# The effects of structure of Nigeria clay in one-dimensional compression

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**ABSTRACT**

An investigation has been made into the effects of geological structure of Nigeria clay in compression by employing comparisons between the soil in the natural state and the same soil in the reconstituted state. Apart from classification and index tests studied, geochemistry and microstructure were investigated using scanning electron microscope equipped with energy dispersive spectrometry and mineralogy studied using X-ray diffraction. Convergence behavior was seen in the soils and the mineralogy is dominated by kaolinites. The effects of structure were determined by applying normalizations and sensitivity analysis. The degree of enhanced strengths in compression were found to be positive and small to medium in magnitude.

## 1. INTRODUCTION

Structure is the combination of bonding (inter particle forces which are not purely frictional) and fabric (arrangement of constituent particles). Bonding is the product of several forces (e.g., electromagnetic, electrostatic) which acts to connect the particles that have developed throughout the geological life of geomaterials (e.g., Cotecchia and Chandler 1997) and fabric includes particle size, shape, distribution and voids. In this work, structure is used for clays in their natural state which indicates structure depends on geological history. Effect of structure is increase in strength and stiffness of geomaterials as a result of bonding and fabric in compression and shearing. Due to effect of structure in one-dimensional compression, natural or intact geomaterials may reach higher stresses compared to stresses reached by reconstituted materials at a given specific volume (e.g., Gasparre and Coop 2008; Okewale and Coop 2017).
Many studies have been carried out on the effects of structure on compression behavior of clays (e.g., Burland 1990; Cotecchia and Chandler 1997; Gasparre and Coop 2008) due to their widespread availability and importance in engineering constructions. However, few of such studies are on Nigeria clays (e.g., Okewale 2020c). This study is essential because the formation or deposition processes are different from other clays around the world and this material is used in infrastructural development in Nigeria and world at large. This study investigates the effects of structure by comparing the

mechanical behaviour of natural clays to the same clays when it is reconstituted. This was achieved by conducting odometer tests on natural and reconstituted samples in addition to index test and mineralogical analysis.

## 2. MATERIALS USED

The samples used are clay samples from Ire Ekiti, Ekiti state south western Nigeria. The samples were collected as block from two locations labelled C and D (Table 1). The sampling locations are underlain by basement complex and the samples were of weathered origin and overlaid by small layer of residual soils and vegetation. The samples were taken at different depths (0.90 – 2.35m), allowing the trend of properties along a profile to be studied. The details of the samples are given in Table 1 and for clarity, acronyms are used. The letter stands for location and number indicates the point of retrieving sample along the depth starting from the top.

Table 1. Details of sample characteristics

| Sample location | Acronym | Depth (m) | LL (%) | PL (%) | PI (%) | CF (%) | Mineralogy (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Q | Fe | Cl | Others |
| C | C1 | 0.90 | 89.5 | 53.3 | 36.2 | 18 | 38.32 | 38.8 | 21.53 | 1.35 |
| | C2 | 1.35 | 86.1 | 56.1 | 30 | 16 | 37.71 | 36.21 | 25.12 | 0.96 |
| D | D1 | 2.35 | 90.9 | 72.1 | 18.8 | 19 | 39.64 | 36.67 | 23.48 | 0.21 |

LL liquid limit, PL plastic limit, PI plasticity index, CF clay fraction, Q quartz, Fe feldspar, Cl clay.

## 3. METHODOLOGY

The gradings of samples were determined using a combination of wet sieving and sedimentation technique due to their nature. Figure 1 presents particle size distributions of the samples. The samples are gap-graded. The curves are fairly similar for all the samples and soil D1 plot above which shows it is finer.

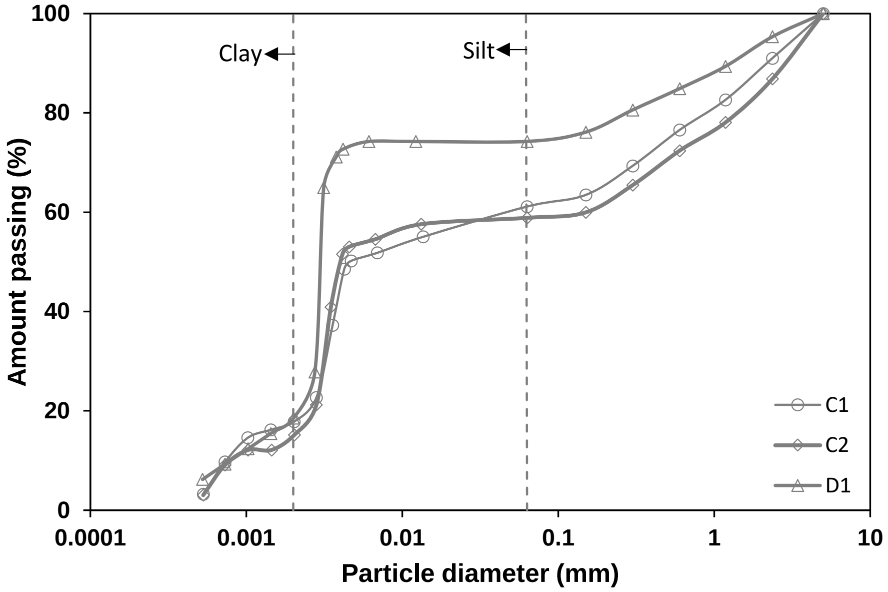


Fig. 1 Particle size distribution curves

The samples can be classified as sandy silty clay. The profiles of grading descriptors; mean particle size ($D_{50}$), coefficient of uniformity ($C_u$) and fines content ($f_c$) are presented in Fig. 2. They do not show a particular trend with depth and the close values can be attributed to shallow depth at which the samples were retrieved. The index property in terms of plasticity was determined through Atterberg limit test and the details are shown in Table 1. The samples have high plasticity and as expected, the plasticity is reducing with depth (Fig. 2d).

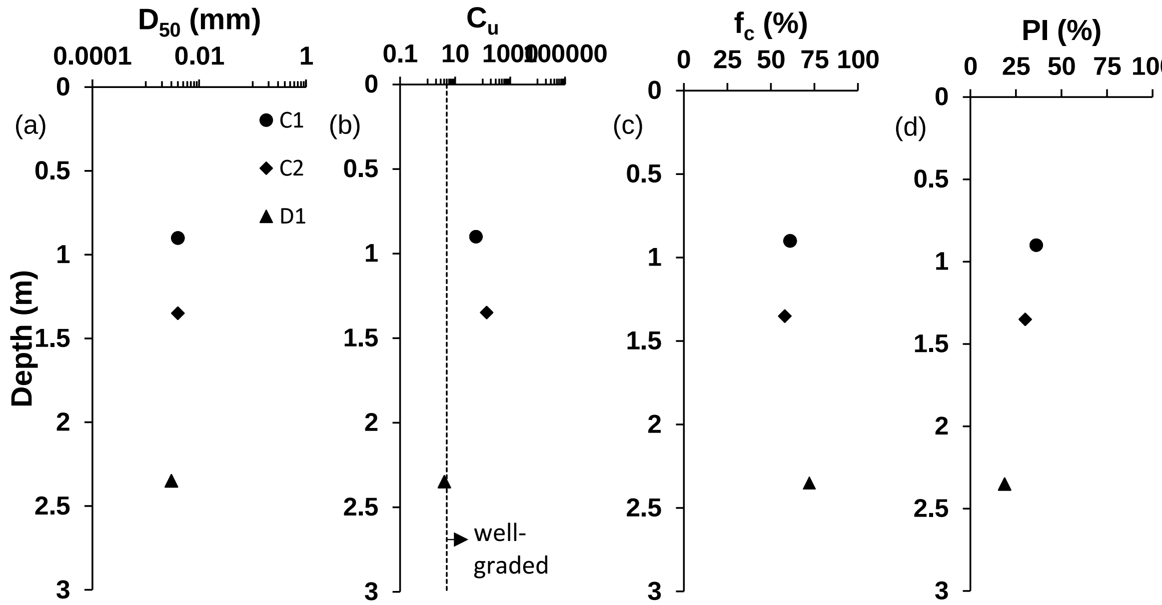


Fig. 2 Profile of grading and index property

The mineralogy was studied using a Shimadzu XDS 2400H diffractometer equipped with JCPDWIN software. The equipment operated at 40 kV and 55 mA, identifying minerals

in the range of 5° ≤ 2θ ≤ 70° with Cu-kα radiation. The samples were scanned at an interval of 0.02° / 0.30s and the samples were analyzed in powdered form. The samples comprise quartz, feldspar and clay minerals similar to related materials (e.g., Okewale 2020b, 2020c) as given in Table 1. The clay mineral is dominated by kaolinites.
The compression behavior of samples was studied using a conventional front loading odometer. A 50 mm diameter and 20 mm height closed base fixed confining ring was used for reconstituted samples and a 30 mm diameter and 20 mm height smaller confining ring of floating type was used for natural samples. The samples were loaded incrementally up to 30 kg. The reconstituted samples were prepared using the in-situ water due to presence of considerable amount of water. In reconstituted samples, natural bonding and fabric have been removed. Samples were placed, mixed, vibrated in a container and then placed in a confining ring and initial height carefully taken under a nominal load. This was followed by flooding of sample to allow for full saturation before stepwise loading to 30 kg. Natural samples were prepared by carefully trimming the block samples in order to minimize the disturbance. The sample is excavated ahead of the ring which was pressed down with a small pressure.
The specific volume v (1 + e, where e is void ratio) was determined using different methods similar to related studies (e.g., Okewale and Coop 2017, 2018a, 2018b, 2020; Okewale 2019a, 2019b, 2020a, 2020c; Okewale and Grobler 2020). This is necessary to improve the confidence in the measurements. The initial specific volumes were obtained from initial height and diameter, sample weight and initial water content. The final specific volumes were derived from final height and diameter, weight and water content back calculating the initial value using volumetric strain obtained in the tests.

## 4. RESULTS AND DISCUSSIONS

Figure 3 presents compression behavior of reconstituted and the natural samples together with their respective one-dimensional normal compression line (1D-NCL). The 1D-NCL was estimated for reconstituted samples and it represents intrinsic behavior resulting solely from constituent particles. Reconstituted compression paths are in broken lines and natural compression lines are in solid line with markers. For different samples, the compression paths converge to a unique line, similar to clays (e.g., Burland 1990) and other geomaterials (e.g., Rocchi et al., 2015). This shows that transitional mode of behavior which has been found in some well graded and gap graded materials (e.g., Martin et al. 2001; Nocilla et al. 2006; Ferreira and Bica 2006; Ponzoni et al. 2014; Zuo and Baudet 2015; Xiao et al. 2016; Okewale 2019a) is not seen here.

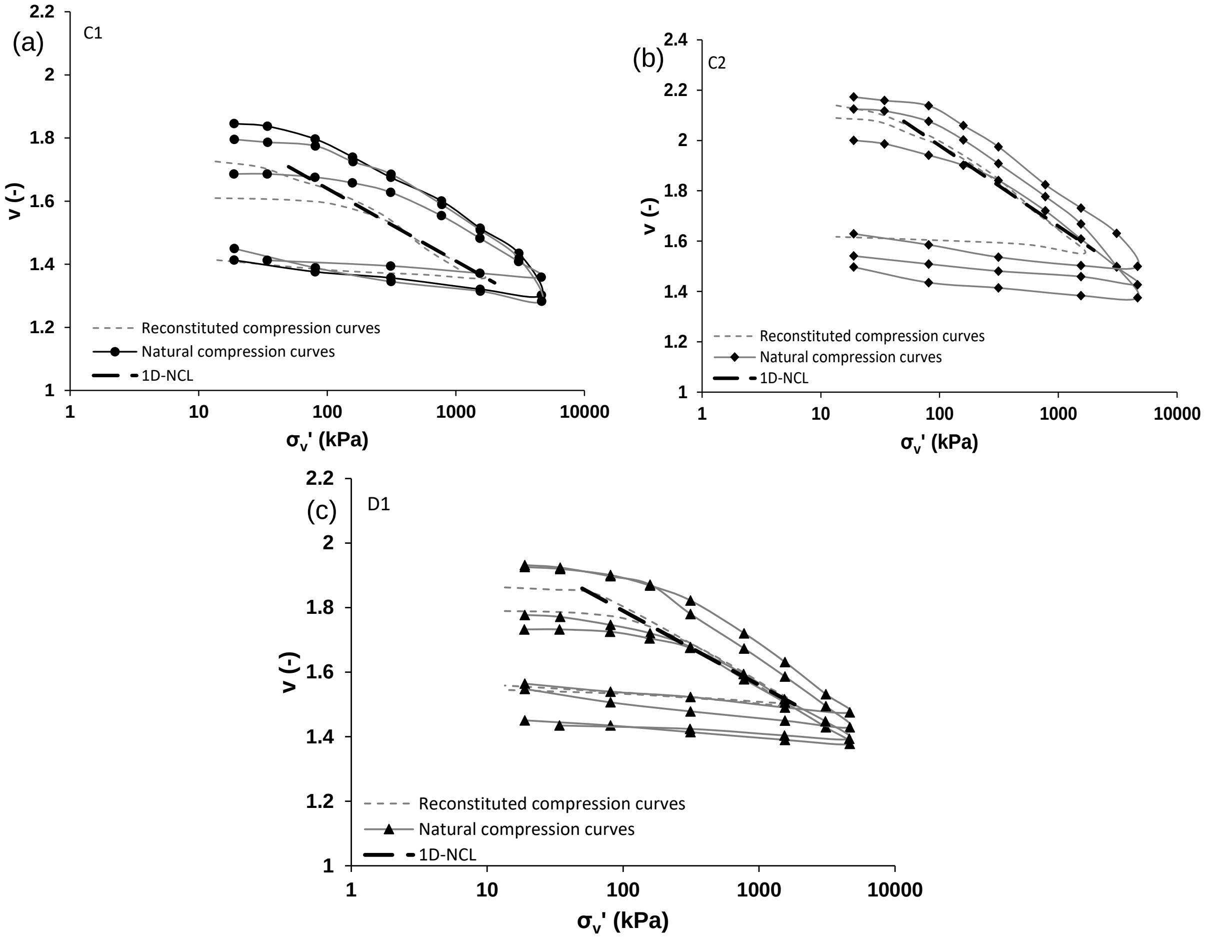


Fig.3 Compression behavior of the samples

Figure 4 presents summary of 1D-NCLs of the samples. The slope of the samples is similar for two samples and other is relatively close. The finer sample plots below the others. Figures 5a and 5b show the profile of compressibility parameters (slope λ obtained as $C_c/2.303$, where $C_c$ is compression index and $N_o$, the intercept of 1D-NCL at 1 kPa). The parameters are estimated from NCLs shown in Fig. 4. The parameters are close in values for the samples and they have direct similarities with no particular trend with depth. Again, this is expected due to grading of the samples and the depth of occurrences.

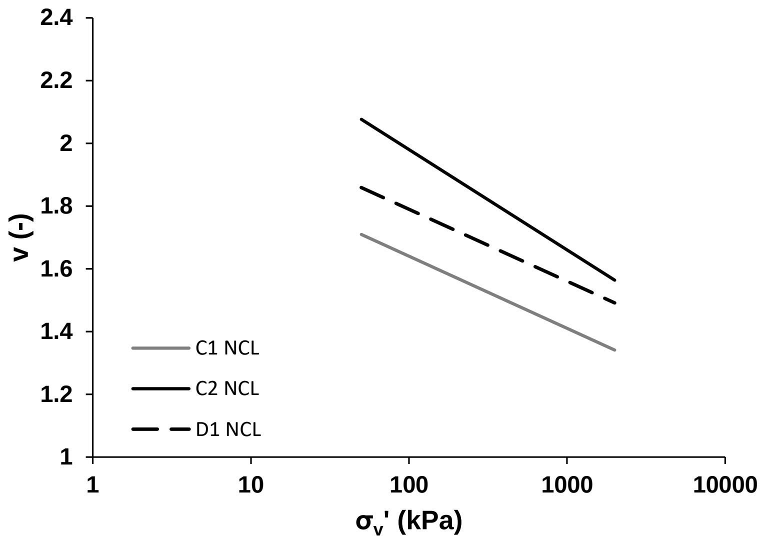


Fig. 4 Summary of 1D-NCLs

The natural compression paths are also shown in Fig. 3. Compression paths reach a state outside intrinsic normal compression line for the samples. The initial specific volumes are variable for the samples. The yield stress which indicates structural breakdown in samples is low. The variations of yield stress and in-situ specific volume with depth are presented in Figs. 5b and 5c respectively.

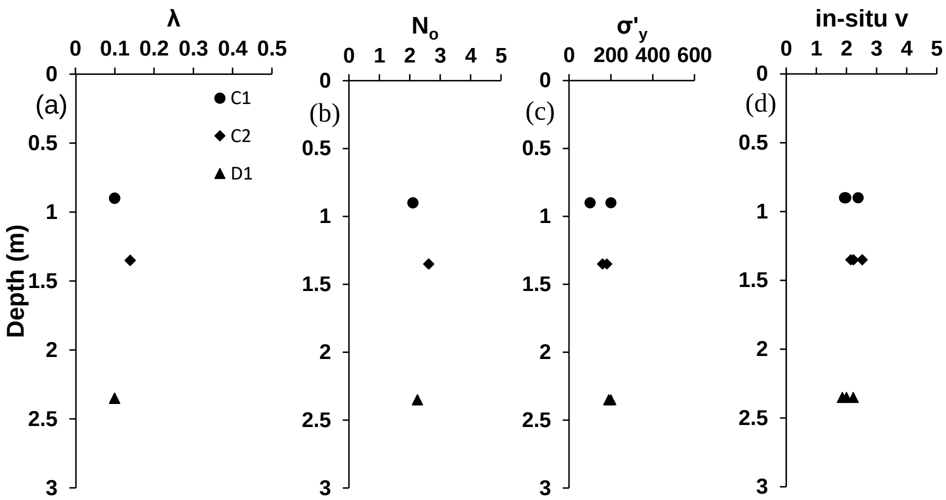


Fig. 5 Profiles of mechanical properties

The yield stress seems increasing slightly with depth and specific volume seems reducing slightly with depth.

The effects of structure are determined using void index ($I_v$) normalization proposed by Burland (1990), where $I_v = (e - e^*_{100})/(e^*_{100} - e^*_{1000})$, $e^*_{100}$ and $e^*_{1000}$ are void ratios on the ICL taken at vertical effective stresses of 100 kPa and 1000 kPa respectively. The $I_v$ makes the ICLs of soil to be unique by normalizing the nature of soil in terms of mineralogy and grading. The limiting range values of void index at specific volume of one (v = 1) are included in the figure and when this value is approached, the compression paths tend to curve.

The degree to which the compression curves of the natural samples cross the intrinsic normal compression line (ICL) indicates the effects of structure. In Fig. 6, the effects of structure is very clear in samples with high initial void index. The magnitude of the effects of structure is similar to those seen in clays (e.g., Burland 1990) and related geomaterials (e.g., Okewale and Coop 2017, 2020). The apparent low effects of structure in samples with low $I_v$ has also been seen in other soils (Cotecchia and Chandler 2000; Rocchi et al. 2015) and this has been referred to as an artefact of normalization rather than true reflection of effects of structure (Gasparre and Coop 2008). The compression paths of the natural samples tend to converge towards ICL after yielding which is an indication that the structure is being broken down by straining in compression. The degree of convergence is slow in some samples while in others it is rapid. At highest stresses reached in the samples, the convergence is complete for some samples, which indicates total breakdown of structure. Some compression curves move back across ICL due to fitting of straight ICL through the reconstituted compression paths.

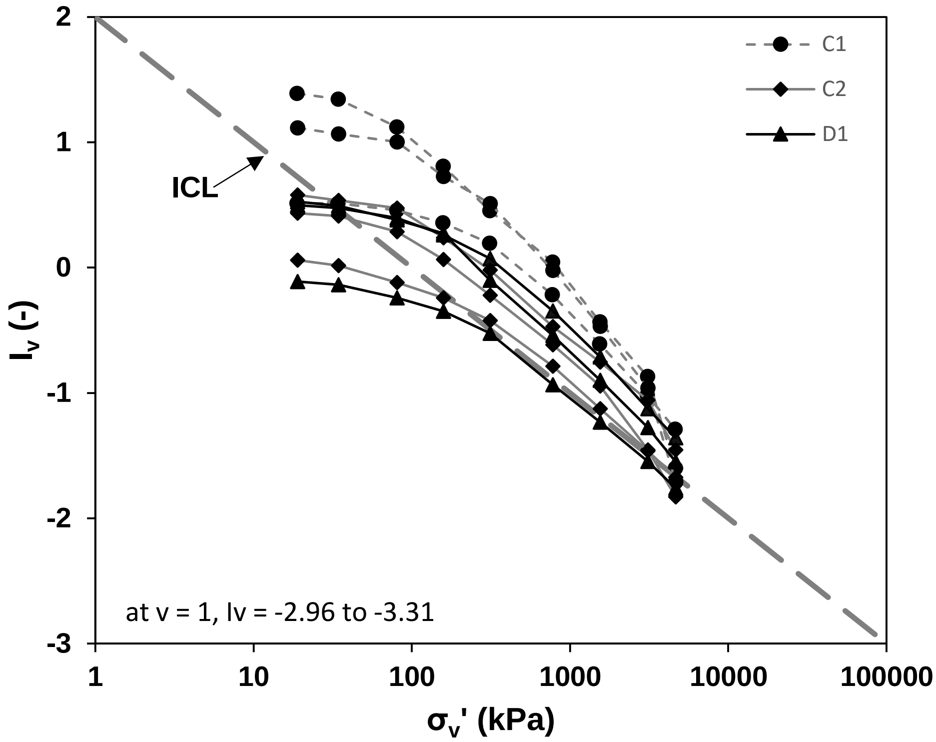


Fig. 6 Effects of structure using void index

Stress and swell Sensitivity were also computed in order to quantify the effects of structure. The stress sensitivity ($S_\sigma$) defined as the ratio of stress at yield ($\sigma'_y$) to the equivalent stress taken on the ICL ($\sigma'_e$) at the same specific volume was used. Figure 7a presents $S_\sigma$ of the samples along the profile and it shows that samples have positive effects of structure, similar to other geomaterials. The effects of structure seem increasing with depth. The positive effects of structure indicate $S_\sigma$ values of greater than one. A modified stress sensitivity called pseudo stress sensitivity ($S_{\sigma,10}$) which is 10 times the yield stress was also computed to quantify the effects of structure in the samples. The effects of structure are positive and the data are similar with no particular trend with depth (Fig. 7b). Swell sensitivity ($S_s$) is defined as the ratio of gradients of swelling lines of reconstituted samples ($C_s^*$) and natural samples ($C_s$) and it is also used for the quantification of the effects of structure. Again, the effects of structure are positive with no trend with depth (Fig. 7c).

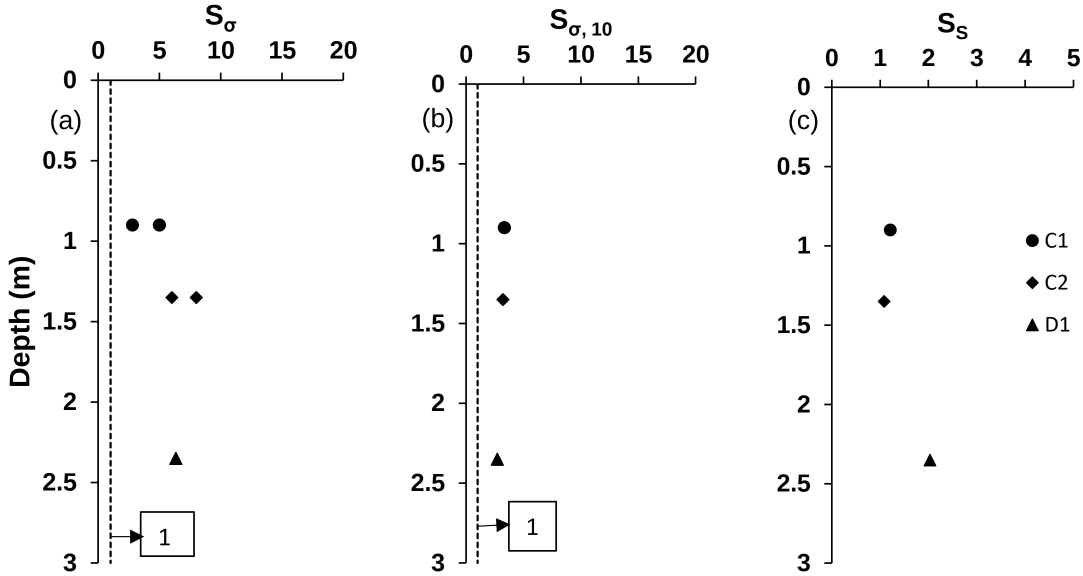


Fig. 7 Effects of structure using sensitivity analyses

Figure 8 presents post yield behavior of samples in terms of variation of current values of stress sensitivity with vertical stress. Only few samples are shown for clarity. The current stress sensitivity is calculated using the current point on the post yield compression curve of the natural samples. The post yield behavior is obtained by quantifying the distance between the post yield compression curve of natural sample and its ICL. This is basically quantifying the structure degradation of natural sample in compression. The stress sensitivity values are reducing with stress which indicates the convergence of compression paths to ICL. The point of complete structural breakdown is indicated by the line of demarcation where $S_\sigma$ is one. For the samples shown, it shows that at the highest stresses reached in the tests, they have not been completely destructured.

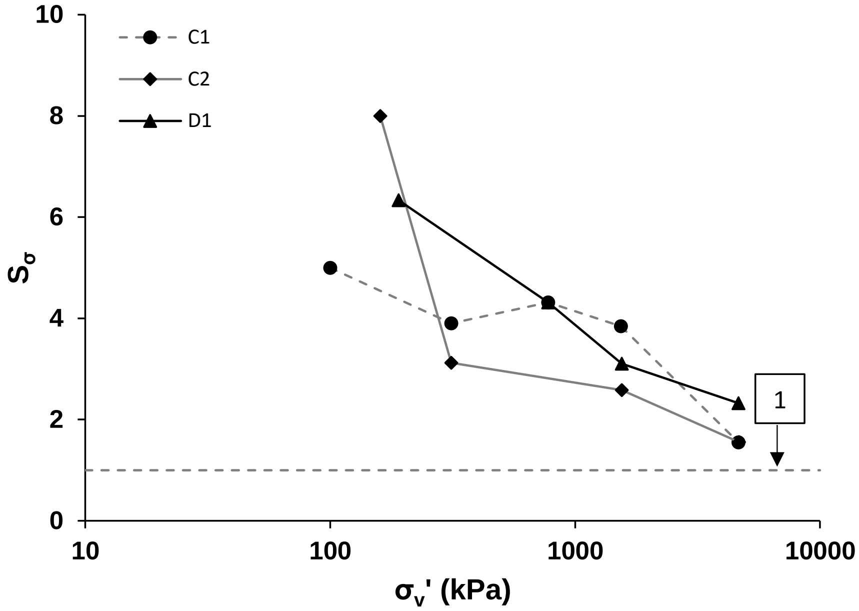


Fig. 8 Post yield behavior of samples

## 5. CONCLUSIONS

The effects of structure on clay from Nigeria have been investigated by conducting one-dimensional compression tests on the samples in the reconstituted and natural states. In addition, classification and index tests were carried out and mineralogy was studied. The samples are gap graded and plastic in nature. The mineralogy composed of quartz, feldspar and clay minerals which was dominated by kaolinites.
The reconstituted samples have convergent behavior within each depth and different NCLs are seen for samples from different depths. The compressibility parameters have no particular trend with depth. The natural compression paths reach a state outside their respective intrinsic normal compression line. The in-situ specific volumes vary slightly for the samples and the trend of yield stress with depth is not clear. Applying normalization to compare the behavior of the natural and the reconstituted samples, the effects of structure are small to medium in compression. Using sensitivity analyses, the effects of structure are positive and small.

## REFERENCES

Burland, J. B. (1990), "On the compressibility and shear strength of natural soils," *Geotechnique*, **46**, 491-514.

Cotecchia, F. and Chandler, R. J. (1997), "The influence of structure on the pre-failure behaviour of natural clay," *Geotechnique*, **47**, 523-544.

Cotecchia, F. and Chandler, R. J. (2000), "A general framework for the mechanical behaviour of clay," *Geotechnique,* **50**, 431–447.

Ferreira, P. M. V. and Bica, A. V. D. (2006), "Problems on identification of the effects of structure and critical state in a soil with a transitional behaviour," *Geotechnique*, **56**, 445–454.

Gasparre, A. and Coop, M. R. (2008), "Quantification of the effects of structure on the compression of stiff clay," *Can. Geotech. J.*, **45**, 1324-1334.

Martins, F., Bressani, L. A., Coop, M. R. and Bica, V. D. (2001), "Some aspects of the compressibility behaviour of a clayey sand," *Can Geotech J.*, **38**, 1177–1186.

Nocilla, A., Coop, M.R. and Colleselli, F. (2006), "The mechanics of Italian Silt; an example of transitional behaviour," *Geotechnique,* **56**(4), 261–271.

Okewale, I. A. and Coop, M. R. (2017), "A study of the effects of weathering on soils derived from decomposed volcanic rocks," *Engineering Geology*, **222**, 53-71.

Okewale, I. A. and Coop, M. R. (2018a), "On the effects of weathering on the compression behaviour of decomposed volcanic rocks," *TuniRock 2018, Hammamet*, Tunisia, pp. 85-90.

Okewale, I. A. and Coop, M. R. (2018b), "Suitability of different approaches to analyze and predict the behaviour of decomposed volcanic rocks," *J. Geotech. Geoenviron. Eng.*, **144**(9), 1-14.

Okewale, I. A. (2019a), "Influence of fines on the compression behaviour of decomposed volcanic rocks," *Int. J. of Geo-Engineering*, **10**(4), 1-17.

Okewale, I. A. (2019b), "Effects of weathering on the stiffness characteristics and the small strain behaviour of decomposed volcanic rocks," *Journal of GeoEngineering*, **14**(2), 97-107.

Okewale, I. A. (2020a), "On the intrinsic behaviour of decomposed volcanic rocks," *Bull Eng. Geol. and the Env*., **79**, 1311–1322.

Okewale, I. A. (2020b), "Applicability of chemical indices to characterize weathering degrees in decomposed volcanic rocks," *Catena*, **189**, 1-13.

Okewale, I. A. (2020c), "Compressibility and the effects of structure of tropical clay in incremental loading oedometer tests," Geotech. Geol. Eng., 1-17.

Okewale, I. A. and Coop, M. R. (2020), "A study of completely decomposed volcanic rocks with transitional mode of behaviour," *Bull. Eng. Geol. Env*. 1-16.

Okewale, I. A. and Grobler, H. (2020), "A study of dynamic shear modulus and breakage of decomposed volcanic soils," *J. GeoEng.,* **15**(1), 53-66.

Ponzoni, E., Nocilla, A., Coop, M. R. and Colleselli, F. (2014), "Identification and quantification of transitional modes of behaviour in sediments of Venice lagoon," *Geotechnique*, **64**, 694–708.

Rocchi, I., Okewale, I. A. and Coop, M. R. (2015), "The behaviour of Hong Kong volcanic saprolites in one-dimensional compression," *Volcanic Rocks and Soils: Rotterdam: Balkema*, pp. 281-287.

Xiao, Y., Coop, M. R., Liu, H. and Jiang, J. S. (2016), "Transitional behaviours in well-graded coarse granular soils," *J Geotech Geoenviron Eng*, **142**, 06016018.

Zuo, L. and Baudet, B. A. (2015), "Determination of the transitional fines content of sand-non plastic fines mixtures," *Soils and Found*, **55**, 213–219.