, synonymous to the soil-water retention curve (SWRC), a relationship between compaction water content and the associated matric suction is a crucial tool in understanding the behaviour and response of compacted soils (Fredlund et al., 2012).

## 2 MATERIALS AND METHODS

### 2.1 *Materials*

In this study, lateritic soil of the kind normally recommended for construction of road subbase and improved subgrade in Uganda was used. Obtained from Kigoma Borrow pit (KB) in the Central Region of Uganda (coordinates 00.35905° Northing and 032.48191° Easting and an altitude of 1219m above sea level), the tested soil was reddish brown in colour. This soil was at the time of sampling being used in the construction of Kampala Northern Bypass Project Phase 2 as both subgrade and subbase material.

Results from sieve and hydrometer analyses revealed that the gravel, sand, silt and clay contents of the tested soil were 72%, 14%, 11%, and 3%, respectively as indicated in Table 1 together with other necessary index properties in the understanding of the tested soil. According to BS classification system, the soil was well graded silty gravel (GWM).

Table 1. Summary of measured index properties.

| Index property | |
|---|---|
| *Standard compaction tests* | |
| Maximum dry density MDD (Mg/m$^3$) | 2.17 |
| Optimum moisture content OMC (%) | 10.5 |
| *Grain size distribution* | |
| Gravel content (> 2 mm, %) | 72 |
| Sand content (0.06≤D≤ 2 mm, %) | 14 |
| Silt content (2 μm ≤D≤ 60 μm, %) | 11 |
| Clay content (≤ 2 μm, %) | 3 |
| Coefficient of uniformity | 214.3 |
| Coefficient of curvature | 23.8 |
| Specific gravity $G_s$ | 2.94 |
| *Atterberg limits* | |
| Plastic limit PL (%) | 22.2 |
| Liquid limit LL (%) | 46.5 |
| Plasticity index PI (%) | 24.3 |
| *California Bearing Ratio, CBR (%)* | 51 |

## 2.2 *Specimen preparation*

In order to realize the objectives of this study, the test specimens were prepared at moisture and densities that corresponded to relative densities specified and adopted in Uganda for construction of the layers for which the tested soil qualify namely roadbed (93%), subgrade (95%) and subbase (98%). Therefore, a density moisture relationship of the tested soil was first determined. Figure 1 is a plot showing the relationship together with the ranges of moisture content over which the different layer specifications could be realised. The compaction test was performed on material passing the 20mm BS sieve in a purposely made two-split mould of 160mm internal diameter and 50mm height fabricated using 10mm thick steel plates. Detachable collar of similar dimensions and slightly wider base plate made it possible to have a full mould height compacted specimen. The compaction energy was calculated to give density similar to the one achieved when a 1.0 litre mould was deployed in accordance with BS 1377-4:1990 clause 3.5.

After knowing the range of water contents over which the target relative densities could be achieved, amounts of water corresponding to compaction moisture contents were added to predetermined amounts of prepared soil and the soil-water thoroughly mixed before compaction into the split mould. Prior to placement of the soil-water mixture into the mould, a thin layer of oil was applied to the sides while 150mm diameter Whatman No. 42 filter paper was placed at the bottom of the mould to prevent sticking of the specimen on to the mould sides and base plate respectively. Soil compacted in one mould (in 2 layers using 4.5kg, 68 blows per layer falling through 450mm) formed a half of a test specimen for matric suction determination while it provided a disc from which an oedometer test specimen was cored. The compaction water contents reported herein were determined using trimmings of the compacted material got in the process of leveling it with the top of the mould.

It should be recalled that for effectiveness of the contact filter paper method intimate contact is mandatory. This may not be guaranteed when the filter paper is placed on the rough surface left by the process of levelling the compacted granular material with the mould. In this study, therefore, the smooth surface and contact created with the filter paper at the bottom of the mould was taken advantage of as the two discs sandwiched the filter paper system by bringing the two bottoms together.

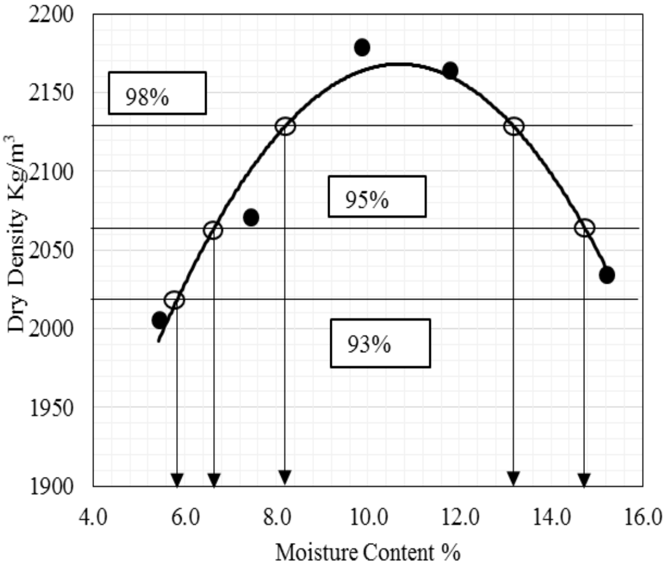

Figure 1. Density moisture relationship and specified relative compaction.

## 2.3 *Determination of matric suction*

Several methods have been suggested in the literature for determination of matric suction of soils: the hanging water column technique (Vanapalli et al., 2008; Azam et al., 2013), pressure plate apparatus, tensiometers and filter paper technique (Fredlund and Rahardjo, 1993; Elgabu, 2013). In this study, the contact filter paper method was used in accordance to ASTM D5298-96 test procedure. Whatman No. 42 filter papers were used.

As illustrated in Figure 2, two initially dry 150mm diameter filter papers enclosing an equally initially dry 90mm diameter filter paper formed the filter paper system which was sandwiched between identical specimens discs carefully prepared as described in section 2.2. To ensure the necessary intimacy, the two halves of the soil specimen were sealed with electrical tape to keep them tightly together. The system was then wrapped with aluminum foil to reduce moisture escape and then left in a desiccator for 14 days for equilibration. The results (Figure 3) of temperature and humidity within the specimen environment monitored using BTH01 humidity-temperature data logger indicate that equilibrium was achieved by the tenth day. Upon equilibrium that was defined by constant temperature and humidity within ±0.3°C and ±1% respectively, the filter papers were removed and immediately weighed to the nearest 0.0001g as recommended. The filter papers were then oven dried at 105°C for 16 hours and weighed to determine the filter paper water content. Care was taken to ensure that the filter paper was not contaminated in the process.

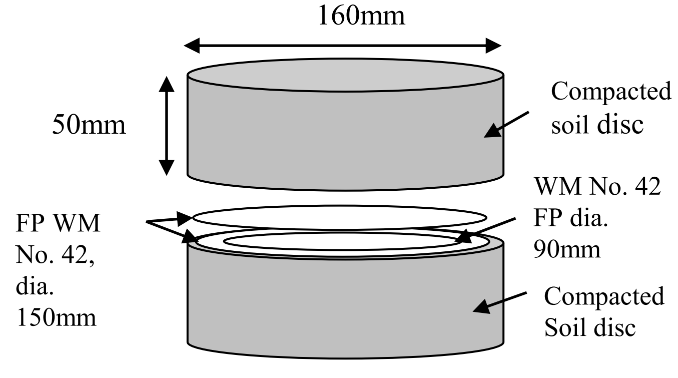

Figure 2. Schematic for Measurement of Matric Suction.

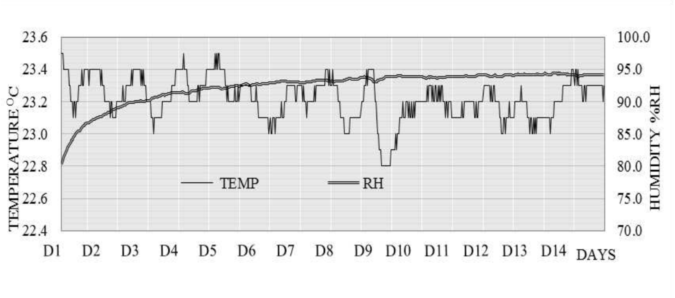

Figure 3. Time history of temperature and humidity around the specimen.

The water content of the filter paper was then used to calculate matric suction using Chandler et al. (1992) calibration equations (1) and (2).

$$\log\psi = 4.842 - 0.0622\,w_f ; w_f < 47\% \qquad (1)$$

$$\log\psi = 6.050 - 2.48\log w_f ; w_f > 47\% \qquad (2)$$

Where $\psi$ = matric suction of the soil; $w_f$ = water content of the filter paper. The procedure was repeated for specimens at different compaction water contents.

With water content and matric suction of the as compacted soil specimen known, a plot of gravimetric water contents versus matric suction was made and the experimental data fitted using the van Genuchten (1980) model shown in equation (3). The fitting parameters were determined using the solver function.

$$w = w_r + ((w_s + w_r)/(1+(\alpha_v\psi)^n)^m) \qquad (3)$$

Where $w$ = gravimetric water content; $w_s$ = gravimetric water content at saturation; $w_r$ = the residual gravimetric water content; $\alpha_v$ = the fitting parameter related to the air entry value; $\psi$ = matric suction; $n$ and $m$ = fitting parameters related to the pore distribution and curve symmetry respectively.

### 2.4 *Measurement of Collapse Index*

The collapse potential test was carried out in accordance to ASTM D5333-96 procedure for single oedometer test method. The test was performed on 75mm diameter by 20mm thick specimens hydraulically cored from the discs prepared as described in section 2.2. The test specimen in the ring was loaded into the oedometer cell and a seating stress of 5kPa applied and subsequent deformations measured. After 5mins of the seating stress, the loading scheme was 12, 25, 50, 100, 200 kPa each loaded after every one hour as the deformations were recorded. The specimens were inundated in the oedometer cell 1hour after placement of 200kPa and allowed to saturate for 24hours as deformations were recorded. For purposes of defining the volume change behaviour of the soil beyond saturation, the stresses were increased stage wise up to a maximum value of 1600kPa with deformations recorded every 24hours for each stress.

Collapse potential (CI) at 200kPa was computed using equation (4).

$$CI = (\Delta h/h_o)x100 \qquad (4)$$

Where $CI$ = collapse potential; $\Delta h$ = change in height of the compacted specimen upon wetting under applied stress for 24 hours; $h_o$ = initial height of the compacted specimen before inundation at that particular stress.

## 3 RESULTS AND DISCUSSION

### 3.1 *Relationship between as compacted gravimetric water content and matric suction*

The relationship between water content and matric suction of as compacted specimens are shown in Figure 4. It can be observed from the scatter plots that matric suction increased with decrease in gravimetric water content. This is consistent with the findings of Miguel and Vilar (2009) on water retention behavior of lateritic soil and indeed all other soils. The increase in matric suction as the water content reduced is linked to the fact that at lower water contents, the soil structure formed after dynamic compaction has liquid water which is disconnected and localized at inter particle contacts (Fredlund & Rahardjo, 1993). Kasangaki (2012) reveals that at low water contents it is the liquid bridge induced adhesive forces that are responsible for soil matric suction. He further argues that at residual conditions, matric suction is due to only the menisci of water and higher energy is needed to remove any further liquid from the voids.

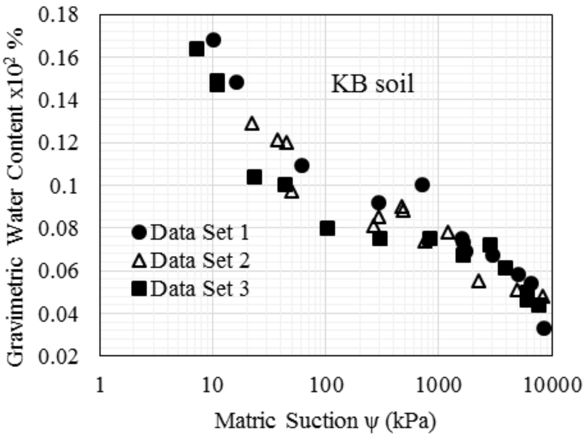

Figure 4. Graphs of gravimetric water content versus matric suction for samples compacted at varying water contents.

Figure 4 seems to suggest that the scatter plots could be well fitted using the bimodal function than the unimodal function. However, when only the same void ratio points were considered (Figure 5) it was obvious that the behavior followed a unimodal function and the van Genuchten (1980) unimodal model described by equation 3 fitted the experimental data well. This result is in tandem with the outcome of the particle size and distribution analysis given in Table 1 which reveals that the tested soil was well graded. According to Zhang and Chen (2005), well graded soils have one pore series and its cumulative pore size distribution and pore size density curves are unimodal. Note that points were considered to have the same void ratio if their void ratio was in the range ±(0.05). According to Kasangaki (2012), Elgabu (2013) and Pasha et al (2016), void ratio influences the matric suction at any given water content of a soil and this is evident in the current study.

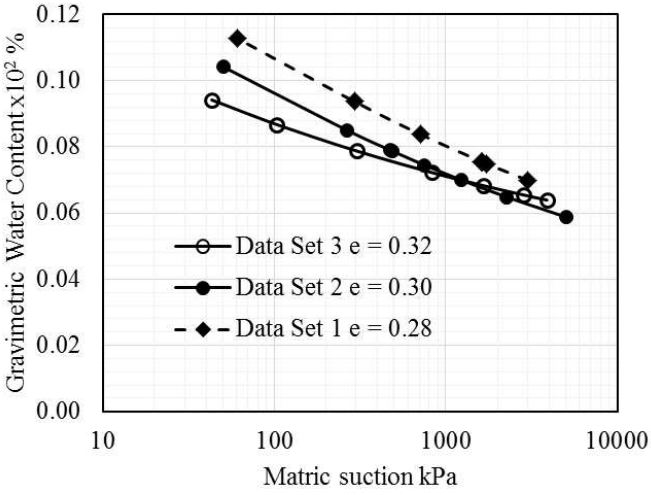

Figure 5. Water content and matric suction curves fitted with VG (1980) unimodal model.

As shown in Figure 5, the curves for all the void ratios tended to converge at matric suction of about 3Mpa which in the fitting process defines the start of the residual zone as applied to SWRC. This means that at higher matric suction as the residual zone approaches, the effect of initial void ratio starts to disappear. Kasangaki (2012) reported that the water retention curve in the residual zone does not depend on the initial void ratio.

The water content –matric suction curves were obtained for samples compacted to relative densities ranging from 90% to more than 100%. The full saturation conditions of 100% as well as the residual conditions were out of range of the relevant relative densities considered in this study. The values reported in Table 2 were thus estimated through the curve fitting process. Table 2 shows the curve fitting parameters for the three data sets with water contents in gravimetric form. As shown in Table 2, the residual water content $w_r$ is 1.4% and the saturation water content $w_s$ is 15.7%.

Table 2. van Genuchten (1980) measured parameters for the three data sets.

| Parameter | Tested Soil | | | |
|---|---|---|---|---|
| | Data Set 1 | Data Set 2 | Data Set 3 | Mean |
| $w_r$ | 0.020 | 0.010 | 0.013 | 0.014 |
| $w_s$ | 0.165 | 0.141 | 0.165 | 0.157 |
| α | 0.055 | 0.057 | 0.167 | 0.093 |
| n | 1.237 | 1.189 | 1.202 | 1.209 |
| m | 0.192 | 0.159 | 0.168 | 0.173 |
| SSE | 0.00129 | 0.0007 | 0.00204 | 0.001 |

### *3.2 Volumetric behaviour of the tested soils*

Figure 6 presents, as an example, the volumetric behaviour of compacted lateritic soil passing 20mm sieve. The compacted soil (with initial conditions of 2.27Mg/m$^3$ dry density, 9.1% water content and 0.30 void ratio) exhibited noticeable collapse following inundation at a pressure of 200kPa. This effect of wetting at a constant applied stress is attributable to the destruction of a number of matric suction related inter-particle contacts created in the soil during compaction. In other words, the apparent bridges created by matric suction reduced as more water ingressed into the soil thereby altering the configuration of the associated menisci of the contact points. Overall, Figure 7 reveals that collapse index was found to decrease as compaction water content increased and hence as initial matric suction decreased. Towards the optimum moisture content, collapse index was insignificantly small and tended to be constant with further increase in moisture content into wet of the optimum. Table 3 gives the collapse indices on the dry and wet of OMC. It is clear from this analysis that matric suction which is a function of moisture content has an effect on the collapse of lateritic soil.

Figure 8 indicates that as matric suction increased, collapse index as well increased within a matric suction range of 50kPa to 1500kPa.

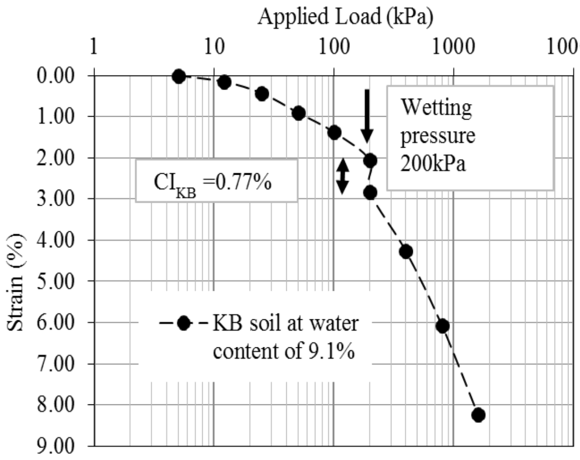

Figure 6. Collapse behaviour of lateritic soil compacted to 2.27Mg/m$^3$ at water content of 9.1%.

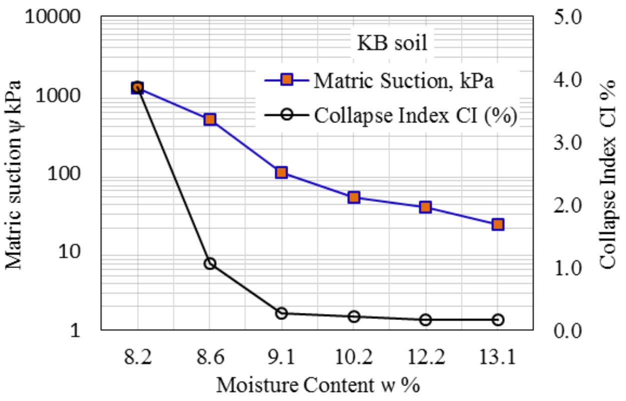

Figure 7. Relationship between water content, matric suction, and Collapse Index.

Table 3. Degree of compaction and collapse.

| Moisture Content, w % | | CI % at 200kPa |
|---|---|---|
| *Dry of OMC* | -2.3 | 3.9 |
| | -1.9 | 1.1 |
| | -1.1 | 0.3 |
| | -0.3 | 0.2 |
| *OMC* | OMC | - |
| *Wet of OMC* | 1.7 | 0.2 |
| | 2.6 | 0.2 |

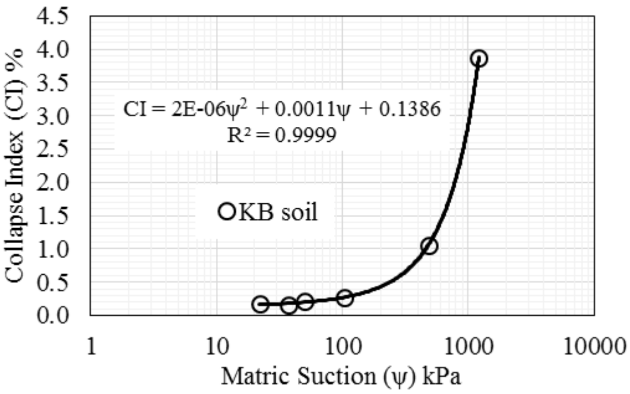

Figure 8. Collapse index versus Matrix suction.

In this suction range volumetric changes are high. Sun et al. (2007) noted that collapse occurs at an intermediate range of suction levels that is neither high nor low. This suggests that there is critical matric suction and moisture content below which the soil will no longer collapse. Equation (5) which was obtained by fitting the experimental data shows that upon wetting, collapse is high for specimen with high matric suction. It also reveals that minimum collapse occurs at zero matric suction and it tends to be asymptotic at matric suction of about 1MPa.

$$CI_{KB} = 2x10^{-6}\,\psi^2 + 1.1x10^{-3}\,\psi + 1.386x10^{-1} \tag{5}$$

Where $CI_{KB}$ = collapse index for soil from Kigoma borrow pit; $\psi$ = matric suction.

### *3.3 Practical implication of results*

The specifications used in Uganda for construction of road pavement layers were used to calculate the allowable practical field densities based on the maximum dry density. The computed densities in Table 4 were used to determine the moisture content (dry and wet of OMC) from the dry density moisture relationship curve shown in Figure 1. The corresponding collapse indexes (CI) were obtained (Figure 9). Based on ASTM D5333 (1996) criterion, the layers constructed at 98% MDD on dry of optimum moisture contents are moderately collapsible (CI of 3.9%) while those constructed at optimum and wet of optimum water contents are slightly collapsible since their CI is in the range of 0.1 to 2.0. Jennings and Knight (1975) classifies the observed collapse on dry of OMC as moderately troublesome while collapse at OMC and wet of OMC as none problematic.

At the present, compaction specifications in Uganda are solely in terms of relative density. This can be achieved over a wide range of moisture contents implying that inherent in this specification is the fact that initial moisture content has no significant impact on the subsequent behaviour of the compacted material. Findings of this study indicate that when lateritic soil is compacted at different moisture contents, different structures are generated resulting in different collapse potentials. On the dry of optimum, collapse on wetting can be destructive. Thus relying on specifications based on degree of compaction alone without specifying moisture content is risky.

Table 4: Degree of compaction and collapse.

| Specification | Allowable Densities Kg/M$^3$ | Water Contents % | | Computed CI % | |
|---|---|---|---|---|---|
| | | Dry of OMC | Wet of OMC | Dry of OMC | Wet of OMC |
| 90% | 1953 | <5.8 | >15.6 | >>>3.9 | 0.2 |
| 93% | 2018 | 5.8 | 15.6 | >>3.9 | 0.2 |
| 95% | 2062 | 6.6 | 14.7 | >3.9 | 0.2 |
| 98% | 2127 | 8.2 | 13.2 | 3.9 | 0.2 |

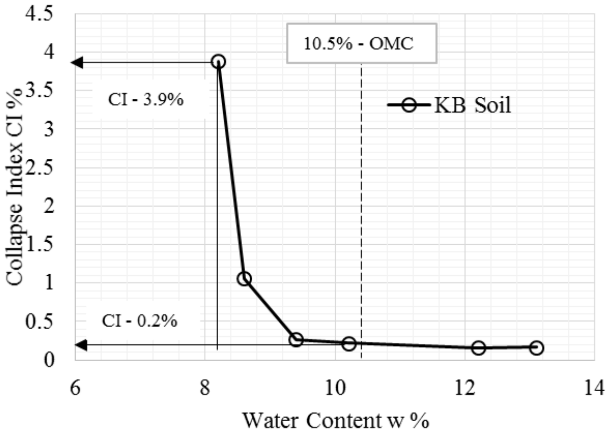

Figure 9. Collapse index against moisture content.

## 4 CONCLUSION

The dependence of matric suction on the compaction water content of dynamically compacted well graded silty gravel (lateritic soil) for relative densities between 90% and 110% MDD was determined using the contact filter paper method. The compaction moisture content increase resulted in decrease in matric suction. The curves plotted within the transition zone. The unimodal van Genuchten (1980) function for water content –matric suction curves fitted the experimental test data for the tested soils with the fitting parameters as $w_r = 1.4\%$, $w_s = 15.7\%$ $\alpha = 0.093$, $n = 1.209$.

Lateritic soils compacted to relative densities recommended for flexible pavement layers are collapsible under varying moisture conditions. The collapse index of these soils decreases with increasing compaction moisture content and hence reducing initial matric suction except at OMC and beyond where collapse on wetting becomes negligibly small and asymptotic to compaction moisture content. Thus relying on specifications based on compaction alone without specifying moisture content is risky. Sufficient wetting after compaction may detrimentally affect the pavement structure.

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