Hydrophysical properties of Humic Latosols from Brazil**

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A b s t r a c t. The hydrophysical properties of the prevalent Humic Latosols (organic matter rich and charcoal stained soils) were related to structural sustainability under loading. Intact cores collected at the Ap, AB, Bw horizons were used for hydrophysical characterization. Precompression stresses at 10 suctions were obtained to estimate the load bearing capacities. We observed the dominance of kaolinite with some occurrences of gibbsite and hydroxy-interlayered vermiculite in the clay mineralogy. The high organic matter content in the Ap horizon favours crumb structure with the structural unit presenting high porosity and water retention. The structure of the AB and Bw horizons was, however, granular with structural units having low porosity. Possible influence of earlier incidences of fire enhanced the organic matter and carbon content in the soil reducing down the profile from 42.5 g kg^{-1} at the Ap to 16.4 g kg^{-1} at the Bw horizon. The C/N ratio increased from 14 at the Ap to 17 at the Bw, and air capacity increased from 18.1% at Ap to 32.0% at Bw. Precompression stress values were: 100.6±40.7 kPa at Ap, 117.4±44.6 kPa at AB, and 116.1±58.9 kPa at Bw. Load bearing capacities at the AB and Bw horizons were homogenous.

K e y w o r d s: Humic Latosols, organic matter, precompression stress, hydrophysical properties

INTRODUCTION

In recent years, there is a growing interest in the understanding of the physicochemical processes of 'organic matter' rich soils regarding their significance in carbon sequestration and enhanced agronomic performance. These studies are often conducted with artificially amended soil. However, some unusual landscape processes in the tropics, particularly in Australia and Brazil, produced some 'naturally' carbon enriched soil that could assist in these studies. For example, periodic fires across the Australian landscapes resulted in a natural process of carbon sequestration from atmosphere to soil by the conversion of biomass to charcoal (Lehmann *et al.*, 2008). Similarly, in the Brazilian landscape, the ancient agricultural management practices that created *Terra Preta do Indio* (deep black soils) were the precursor to biochar application in agriculture (Lehmann *et al.*, 2008). Moreover, in the Brazilian landscape, there exist some well drained, fairly weathered soils with notably high levels of organic carbon (OC) covering approximately 144 000 km^2 and classified as Humic Latosol (HL) (Umbric Ferralsols – WRB, Ker, 1988; Marques *et al.*, 2011).

Humic Latosols developed from gneiss of the precambrian complex, with an udic moisture regime and isothermic/thermic regime and are generally dystrophic (Marques *et al.*, 2011; Silva *et al.*, 2007). The dystrophic condition and formerly prevailing mild temperatures inhibit microbial activity and favour the accumulation of organic matter. Their profiles are characterized by the development of a thick A horizon in a solum which is predominantly kaolinitic. Humic Latosols can be classified as Hydrol, Humic or Low-Humic, depending on the ratios of the minerals: kaolinite, gibbsite, goethite, magnetite, mica, quartz, smectite and allophane in the sample (Sherman and Alexander, 1959). Humic Latosols contain substantial amounts of allophane (between 5 and 30%) in their fine clay fraction, giving it a dark colour (chroma <4) (Embrapa, 2013). A pedo-geomorphological study and radiocarbon dating on four profiles of HL in Brazil revealed that the strongly developed umbric epipedons were very old and had a continuous and progressive melanization (a darkening process of the soil by addition of

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organic matter) with depth, which is strongly influenced by the decomposition and redistribution of charcoal fragments by soil fauna (Silva and Vidal-Torrado, 1999).

The marked content of soil organic matter in Humic Latosols makes it an important reservoir of organic carbon (Andrade *et al*., 2004; Fontana *et al*., 2008), thus requiring proper management to forestall degradation. This is important, considering that up till now the mechanism of accumulation and stabilisation of organic matter in Humic Latosols is not properly understood (Marques *et al*., 2011; Silva and Torrado, 1999). Humic Latosols are similar in physical properties to the Terra Preta do Indio soils of Brazil which hold large reserve of organic carbon (Lehmann *et al*., 2008). However, their formation processes and chemical properties are quite different. Whereas Terra Preta do Indio was formed primarily under human influence with uneven vertical and horizontal distribution of organic carbon, high phosphorus content (200-400 mg kg^{-1}) and cation exchange capacity dominated by Ca^{2+} and Mg^{2+}, Humic Latosols are natural phenomenon (Novotny *et al*., 2009). The charcoal fragments occurring in the top slope and decreasing gradually in carbon content with depth are not associated with lithic artefacts or pieces of pottery. Humic Latosols has low concentrations of phosphorus and the exchange complex is dominated by Al^{3+} (Ker, 1997; Marques *et al*., 2011).

Humic Latosols are relatively fertile and well cultivated in the Brazilian mechanized agriculture system for the production of eucalyptus, coffee, and soybean (Marques *et al*., 2011). However, the elevated organic matter and clay content associated with all types of Humic Latosols implies higher susceptibility to shearing and compaction amongst other forms of degradation under mechanized agriculture. Compaction will degrade the soil structure and negatively alter the pore geometry and functions. These alterations affect the soil quality and impact negatively the environment in terms of CO_2 emissions and carbon sequestration (Parfitt *et al*., 1997). Moreover, it has been reported that organic matter decomposition due to land conversion for agriculture is a major driver of climate change (Watson *et al*., 2000). It is therefore presumed that adequate understanding of the physical processes relating to the accumulation and stabilisation of organic matter in Humic Latosols would contribute to a better understanding of the carbon cycle (Calegari, 2008; Marques *et al*., 2011).

Land conversion in mechanized agriculture generally decreases the size of the soil aggregate. Additionally, the organic matter would decrease and the free Fe oxides in the converted land would increase, while the aggregation of soil particle decreases (Teh Boon Sung, 2012). The implication of this on the structure of Humic Latosols may be damaging and there has been no study that determines the intrinsic strength of Humic Latosols, despite their increased cultivation under mechanized agriculture in Brazil. Similarly, the structural configuration of Humic Latosols is important in carbon sequestration potential. Thus our objectives in this study were to characterize the hydrophysical behaviour

of typic Humic Latosols from Brazil, evaluate the stress-strain responses at different matric potentials, and estimate the load bearing capacity for different horizons.

MATERIALS AND METHODS

Working with detailed classification and characterization of the prevalent Humic Latosols found in Brazil by Calegari (2008) and Marques *et al*. (2011), we selected a representative sampling site with high proportion of clay particles within Minas Gerais State, Brazil. At the site, intact soil cores were collected in 6.5 x 2.5 cm rings in the Ap (0-10 cm), AB (60-80 cm) the A-B horizon transition, and in the Bw (100-120 cm) horizon. At each horizon, 45 samples were collected by carefully pushing the rings into the soil using Uhland sampling device. The ring filled with soil was removed from the sampler and wrapped in plastic materials and waxed to preserve the structure during transport to the laboratory.

In the laboratory, the soil samples were carefully trimmed to the size of their rings, to determine the field bulk density. Scraped samples near the intact soil cores were air-dried, passed through a 2 mm sieve to do standard physical and chemical characterization of the studied soils following the standard procedures used in Brazilian laboratories as described in Embrapa (1997). Particle size distribution was determined using the pipette method after dispersing with 1 mol l^{-1} NaOH, and shaken in motorized agitator end-over-end for 24 h. Water dispersible clay (*WDC*) was determined in the same way as particle size using H_2O instead of NaOH. The clay dispersion ratio (*CDR*) was calculated as:

$$CDR = \frac{WDC\,(\text{g kg}^{-1})}{TC\,(\text{g kg}^{-1})}, \tag{1}$$

and the clay flocculation index (*CFI*) was computed as:

$$CFI = \frac{TC \cdot WDC}{TC}. \tag{2}$$

Particle density was determined using 95% hydrated alcohol with 20 g of oven-dried soil material in a 50 ml pycnometer. Total porosity (TP), air capacity (AC), and other pore parameters were calculated according to Hartge and Horn (2009) from the water retention data. Organic carbon (OC) was determined using the wet combustion method. The aggregate stability index (ASI) was established by screening in water, with a set of 2, 1, 0.5, 0.25 and 0.105 mm sieves, and the geometric mean diameter of aggregates (GMD) was determined following the procedure of Sutherland and Ziegler (1997). The stability index (SI), which indicates the level of organic matter required to maintain the structure, was obtained based on the expression:

$$SI = (OM (C + S)-1)100, \qquad (3)$$

where: SI – stability index (%), C – clay content (%), S – silt content (%), and OM – organic matter content (%). We determined Si, Al, Fe, Ti and Mn after digestion with 9.4 mol l^{-1} H_2SO_4. Gibbsite (Gb) and kaolinite (Ka) contents were determined in the iron-free clay fraction, while goethite (Gt) and hematite (Hm) contents were determined in the iron-concentrated clay fraction according to Kampf and Schwertmann (1982). X-ray diffractograms of the clay fraction were obtained using a Philips diffractometer, with CoKα radiation and Fe filter. The non-oriented slides were scanned from 4 to 50°2θ, using 0.02°2θ steps and 1 s counting time per step.

Water retention at the studied horizons was characterized using intact samples in replicates, desiccated to -1, -2, - 4, -6, -8, -10, -33, -100, -500 and -1 500 kPa after initial saturation by capillary. The water content was obtained gravimetrically by drying the samples at 105°C for 48 h. Uni-axial compression test was implemented at these suctions using a pneumatic S-450 Terraload floating ring consolidometer (Durham Geo Enterprises, USA). For the test, the sample held within the coring cylinder and placed in compression cell was submitted to vertical pressures of 25, 50, 100, 200, 400, 800 and 1 600 kPa in steps. Each pressure step was applied until the sample compressed and came to equilibrium. At this point, there would be little or no further deformation in the sample and the excess pore water pressure within the sample was approximately equal to zero. Thus, the final or equilibrium stress was the effective stress (Holz and Kavaz, 1981). 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 was reached (Ajayi *et al*., 2013). For tropical soils, it has been established that the 90% of the maximum deformation of soil sample is attained at about 15 min in partially saturated condition (Dias Jr., 2003). Free drainage was ensured by sinter metal plates beneath and above the soil samples. The final water content of each sample was determined by oven-drying at 105-110°C for 24 h. The stress versus strain data were used to construct the soil compression curves for the measured suctions and the precompression stress (σ_p) was determined following the procedure of Dias Jr. and Pierce (1995).

RESULTS AND DISCUSSION

The studied Humic Latosols were slightly acidic at the 3 horizons with the pH (in water) declining from 5.1 at the Ap -horizon to 4.7 in the Bw-horizon. This is consistent with the behaviour of Latosols. The organic carbon, total carbon concentration and cation exchange capacity (CEC) were the highest in the Ap horizon, decreasing down the profile (Table 1). The low range of CEC in Latosols had been related with the presence of low activity clay, kaolinite and oxides (Tawornpruek *et al*., 2006). The CEC as observed here is not directly related to soil organic matter concentration, since much of the exchange capacity in these soils is due to kaolinite (Hart *et al*., 2003) and many exchange sites on the organic matter are occupied by [Al^{3+}] which is not readily exchanged (Schnitzer, 1986; Tawornpruek *et al*., 2006).

The texture at the sampled horizons was clay with very low silt content. Bulk density (*BD*) values ranged from 1.19 to 1.28 Mg m^{-3}. The values are in the median range of the 0.7-1.7 Mg m^{-3} bulk density observed in Latosols types found in Brazil (Ajayi *et al*., 2009). The bulk densities of the Latosols types have been related to the proportion of iron oxides or gibbsite which influences the arrangement of the kaolinite plates either into blocky or granular structure (Ajayi *et al*., 2009; Severiano *et al*., 2013). The particle density ranged from 2.30 to 2.44 kg dm^{-3}, while the packing density ranged from 1.68 to 1.70 Mg m^{-3}. The packing density, though not commonly used in agricultural soil mechanics, gives a clue to the arrangement in packs of the soil particles and aggregates. It is computed as:

$$PD = BD_d + 0.0009C, \qquad (4)$$

where: BD_d is the dry bulk density and C is the clay content (Jones *et al*., 2003). The packing density results showed that Humic Latosols are moderately packed along the profile in a uniform manner. The values were higher than the average for most variants of Latosols in Brazil (Ajayi *et al*., 2009), possibly due to the level of organic carbon in the soil matrix. The particle density values were lower than the average 2.65 Mg m^{-3} used for mineral soils.

The clay-dispersion ratio (*CDR*) and water dispersible clay (*WDC*) were very high in the Ap and AB horizons, indicating a likelihood of high erodibility at the thick epipedon that characterizes humic Latosols (Igwe, 2005; Marques *et al*., 2011), therefore adequate management is essential to maintain HL when cultivated. This observation contrast the suggestion of high micro-aggregates stability resulting from the cementing action of OM and aggregation action of Fe and Al oxides, particularly in clayey soils (Donagemma *et al*., 2003). Both indices were very low in the Bw-horizon, possibly due to smaller content of OM in both the Fe and Al oxides at this horizon. This difference in the behaviour of the clay fraction in water between the A and B horizons was similarly observed by Nguetnkam and Dultz (2012) in a study on Oxisols in Central North Cameroon. In a study on Ultisols in a tropical catchment, WDC was observed to be influenced by the several factors including pH, soil organic carbon and CEC (Igwe and Udegbunam, 2008). We did not notice any distinct influence of these parameters on the measured WDC. A study by Józefaciuk *et al*. (1995) had similarly shown that the total

and divalent iron contents, surface area and average adsorption energies of water dispersible clay were complicated functions of the pH. The relationship reflects the simultaneous effect of mineral destruction and aggregate disruption processes under the influence of protons on soils.

The XRD (not presented) showed the dominance of kaolinite over gibbsite and the presence of hydroxy-interlayered vermiculite (HIV) in the clay mineralogy. It would therefore be expected that Humic Latosols would only shrink and swell minimally. Moreover, the prevalence of organic matter would hinder the formation of a blocky structure by the kaolinite sheets, thereby favouring a crumb structure in the Ap-horizon (Resende *et al.*, 2014). This structure contributes to the observed low bulk density which makes Humic Latosols particularly susceptible to compaction. The occurrence of HIV has been reported in some Latosols in Brazil (Ker, 1997). Although not measured, charcoal fragments were observed to be scattered in the soil matrix suggesting that, in addition to other formation factors, natural fires, charcoal fragments decomposition and redistribution by soil fauna in former times possibly played an important role in the pedogenesis of some of the Humic Latosols of Brazil (Marques *et al.*, 2011; Tomasi *et al.*, 2012), similar to the chernozemic soils in Germany (Schmidt *et al.*, 1999) and volcanic ash-rich soils in Japan (Shindo *et al.*, 2004).

Humic Latosols retain water very well along their profile with more water retained at the Bw-horizon (Fig. 1). This may be attributable to the prevalence of clay particles, organic matter levels and the previously noted occurrence of HIV in the clay mineralogy (Martin *et al.*, 1998). The presence of HIV in the clay mineralogy affects the available adsorption sites between the mineral layers, thereby enhancing water retention (Ajayi *et al.*, 2013). The adequate water retention behaviour apparently makes the soil more productive in agriculture and forestry, but more susceptible to compaction in mechanised agriculture, if the soil is moist or wet at preparation epoch.

The precompression stress values obtained for the samples at various suctions between near saturation (0 kPa) and permanent wilting point (-1 500 kPa) are presented radially in Fig. 2. Similar to observations in several previous studies (Iori *et al.*, 2013), the precompression stress increases as the water dries out, indicating that the internal bonding force between the soil particles weakens as the water level in the soil increases (Horn *et al.*, 2004). Although there is no clear trend in terms of which of the horizons have the highest precompression stress, it does appear that at suction level critical in agriculture (- 10 kPa to - 100 kPa) the Bw-horizon had higher values of precompression stresses, while the Ap-horizon had the lowest values. To appreciably understand the distribution of the measured precompression stresses at the various horizons, a box plot (Fig. 1b) was prepared. This clearly described the magnitude of variation in the Bw horizon while showing the median values of

the precompression stress were slightly higher in the AB, transition zone, and lowest at the topsoil, Ap. Since the precompression stress reflects the pedogenetic processes and anthropogenic effects (Horn *et al.*, 2004) and the maxi-

T a b l e 1. Characteristics and behaviour of the Humic Latosols (HL) at the studied horizons

Parameter	Horizon		
	Ap	AB	Bw
Clay (g kg^{-1})	660	690	710
Sand (g kg^{-1})	300	280	280
Silt (g kg^{-1})	40	30	10
CECe (cmol$_c$ dm^{-3})	2.27	1.19	1.07
pH$_{water}$	5.15	4.80	4.70
Particle density (kg dm^{-3})	2.44	2.30	2.38
WDC (g kg^{-1})	468.5	490.1	65.4
CDR	0.710	0.710	0.092
CFI	0.290	0.290	0.908
Stability index	4.6	7.9	10.7
Total pore volume (%)	56.59	53.34	62.33
Air capacity (%)	18.12	16.64	32.04
Field capacity (%)	38.47	39.92	30.29
Total water (%)	21.44	22.50	22.45
Organic carbon (g kg^{-1})	42.5	17.5	16.4
Total carbon (g kg^{-1})	55.7	22.8	18.7
Nitrogen	3.9	1.5	1.1
CEC$_{pH\,7}$ (cmol$_c$ dm^{-3})	8.46	6.59	5.61
Packing density	1.70	1.67	1.68
Bulk density (Mg m^{-3})	1.28	1.22	1.19
Plastic limit (%)	0.27	0.32	0.31
Liquid limit (%)	0.51	0.48	0.58
C/N Ratio	14	15	17
GMD (mm)	3.59	3.83	3.91
Wide coarse pores (%)	32.02	30.78	51.44
Narrow coarse pores (%)	20.53	17.53	4.22
Medium pore (%)	9.56	9.51	8.35
Fine pores (%)	37.89	42.18	36.02

mum vertical overburden stress that the soil has sustained in the past (Holtz and Kovacs, 1981), the magnitude of variation in the AB and Bw horizons, though unexpected, may be related to differential pedogenetic activities at this layer. The relatively higher precompression stress values in the Bw horizon is consistent with some previous studies on another variety of Latosols at this horizon in Brazil (Ajayi *et al*., 2009) and had been shown to be lower than the critical strength for root elongation (Römkens and Miller, 1971). Thus, the development of deep-rooted plants will be unhindered in Humic Latosols. Comparing the range of values of the precompression stresses obtained, Humic Latosols are intermediate between the blocky and granular structured Latosols. Latosols structure is strongly influenced by the clay mineralogy and oxide contents (Ajayi *et al*., 2009).

Kaolinitic Latosols with high amount of iron oxides and no gibbsite form blocky structure resulting in high precompression stress values, while gibbsitic Latosols are granular in structure and have low precompression stress values.

Precompression stress, when measured at different water content or suction, is a useful indication of the sample internal strength (Pais *et al*., 2013) but does not provide sufficient information for decision making in agriculture and forestry operations, since soil water varies over very short time span. We therefore estimated the load bearing capacity (LBC) of the Humic Latosols at the studied horizon from the measured precompression stress values at various suctions. The LBC provides a better insight into the variation of the soil internal strength with water contents (Fig. 2a),
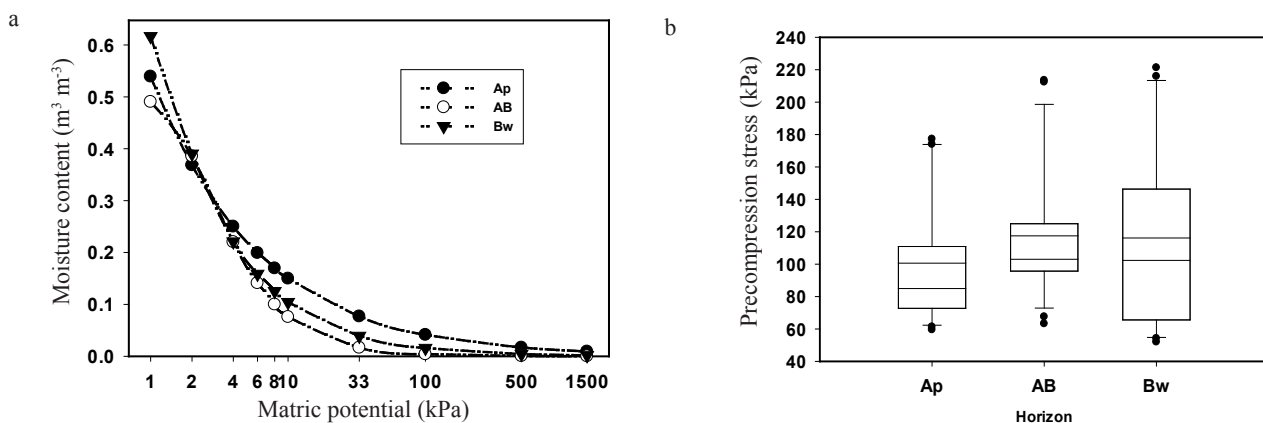

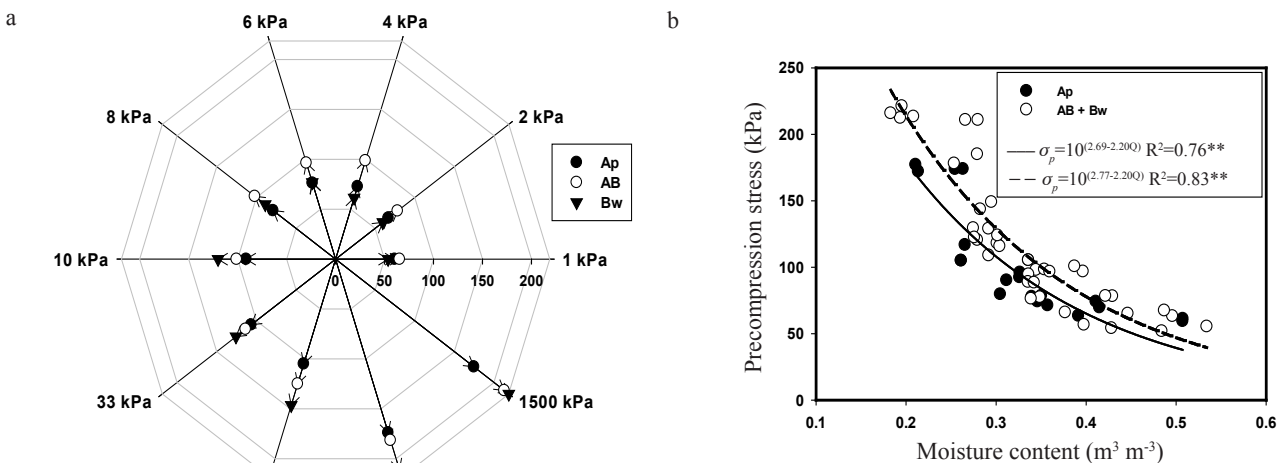**Fig. 1.** Water retention (a) and distribution of the precompression stress (b) at the 3 horizons studied.

Fig. 2. Variation in precompression stresses with suction (a) and load bearing capacity equations after statistical comparison (b).

T a b l e 2. Statistical comparison of the load bearing capacity equations at the studied horizons

Horizon	F		F			
			Angular coefficient, b		Intercept of regression, a	
	5%	1%	5%	1%	5%	1%
Ap *vs*. Bw	H	H	NS	NS	*	**
Ap *vs*. AB	NH	H	NS	NS	*	**
Bw *vs*. AB	H	H	NS	NS	NS	NS

H – homogenous, NH – not homogenous, NS – not significant.

and describe the capability of the soil structure to withstand stresses induced by field traffic without changes in the three-dimensional arrangement of its constituent soil particles (Alakukku *et al*., 2003). The Ap horizon had the lowest capacity at all water contents compared to the AB and Bw horizons. This indicates that the Ap horizon is more susceptible to compaction if stresses higher than the precompression stress are applied by agricultural machinery. It is noteworthy that, at the water range of 0.2 and 0.4 m³ m⁻³ where most field operations are carried out, the maximum capacity in the horizons was below 150 kPa, particularly in the Ap horizon, highlighting the vulnerability of Humic Latosols to compaction and the associated degradation (Dias Jr. *et al*., 2005).

To examine possible differences in the in LBC at the different horizons, we implemented the Snedecor and Cocharan (1989) procedure to test for homogeneity of the LBC equation parameters. In the procedure, two equations are picked and compared together by examining the intercept 'a', slope 'b' and the homogeneity parameter data (F). To obtain 'a' and 'b' values in each LBC equation for comparison, the LBC equation in the exponential form ($\sigma_p = 10^{(a+b\theta)}$) was transformed into a linear model by obtaining the logarithm of both sides of the equation, giving an equation of the form:

$$\log(\sigma_p) = \log(10^{(a+b\theta)}) \leftrightarrow \log \sigma_p = a + b\theta \qquad (5)$$

(Dias Jr. *et al*., 2005). The results presented in Table 2 indicated that the LBC data for the Ap and Bw horizons were homogenous but there were significant differences in the parameter 'a' the intercept of the regression lines at both 5 and 1% levels. Similarly, when the LBC for the Ap and AB horizons were compared, we observed significant differences in the 'a' parameter and the LBC data were not homogenous at 5%. However, when the LBC equations of AB and Bw horizons were compared, there were no significant differences in all the LBC parameters and the data were statistically homogenous at all levels. This imply that the LBC for the Bw and AB horizons were statistically similar but different from that the Ap horizon. A representative

LBC for AB and Bw horizons was then constructed by pooling their data together (Fig. 2b). The fitted parameter 'a' was related to the packing state of the solid particles expressed by soil bulk density and air-filled porosity which affect the pore water pressure, while the parameter 'b' is influenced by soil properties such as texture and organic matter content (Peng *et al*., 2004). Our results in this study further suggest that the parameter 'a' is better related to the packing density of the soil (influenced by pedogenetic processes) which influences the intrinsic strength of the dry soil, while the parameter 'b' reflects the textural properties which influence water retention.

CONCLUSIONS

1. Water retention is high at all suctions and in all studied horizons of Humic Latosols.

2. Load bearing capacity of studied soil is low, implying higher susceptibility to compaction.

3. Parameter 'a' of the Load Bearing Capacity equation is dependent on the packing state of the soil, better expressed by the packing density, whereas the parameter 'b' depends on the texture and influences the water retention.

4. Bulk density and precompression stress are intermediate between the Kaolinitic Latosols (high) and Gibsitic Latosols (low), which is related to their differential structure.

5. Organic carbon contents of Humic Latosols are high and do not decrease exponentially with depth, thus will be a good target for mechanized agriculture.

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