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# Compressive response of some agricultural soils influenced by the mineralogy and moisture

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A b s t r a c t. This study aimed to investigate the mineralogy, moisture retention, and the compressive response of two agricultural soils from South West Nigeria. Undisturbed soil cores at the A and B horizons were collected and used in chemical and hydrophysical characterization and confined compression test. X-ray diffractograms of oriented fine clay fractions were also obtained. Our results indicate the prevalence of kaolinite minerals relating to the weathering process in these tropical soils. Moisture retention by the core samples was typically low with pre-compression stress values ranging from 50 to 300 kPa at both sites. Analyses of the shape of the compression curves highlight the influence of soil moisture in shifts from the bi-linear to S-shaped models. Statistical homogeneity test of the load bearing capacity parameters showed that the soil mineralogy influences the response to loading by these soils. These observations provide a physical basis for the previous classification series of the soils in the studied area. We showed that the internal strength attributes of the soil could be inferred from the mineralogical properties and stress history. This could assist in decisions on sustainable mechanization in a data-poor environment.

K e y w o r d s: precompression stress, mineralogy, load bearing capacity

## INTRODUCTION

Increasing the cropland areas and the annual crop production cycle are very essential to achieve self-sufficiency in food production and economic stimulation in developing nations. These often involve mechanization of land clearing and development processes. This sometimes requires the use of heavy machinery and equipment particularly in the rainforest S-W Nigeria, where the terrain is far from being flat. If not properly planned, mechanized land clearing and development may have negative consequences on the soil, causing deformation through compaction and shearing. Such structural changes in the soil will alter the pore size shape, distribution, and connectivity (Horn and Smucker, 2005; Keller and Lamandé, 2010). Compaction, for example, affects the soil physical fertility by impeding the storage and supply of water and nutrients while increasing the aggregate strength and resistance to root penetration, decreasing infiltration and water holding capacity, thereby reducing fertilization efficiency and consequently crop yield (Keller and Lamandé, 2010; Saffih-Hdadi, 2009).

The response of soil structure to loading is largely dependent on the intrinsic strength attributes of the soil (Ajayi *et al*., 2009) often expressed as the load bearing capacity (LBC). Several parameters had been used to estimate the intrinsic strength of soils and evaluate the susceptibility or otherwise to compaction. Common parameters include the precompression stress values (Rucknage *et al*., 2007), penetration resistance (Almeda *et al*., 2012; Gao *et al*., 2012), shear strength parameters (Besalatpour *et al*., 2012; Zhang *et al*., 2001), packing density (Spoor *et al*., 2003), and rheometry parameters (Markgraf, 2011). Amongst the various parameters, the use of precompression stress for characterizing soil strength and load bearing capacity of soils is consolidated, probably because it is the only parameter that reflects the stress history of the soil. Precompression stress had been used on a farm and regional scale to define precaution and critical values to avoid subsoil compaction in mechanized agriculture (Dias Junior 2005; Horn *et al*.,

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2005; Horn and Fleige, 2007). It is also used to evaluate the impact of different tillage and land use practices on soil structure on varying time scales (Canarache *et al*., 2000; ) and as a criterion in other environmental protection issues (Baumgarten *et al*., 2011). The precompression stress values had been related to soil pedologic and anthropogenic factors including mineralogy (Ajayi *et al*., 2009; Baumgarten *et al*., 2011). A good pedologic background would form the basis for the use of precompression stress as a criterion for planning in data-poor environments of most developing nations.

In this study, our objectives were to investigate the mineralogy of some agricultural soils from a landlocked State in S-W Nigeria (Ekiti), determine the precompression stresses, and examine possible interactions with respect to using them as guidelines in mechanized agriculture.

## MATERIALS AND METHODS

Intact soil cores in 30 replicates were collected at the A horizon (5-10 cm) and B horizon (80-100 cm) at Ikere (5°23'16.94"E, 7°25', 13.22"N, 353 m) and Ilasa (5°42' 44.66"E, 7°47'23"N, 550 m). The selected sites have the potential for farm operations involving agricultural machinery due to the expanse of land and relative good yield from current small scale farm holdings. The samples were collected in 6.5 x 2.5 cm aluminium rings using a Uhland sampler. The sampling device was pushed carefully into the soil using a falling weight. At each sampling point, the ring filled with soil was removed from the sampler, wrapped with plastic materials and paraffin wax, and stored safely until compressibility and other tests were performed. All the samples were carefully packed and air freighted to the Soil Science laboratories of the Federal University of Lavras, Lavras MG Brazil, for analyses.

The field bulk density of each sample was determined using the premeasured ring parameters, and the scraped soil near the intact soil cores were air-dried, passed through 2 mm sieve, and used for other analyses. Chemical and physical analyses were conducted following the standard procedures described in Embrapa (2011). Particle size distribution was determined by physical dispersion using a fast agitator (10 000 r.p.m.) and chemical dispersion by contact of the sample with NaOH 1 mol $l^{-1}$ for 24 h. Sand particles (2.00-0.05 mm) were quantified by wet sieving, the clay content (<0.002 mm) was measured by the pipette method, and the silt content (0.05-0.002 mm) was determined from the difference. Particle density was determined using 95% hydrated alcohol on 20 g air-dried soil material in a 50 ml pycnometer. Moisture retention at -2, -6, -10, -33, -100, -500, and -1 500 kPa were obtained for the 2 profiles using disturbed samples. The values obtained were fitted with the unimodal van Genuchten retention function (van Genuchten, 1980). For the mineralogical characterization, X-ray diffractograms of the clay fraction were obtained using a Philips diffractometer with CoK$\alpha$ radiation and a Fe filter. The non-oriented slides were scanned from 4 to 50° (2$\theta$), using 0.02° steps and 1 s counting time per step.

For the compression test, the prepared soil cores held within the sampling rings in replicates were saturated by capillary and drained and to -2, -6, -10, -33, -100, -500, and -1 500kPa. The lower tension adjustment was done on pressure table, while higher tensions drainage was from ceramic plates placed inside pressure chambers. The drained samples were thereafter submitted to a uniaxial compression test using a pneumatic S-450 Terraload floating ring consolidometer (Durham Geo Enterprises, USA). During the test, the samples held within the coring cylinders were placed inside the compression cell. Vertical stresses of 25, 50, 100, 200, 400, 800, and 1 600 kPa were then applied sequentially. Each stress increment was applied and the sample was allowed to compress and come to equilibrium with little or no further deformation possible, and the with the excess pore water pressure within the sample approximately equal to zero. Thus, the final or equilibrium stress is an effective stress. To establish the relationship between the applied load and deformation in the sample during the compression test, the deformation rate in form of dial reading was assessed at elapsed times of 0.25, 0.5, 1, 2, 4, 8, 15, 30, 120 min or stopped when 90% of the maximum deformation had been reached. 90% of maximum deformation was determined by plotting the dial readings on an arithmetic scale (ordinate) versus the square root of the corresponding elapsed time (abscissa) and a straight line was drawn through the data points in the initial part of the curve obtained until this line intercepts the y axis (dial readings). A second straight line was drawn from this intersection with all abscissas 1.15 times as large as corresponding values on the first line. The intersection of the second line and the laboratory curve is the point corresponding to 90% consolidation (Taylor, 1948) (Fig. 1). For Brazilian/tropical soils, it has been established that 15 min is enough to reach the 90% of the maximum deformation in partially saturated soils (Dias Junior, 2003). When the 90% deformation is reached before the 15 min schedule, the dial reading will be less or equal to 5, thus the

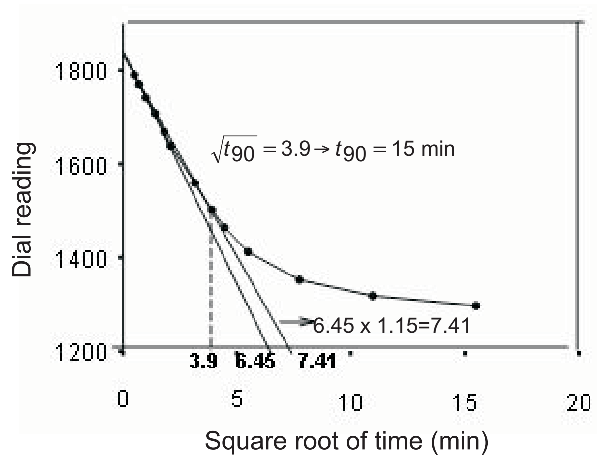


**Fig. 1.** Square root of time versus dial reading for establishing a 90% consolidation point.

next pressure step is applied. Free drainage was ensured by sinter metal plates beneath and above the soil samples during the test. Moisture loss during the test was established by taking the weight of the sample before and after the test. The final water content of each sample was determined by oven-drying at 105°C for 24 h. Thus, the final void ratio and sample moisture content could be determined besides other parameters.

The stress versus strain data were used to predict the soil compression curves, from which the precompression stress ($\sigma_p$) was determined following the procedure of Dias Junior and Pierce (1995) based on the Cassagrande method. The precompression stress values were thereafter plotted against the soil moisture content or soil matric potential and a regression line fitted from a function in the form $\sigma_p = 10^{a+b\theta}$ (Dias Junior, 2003).

## RESULTS AND DISCUSSION

The particle-size-distribution, textural class, and particle and bulk densities of the samples are presented in Table 1. The textural class and particle size distribution agreed with previous studies on the major agricultural soil in South West Nigeria by Adekalu and Osibitan (2001), with relatively higher silt content in comparison with soils from other parts of the country. The silt-clay ratio, which is mostly used to understand the weathering-leaching history, exhibited marked differences in the A and B horizons at Ilasa. The low clay content in the A horizon may have resulted from the erosive effect of the characteristic storm events of the studied site, which significantly washed off the clay and silt fractions. The organic matter content is generally low like in many well-drained tropical soils.

The X-ray diffractograms (XRD) of the <2 $\mu$m clay fraction from both sites are presented in Fig. 2. The dominance of low activity clay mineral, kaolinite relative to aluminium- and iron-oxides, is shown. This result is consistent with the observation from previous studies (Adekalu and Osunbitan, 2001; Lal, 1979). The implication of this on soil structure had been observed to include minimal shrinkage and swelling (Miranda-Trevino and Coles, 2003). In Ilasa, the absence of gibbsite and the very low content of iron oxides in the clay fraction will favour a face-to-face arrangement of the kaolinite plates, resulting in high bulk density of the samples (Ajayi *et al*., 2009). The cohesive aspect of this soil, easily identifiable in the field when the soil is somewhat dry, is a distinctive character of this soil class, similar to hard-setting soils (Giarola *et al*., 2003). Contrarily, in the samples from Ikere, the presence of gibbsite in the clay fraction hinders the face-to-face arrangement of the kaolinite sheets. The gibbsite would act as a wedge between the kaolinite sheets, thereby favouring a granular structure of the soil ( Ajayi *et al*., 2009; Bartoli *et al*., 1992). Based on morphological observations and measurements, highlighting the aspect of the subsoil below the A horizon, the soil-landscape relationships, and expert judgement, the soil at the studied sites were classified as Ultisols at Ilasa and Inceptisols at Ikere. This agrees with the results of the previous study performed by Adekalu and Osunbitan (2001) in the same region.

Moisture retention by the homogenized samples at various suction are presented in Fig. 3. At saturation, moisture retention was higher in the B horizon of the Ilasa site, where the clay content was highest. At field capacity of *ca*. 6 kPa and consistently till permanent wilting point (1 500kPa), moisture retention was the lowest in this sample in spite of having the highest clay content. Samples from the B-horizon of Ikere with the lowest clay content retained more water at saturation than those from the A horizon of Ikere and Ilasa. From field capacity and beyond, moisture retention was higher in the Ikere samples relative to the Ilasa samples in spite of having comparatively lower clay content. This suggests that moisture retention may not be directly proportional to the clay content of soil samples as sometimes reported (Wäldchen *et al*., 2012). The presence of VH (hydroxy-interlayered vermiculite) in both the A and B horizon samples from Ikere (Fig. 2) alters the surface area configuration creating more adsorption interphase between the layers for higher moisture retention than the kaolinite (Pai *et al*., 2004; Wang *et al*., 2004).

Similarly, there was no linear relationship between moisture retention and the organic matter content in this study as sometimes argued (Rawls *et al*., 2003). The complexity of the relationship between moisture retention and

**Table 1.** CEC characteristics of the studied soils

| Soil | Particle density | Bulk density | Sand | Silt | Clay | pH $H_2O$ | CECe | CECp | Al | OM | Fe | Soil texture |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (Mg m$^{-3}$) | | | (g kg$^{-1}$) | | | | (cmol dm$^{-3}$) | | (g kg$^{-1}$) | (mg dm$^{-3}$) | |
| Ilasa A | 2.85 | 1.33 | 453 | 189 | 358 | 5.4 | 3.2 | 6.4 | 0.4 | 14 | 90.4 | SC |
| Ilasa B | 2.85 | 1.25 | 345 | 105 | 550 | 5.6 | 3.2 | 5.8 | 0.3 | 8.0 | 76.8 | Clay |
| Ikere A | 2.68 | 1.37 | 558 | 132 | 310 | 6.1 | 7.0 | 8.5 | 0 | 9.0 | 73.4 | SCL |
| Ikere B | 2.68 | 1.40 | 593 | 134 | 273 | 6.2 | 7.0 | 8.7 | 0 | 6.0 | 99.5 | SCL |

CECe – effective cation exchange capacity, CECp – cation exchange capacity at pH 7.0; SCL – sandy clay loam, SC – sandy clay.

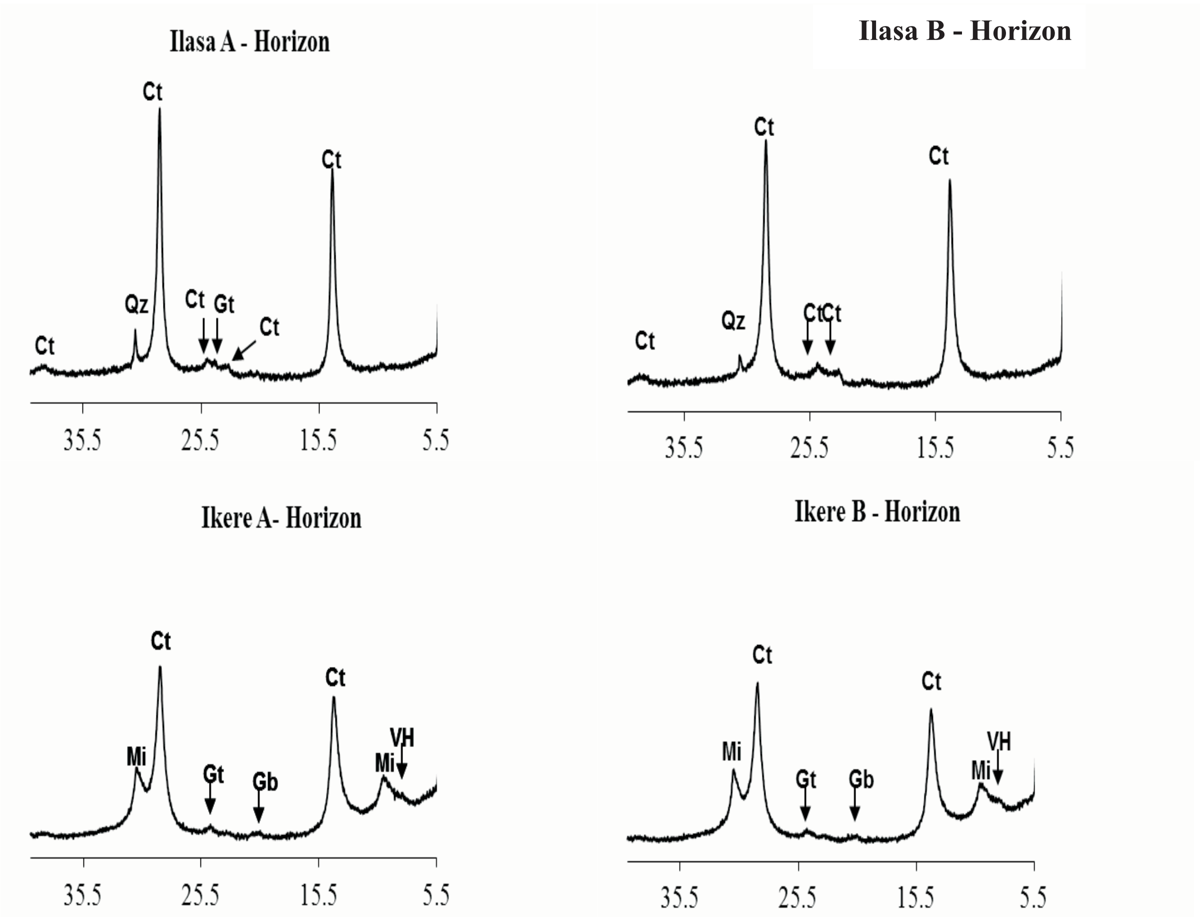


**Fig. 2.** Fine clay fraction X-ray diffractograms of the studied soils highlighting the mineral content and distribution. VH - hydroxy-interlayered vermiculite, Mi – mica, Ct – kaolinite, Gb – gibbsite, Gt – goethite, Qz – quartz.

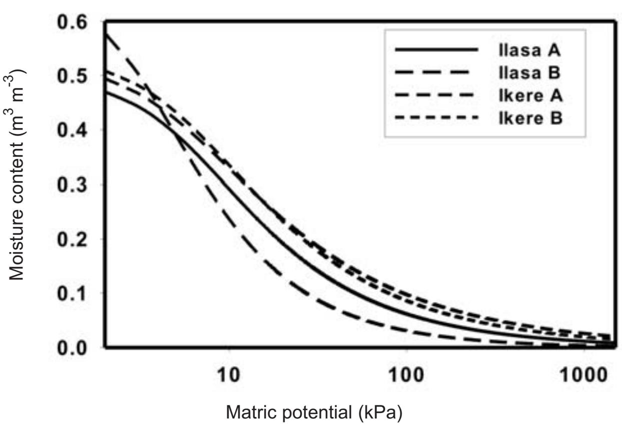


**Fig. 3.** Moisture retention by clay fraction samples from the various sites.

parameters of the soil is not surprising. Some previous research results have shown that water retention is a complex function of soil structure and composition (Cui *et al*., 2010; Rawls *et al*., 2003). We observed in this study that the interaction between moisture retention and the clay content of the sample varied at different matric potential. The clay content was noted may become more influential in moisture retention of samples as the soils dries out (Williams *et al*., 1983). Our results agreed with the findings of Lal (1979) on the relationship between physical properties and moisture retention characteristics of some Nigerian soils. However, it was observed that while it was possible to saturate the homogenized samples to a moisture level as high as 0.5 and 0.6 $cm^3$ $cm^{-3}$ at 2 kPa (Fig. 2), the core samples saturated similarly held moisture between 0.28 and 0.3 $cm^3cm^{-3}$. Therefore applying laboratory derived values using homogenized samples needs careful calibration in relation to in-situ field conditions; more so, the moisture status of the soil and its dynamics largely influence compressive response of soils.

The changes in the void ratio in response to vertical loading at some selected soil moisture contents in the studied soils are presented in Fig. 4. The selected gravimetric water contents (0.05, 0.09, 0.14, 0.17, 0.19, 0.22 kg kg$^{-1}$) represent the driest to the wettest conditions of the core samples when saturated and desiccated to 1 500 kPa. Although these moisture contents were not obtained at simultaneous matric potential in both the site and profile, we selected the points for the purpose of comparing with respect to the weight of water held within the soil mass irrespective

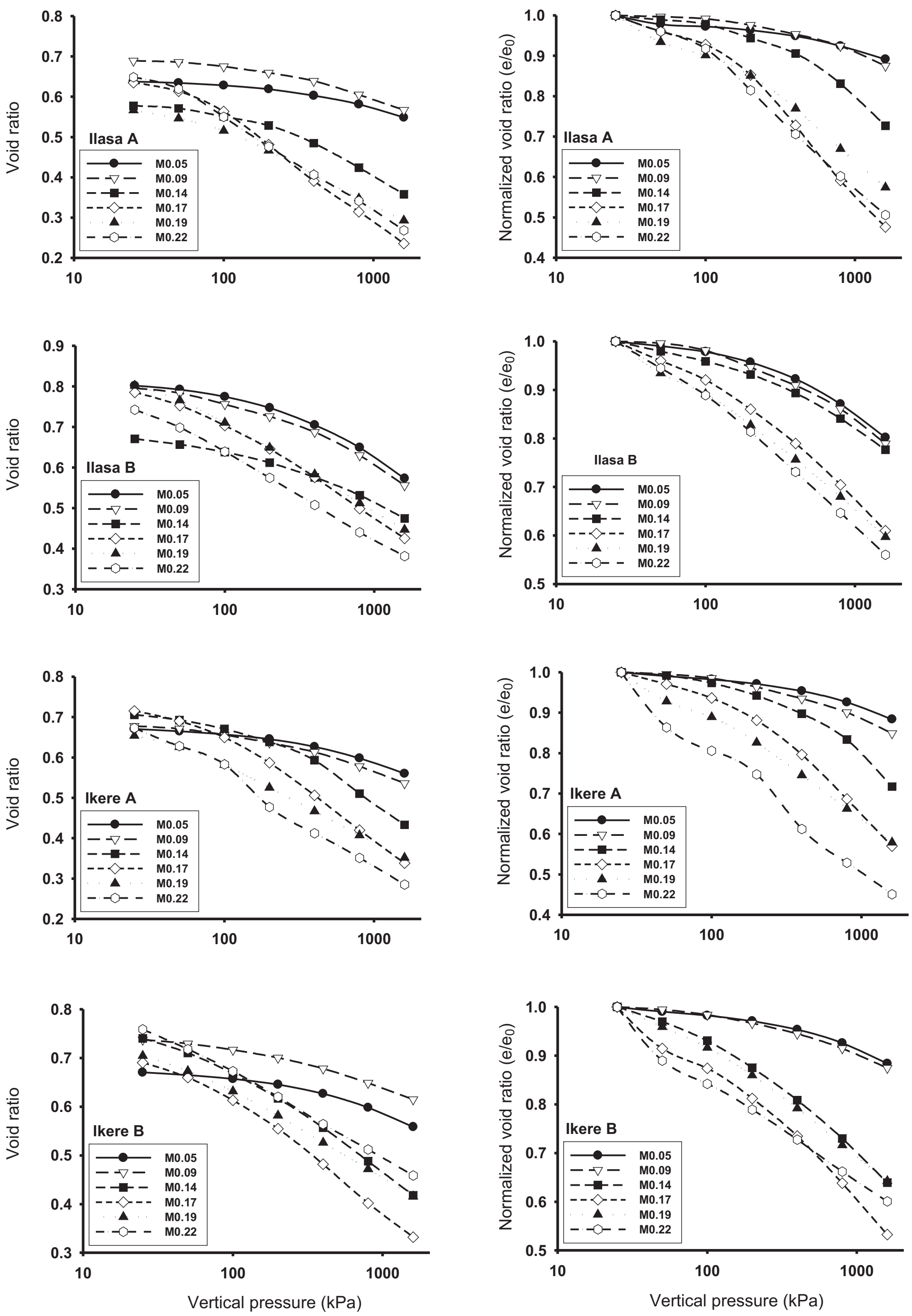


**Fig. 4.** Stress *vs*. void ratio responses for the studied samples at 6 uniform moisture contents.

of structural configuration. The strain values were normalized to accentuate the effect of the moisture content on the responses. The curves had both the elasto-plastic (bi-linear curve) and the S-shaped models widely used in characterizing confined compression tests (Tang *et al.*, 2009). However, closer examination showed the dominance of the elasto-plastic model. The normalized curves indicate that the compression curve changes from the elasto-plastic shape to the S-shape models as the moisture content increases. This observation may be explained under the assumption that the soil moisture status moderates the dominance of either physico-chemical parameters (clay mineralogy) or textural parameters (physical particle properties and fibres of organic matter) of soils under loading (Ajayi *et al.*, 2009; Markgraf *et al.*, 2011). It would have been interesting to see the shift in the curves when the soil became wetter (40-60 kg $kg^{-1}$), but this was not achievable in the core samples used in this study. The highest moisture content recorded in any core sample saturated by capillary and equilibrated to 2 kPa resulted in a moisture range between19-22 kg $kg^{-1}$. It was, however, suggestive that the compression curve would continue to assume the S-shaped model as the moisture content increased.

The observed changes in the soil compression curves can be explained with the 3-phase system description of soil compaction processes by Horn *et al.* (1995) and the coupled process theory (Horn, 2003). External pressure on wet soil first results in deformation of the available air-filled pores within the soil matrix, forcing a re-arrangement in porosity (between macro- and micro-pores) and minute volume changes, depending on several interrelated factors of the soil physicochemical parameters and stress history (Horn, 2003; Wiermann *et al.*, 2000). If the pressure is sustained, the air-filled pores re-arrange and thin out, thus stress is transmitted to the moisture filled pores altering the pore water pressure depending on the pore continuity. The continuity of pores is influenced by textural parameters and the magnitude of the external pressure. The extent and dynamics of the pore water pressure determine the slope length in the S-shape curve and this depends on the initial moisture content and the inter-granular cohesiveness of the soil particles. If the initial moisture content is high, the slope will be low and the slope length long; thus the S-shape becomes distinct (Barik *et al.*, 2011; Tang *et al.*, 2009). Previous work of Baumgartl and Köck (2004) has shown that these processes are largely influenced by the permeability (physicochemical parameters) and hydraulic conductivity (textural parameter) of the soil. In the analysis of the compression curves in this study, it was observed that the moisture content more than the initial void index or bulk density influences the shape of the compression curve.

The deformation (changes in bulk density) as a function of applied stresses was plotted to calculate the precompression stress following the Cassagrande method as earlier described. The calculated values of precompression stresses and the corresponding moisture contents were used to estimate the load bearing capacity (LBC) (Fig. 5). The LBC, which is a regression equation between the moisture content and precompression stresses, was compared for the A and B horizons of both sites. The parameters of the equation and their coefficient of determination are presented. All the equations were significant at a 1% probability level for the t-Student test and the coefficient of determination ranged from 0.87 to 0.95. The estimated linear '*a*' and angular '*b*' coefficients of the load bearing capacity equation ranged from 2.59 to 2.95 and from 1.65 to 3.96, respectively. In the LBC curves, the dependence of soil precompression stress on the water content in the soil was evident. Bearing capacities of the soil are reduced as the moisture content increases. This observation was consistent with the results of several studies on the strength of soil samples (Dias Junior *et al.*, 2007; Peng *et al.*, 2004). Peng *et al.* (2004) have explained that parameter '*a*' indicates the intrinsic strength of dry soil while parameter '*b*' reflects the soil packing state.

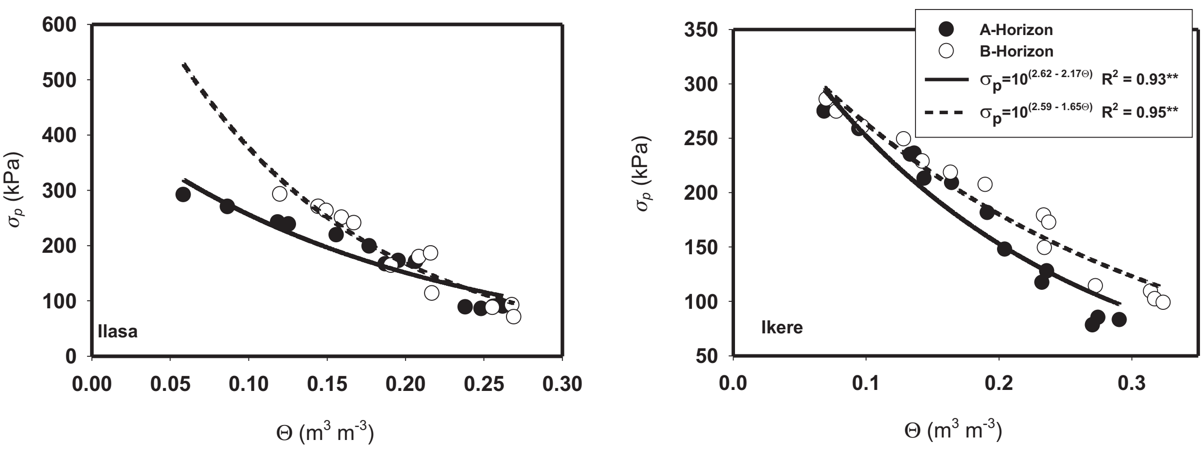


**Fig. 5.** Load bearing capacity curves of the studied soils.

**T a b l e 2.** Comparison of the load bearing capacity models for homogeneity for the studied sites

| Sites | F | | | | | |
|---|---|---|---|---|---|---|
| | 5% | 1% | Angular coefficient, b | | Intercept of regression, a | |
| | | | 5% | 1% | 5% | 1% |
| Ikere A *vs*. Ikere B | H | H | * | ns | * | ns |
| Ilasa A *vs*. Ilasa B | H | H | * | ** | * | ** |
| Ikere A *vs*. Ilasa A | H | H | ns | ns | ns | ns |
| Ikere B *vs*. Ilasa B | H | H | * | ** | ns | ns |
| Ikere A+B *vs*. Ilasa A+B | H | H | ns | ns | ns | ns |

H – homogeneous.

Pressures that could be sustained at both sites were between 50 and 300 kPa. The LBC of the B horizon of Ilasa had a sharp slope resulting in high bearing capacity when the soil was dry. This observation can be explained by the natural densification probably related to the soil formation process. However, the high precompression stresses at the very low moisture content further confirm the dominance of textural parameters in the sustenance of the applied pressure. The implication of these results is that the soils from the study sites may be able to sustain load from most equipment used in agricultural mechanization activities. However, it must be noted that the moisture range from the field samples was low, peaking at 0.23 kg $kg^{-1}$.

The observed precompression stress and differences in the load bearing capacities may be related to the relative proportion of kaolinite in the clay fraction (Miranda-Trevino and Coles, 2003). Kaolinite exhibits high chemical stability and a low expansion coefficient. As a consequence of its well-packed structure, kaolinite particles are not easily broken down and the kaolinite layers are not easily separated. Tripathy *et al*. (2002) have observed that the inter-particle forces of attraction in kaolinite result in a structure or particle arrangement which influences shear strength in soil. Other studies done on Ultisols and similar soils from other parts of the world agree with our results (Silva and Cabeda, 2006). Our results suggest that the fitted parameter '*a*' is related to the packing state of the solid particles expressed by soil bulk density and air-filled porosity (macro-pores) which affect the pore water pressure.

The load bearing capacity equations were compared for homogeneity of their parameters (Snedecor and Cochran, 1989). For the homogeneity test, the equations are compared together by examining the intercept (a), slope (b), and the homogeneity parameter data (F). The results suggest that the data-set of some studied profiles are statistically homogenous, thus they could be pulled together to construct a representative LBC curve (Table 2) .

The results provide some insight into the observation on the load bearing capacities of the studied soils. The A and B horizon of both sites were homogenous in the F - values, but at Ikere, there were differences in both parameter 'a' - intrinsic strength of dry soil and parameter 'b'- soil packing state. However, the differences were not sufficient to reject the statistical homogeneity of the profiles. When the data set for the 2 studied horizons and sites were compared, it was observed that the 2 sites were not only homogenous, but the angular and intercept parameters were not statistically different, thus the data set could be pulled for a representative bearing capacity covering the 2 sites. This observation provides a soil physical explanation for the general categorization of the soil in the area studied by Adekalu and Osunbitan (2001). This is very important in a developing country like Nigeria, where analyses of soil physical and mechanical parameters are scarce, but rapid mechanization without damaging the environment is required.

## CONCLUSIONS

1. This study shows that the mineralogy of the soil in the agriculture belt of Ekiti State, Nigeria, is dominated by the secondary mineral kaolinite, which is play in structural orientation.

2. The structural orientation of the dominant minerals in the soil has a remarkable influence on the moisture retention, precompression stress, and load support capacity of the soil. Mineralogy provides a soil-physics basis for the previous 'series' classification of soil in the study area. This would allow larger-scale load support capacity and compaction susceptibility mapping as a precursor in mechanization planning.

3. As a result the soils are most often naturally adensed with high precompression stress values and load support capacity with commensurate high susceptibility to compaction. Carefully designed tillage is required to ensure good soil structure for enhanced moisture holding and root penetration.

4. The soil moisture status influences the shape of the soil compression curve changing it from the elasto-plastic shape to S-shaped models as it increases.

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