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## Strength attributes and compaction susceptibility of Brazilian Latosols

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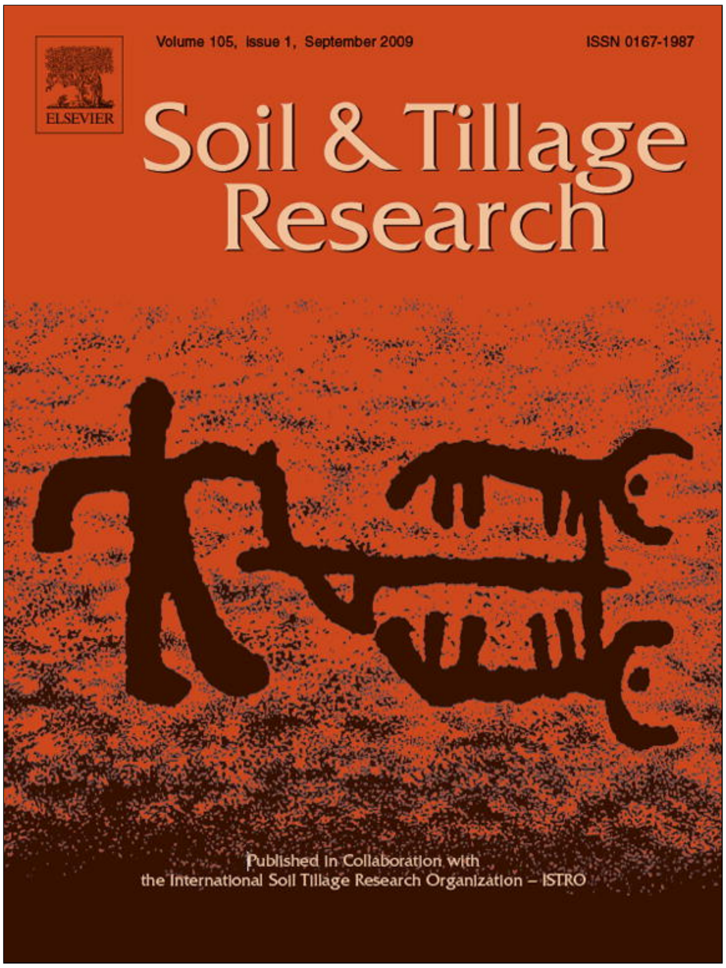
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# Strength attributes and compaction susceptibility of Brazilian Latosols

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ABSTRACT

In this study, strength attributes and compaction susceptibility of the main classes of Brazilian Latosols (Oxisols), under native vegetation, were studied using the load bearing capacity models relating precompression stress, compression index and water potential through statistical regression models. These models were developed based on the results of the analysis of undisturbed soil samples collected at the B horizon at the different sites. The results showed that the maximum value of the compression index was 0.53 for the Acric Red Latosol, indicating its higher susceptibility to soil compaction. The Dystrocohesive Yellow Latosol had the highest load bearing capacity, while the Acric Red Latosol had the lowest one. The Dystrocohesive Yellow Latosol due to its high load bearing capacity and bulk density (mechanical resistance) behave similarly to hardsetting soil, in which the plants root system has severe physical restrictions to explore deeper horizons during the dry periods. Differences in the load bearing capacity and compaction susceptibility were found to be influenced by soil structure which is associated with clay mineralogy in these very weathered-leached soils and water potential. The study also showed that soil compression index is influenced by water potential and clay mineralogy also. Our work has laid a foundation for estimation of compaction susceptibility of Latosols.



## 1. Introduction

The geographical extent of the soil order Latosols (Oxisols—*U.S. Soil Taxonomy*, Sols ferralitiques—*French classification*, and Ferralsols—*World Reference Base for Soil Resources*) has been established in several studies in Brazil. It is found in almost all states of the country (associated with different parent materials) in spite of the varied climatic conditions (Ker, 1997). According to the distribution map of the various classes of soils in the study by Camargo et al. (1987), Latosols cover about 65% of the land mass in Brazil.

Latosols represent by far the major soils under mechanized agriculture and forestry operations in Brazil. Latosols have good potential in response to chemical correction (lime, gypsum and fertilizer application) and exhibit good drainage attributes (Marques et al., 2004). They are highly weathered, strongly leached and friable, dominated by 1:1 clay minerals, Fe-and Al-oxides (in this paper, this general term includes oxides, hydroxides and oxihydroxides), quartz and other highly resistant minerals (Curi, 1983)

The structure of the Brazilian Latosols is mainly associated with the kaolinite and gibbsite minerals content. Whereas kaolinitic Latosols tends to exhibit blocky structure and higher bulk density, the gibbsitic Latosols present granular structure and lower bulk density (Embrapa, 2006; Ferreira et al., 1999a,b). The horizons are poorly differentiated, because differences in properties with depth are so minimal (Curi, 1983).

In mechanized agriculture and forestry harvesting prevalent in Brazil, there are growing concerns on the possible damage to the soil structure in view of increasing mass of machineries and equipment used in field operations (Larson et al., 1980; Peng et al., 2004; Dias Junior et al., 2007; Veiga et al., 2007). The ability of soil to withstand pressure exerted by applied loads depends on its strength, which influences the resistance of soil to compaction. It has been linked to several intrinsic attributes of the soil including texture, clay mineralogy, structure, bulk density, porosity, pore-size-distribution and pore-shape (Ohu et al., 1986; Horn, 1988).

Soil strength (mechanical resistance) and compaction susceptibility may be assessed by different parameters from soil compression curves (bulk density plotted versus log applied pressure), as discussed in some scientific articles (Larson et al., 1980; Horn, 1988; Dias Junior and Pierce, 1996; Alakukku et al., 2003; Imhoff et al., 2004; Gregory et al., 2006; Veiga et al., 2007). The compression curve is composed of two regions: a region of

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plastic and unrecoverable deformation called the virgin compression curve, and a region of small, elastic and recoverable deformation called the secondary compression curve (Larson et al., 1980; Dias Junior and Pierce, 1995; Gregory et al., 2006). The slope of the virgin compression line is called the compression index (CI). The point that separates these two regions in a compression curve is the precompression stress ($\sigma_p$). These parameters define the soil compression curve and may change with soil type, initial moisture content or water potential and management history (Culley and Larson, 1987; Larson et al., 1988; Alakukku et al., 2003). The precompression stress have been used as an indicator of the load bearing capacity and mechanical strength of a soil, to estimate quantitatively the compaction risk (Alakukku et al., 2003) in a specific soil condition at given moisture content or water potential (Oliveira et al., 2003; Peng et al., 2004; Dias Junior et al., 2007).

The precompression stress might be derived from a confined compression test, shear strength derived from a triaxial or a direct shear test, and penetration resistance measurements among other methods (Horn and Lebert, 1994; Arvidsson, 2001; Zhang et al., 2001; Horn and Fleige, 2003; Arvidsson and Keller, 2004; Dias Junior et al., 2005, 2007; Veiga et al., 2007). The various soils present mechanical strength values which can be quantified from precompression stress (Dias Junior et al., 2007; Veiga et al., 2007), being this a dynamic attribute influenced by structure, texture, water suction and bulk density (Horn, 1988), besides pedogenetic processes, anthropogenic effects, or hydraulic site-specific conditions (Horn et al., 2004). The soils would also be submitted to an additional soil compaction as long as their internal strength is smaller than the applied pressure (Veiga et al., 2007).

Precompression stress also gives an indication of the maximum pressure that should be applied to a soil in order to avoid soil compaction (Défossez and Richard, 2002; Dias Junior et al., 2005) and it is a useful indicator of the soil's load bearing capacity (Dias Junior et al., 2005; Rücknagel et al., 2007). If the applied pressure to a soil does not exceed the precompression stress value the soil reacts elastically. However, if it exceeds, there would be plastic deformation in the soil (Horn and Lebert, 1994).

Load bearing capacity is a relationship between precompression stress and moisture content (Dias Junior and Pierce, 1996) or water potential (Oliveira et al., 2003) and it means the capability of a soil to withstand stress induced by field traffic without changes in the three-dimensional arrangement of its constituent soil particles (Alakukku et al., 2003). Likewise, these authors suggested that the risk of subsoil compaction is high when the exerted stresses are higher than the load bearing capacity of the subsoil and that the wetness decreases the load bearing capacity. Several studies in tropical and temperate soils showed that the load bearing capacity exponentially decreases as a function of increasing moisture content (Dias Junior and Pierce, 1996; Silva et al., 2002; Peng et al., 2004; Assis and Lanças, 2005; Dias Junior et al., 2007; Gontijo et al., 2008) or increases as a function of increasing water potential (Oliveira et al., 2003; Ajayi et al., 2009).

The soil compression index is an attribute estimated from compression curves and it is an indicator of susceptibility of soil to compaction (Larson et al., 1980; Imhoff et al., 2004; Gregory et al., 2006).

Keeping in mind the above considerations, the objectives of this study were: (1) to determine the values for the precompression stress and the compression index of the various classes of Brazilian Latosols under native vegetation, and (2) to assess the load bearing capacity of these Latosol classes through statistical regression models.

## 2. Materials and methods

### 2.1. Site description and sampling protocol

Undisturbed soil samples were collected from four representative sites under native vegetation in Brazil. The selected sites represent geographically distinct sub-regions, wide ranges of ecological conditions and cultivation practices, beyond differential clay mineralogy. They also present the ranges of Latosols that had been associated with different types of parent materials in Brazilian conditions (Table 1).

Ten undisturbed samples were collected in the B horizons at all the sites using aluminium rings with 6.5 cm diameter and 2.5 cm height. The sampling device was pushed carefully into the soil using a falling weight. The sampling pits (1 m width × 2 m length × 1 m depth) were dug very carefully to guard against self-compaction of the soil. They were collected randomly in each pit to ensure good representation. The samples were collected between 80 and 100 cm depth at the sites, because in the B horizon the structure is truly expressed once in the A horizon the granules behave as blocks due to higher swelling-shrinking characteristics. As these Latosols are very much homogeneous in morphology, we decided to collect the samples in the "clean B horizon" in order to avoid as much as possible the organic matter influence on soil attributes. In this way, our data can be extrapolated to the B horizon top where possible damage due to traffic can occur. Also in some Brazilian regions having dry periods, the cohesive Latosols are being prepared up to 120 cm depth using ripper subsoilers aiming to favor an adequate root distribution of perennial plants, such as *eucalyptus* sp. In addition to that, with the mechanical resistance breakdown by the subsoiler, the precompression stress of the soil is much reduced (Gontijo et al., 2008). At each point of sample collection, the ring filled with soil was removed from the Uhland sampler, and wrapped with plastic materials and paraffin wax until compressibility and other tests were performed.

### 2.2. Laboratory experimental procedure

In the laboratory, the soil samples were carefully trimmed to the size of their respective rings, whose inner diameter, height and weight had been pre-measured. The disturbed soil samples scraped near the intact soil cores were collected, air-dried, sieved

**Table 1**
Sampling sites and soil descriptions.

| Label and location | Geographical coordinate and altitude | Climatic description | Brazilian soil classification | Parent material | Native vegetation |
|---|---|---|---|---|---|
| (DRL1) Lavras county, Minas Gerais State | 21°13′47″S; 44°58′6″W 918 m | Gentle temperate with dry winter and rainy summer | Dystroferric Red Latosol | Gabbro | Forest |
| (ARL) Uberlândia county, Minas Gerais State | 18°58′37″S; 48°12′05″W 866 m | Tropical monsoonal with dry winter and rainy summer | Acric Red Latosol | Tertiary detritic cover sediments | Cerrado |
| (DYL) Aracruz county, Espírito Santo State | 19°47′10″S; 40°16′29″W 81 m | Moisty tropical with dry winter and rainy summer | Dystrocohesive Yellow Latosol | Barreiras group sediments | Forest |
| (DRL2) Santo Ângelo county, Rio Grande do Sul State | 28°16′16″S; 54°13′11″W 290 m | Moisty tropical without long dry period | Dystroferric Red Latosol | Basalt | Forest |

(2 mm) and subjected to particle-size-distribution analysis using the pipette method (Gee and Bauder, 1986), particle density using pycnometer (Blake and Hartge, 1986b) and organic matter (Embrapa, 1997). Bulk density was determined as dry soil weight per unit volume of the intact soil cores (Blake and Hartge, 1986a).

For the mineralogical characterization, 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).

The moisture retention curves were performed using undisturbed soil samples (three replications per site). For the uniaxial compression tests, seven samples at each site were prepared and soil cores were saturated by capillary with distilled water, and equilibrated to a water suction ($\Psi_m$) to 2 and 6 kPa on a pressure table and 10, 33, 100, 500 and 1500 kPa on ceramic plate inside a pressure chamber (Klute, 1986).

The undisturbed soil samples at the different water suctions were then subjected to uniaxial compression test using a pneumatic S-450 Terraload floating ring consolidometer (Durham Geo Enterprises, USA). For the test, the undisturbed soil samples were kept within the coring cylinders, which were placed into the compression cell, and afterwards submitted to pressures to 25, 50, 100, 200, 400, 800 and 1600 kPa. Each pressure was applied until 90% of the maximum deformation was reached (Taylor, 1948) and then the pressure was increased to the next level. The 90% of maximum deformation was determined by drawing a straight line through the data points of the initial part of the curve obtained when dial readings were plotted versus square root of the time, 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 the corresponding values on the first line. The intersection of this second line and the laboratory curve is the point corresponding to 90% consolidation (Taylor, 1948).

### 2.3. Analyses

The applied pressure versus deformation data were used to construct the soil compression curves, from which the compression index (CI) and precompression stresss ($\sigma_p$) were determined following the procedure of Dias Junior and Pierce (1995). The compression index, CI, slope of virgin compression line was estimated for each sample based upon the slope of the virgin compression line [Eq. (1)] plotted as bulk density against log applied pressure (Larson et al., 1980; Bradford and Gupta, 1986).

$$CI = \frac{Bd_k - Bd_\alpha}{\log(\sigma_\alpha/\sigma_k)} \quad (1)$$

where CI is a compression index (slope of virgin compression line), $Bd_k$ and $Bd_\alpha$ are bulk densities ($Mg\ m^{-3}$) determined at the end of compression line (applied pressure 1600 kPa) and determined at applied pressure 800 kPa, respectively; $\sigma_\alpha$ and $\sigma_k$ are the pressure applied 1600 and 800 kPa.

The precompression stress, $\sigma_p$, was estimated for each sample using a spreadsheet procedure according to Dias Junior and Pierce (1995).

The precompression stress values were thereafter plotted against water suction ($\Psi_m$) and a regression line was fitted from an exponential function in the form $\sigma_p = a + b \ln \psi_m$ (Oliveira et al., 2003) that is the load bearing capacity model of the soils under study. The parameters *a* and *b* represent empirical parameters of adjustment of the model. The regression analyses were accomplished using the software Sigma Plot 10.0 (Jandel Scientific).

The volumetric total porosity (VTP) was estimated using the relationship between bulk density and particle density (Vomocil, 1965) [Eq. (2)]:

$$VTP = \left[1 - \left(\frac{Bd}{Pd}\right)\right] \quad (2)$$

where, Bd ($Mg\ m^{-3}$) is bulk density and Pd is particle density ($Mg\ m^{-3}$).

The pore size distribution was characterized from soil water retention, using the concept of equivalent diameter derived from a capillary model considering microporosity, pores with effective diameter smaller than 50 $\mu$m (water retention at $\Psi_m$ 6 kPa) and macroporosity, pores with effective diameter greater than 50 $\mu$m (total porosity − microporosity).

## 3. Results and discussion

### 3.1. Relationship between soil attributes and strength indices

Table 2 shows the different morphological, physical and mineralogical attributes measured for different classes of Latosols examined in this study. The clay content in the Red Latosols (DRL1, ARL and DRL2) is higher than 600 g kg$^{-1}$ (Table 2). Even the Yellow Latosol (DYL) is clayey (>350 g kg$^{-1}$).

In general, in soils with a very high bulk density as the Dystrocohesive Yellow Latosol (DYL) the plant root system has physical restrictions to develop during the dry seasons. In such cohesive soils (similar to hardsetting behavior, Giarola et al., 2003) in Brazilian regions with accentuated dry periods the mechanical operations include subsoiling until 120 cm depth.

The relationship between water potential and compression index was investigated (Fig. 1). The compression index is a reflection of the decrease in void ratio or bulk density per unit increase in the logarithm of the applied stress (Larson et al., 1980; Imhoff et al., 2004; Gregory et al., 2006). It is a measure of the susceptibility of the soil to compaction. Our results revealed that the compression index was directly related to water potential (Fig. 1), indicating a higher susceptibility to compaction as water potential increases, except for yellow soil (DYL). The fact that this cohesive soil (when dry) becomes very friable (when moist) (Corrêa et al., 2008) and its average geometric diameter is much reduced in water (0.71 mm) in comparison with dry conditions (2.68 mm) (Ferreira et al., 1999b) helps to explain such differential behavior. The increase in soil strength is a result of increased

**Table 2**
Some attributes of the Latosols studied.

| Soil class | Munsell color (moist) | Soil structure | Sand | Silt | Clay | Bd | Pd | Hm/(Hm + Gt) | Gb/(Gb + Ka) | OM |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | g kg$^{-1}$ | | | Mg m$^{-3}$ | | | | dag kg$^{-1}$ |
| (DRL1) Lavras county, Minas Gerais State | 10R 4/8 | Granular | 160 | 190 | 650 | 1.06 | 2.80 | 0.73 | 0.45 | 1.5 |
| (ARL) Uberlândia county, Minas Gerais State | 2.5YR 4/8 | Granular | 300 | 80 | 620 | 0.96 | 2.67 | 0.83 | 0.54 | 1.3 |
| (DYL) Aracruz county, Espírito Santo State | 10YR 6/6 | Blocky | 490 | 60 | 450 | 1.73 | 2.70 | 0.00 | 0.00 | 0.7 |
| (DRL2) Santo Ângelo county, Rio Grande do Sul State | 10R 5/6 | Blocky | 90 | 170 | 740 | 1.30 | 2.80 | 1.00 | 0.00 | 1.6 |

Bd = bulk density; Pd = particle density; Hm = hematite; Gt = goethite; Gb = gibbsite; Ka = kaolinite; OM = organic matter.

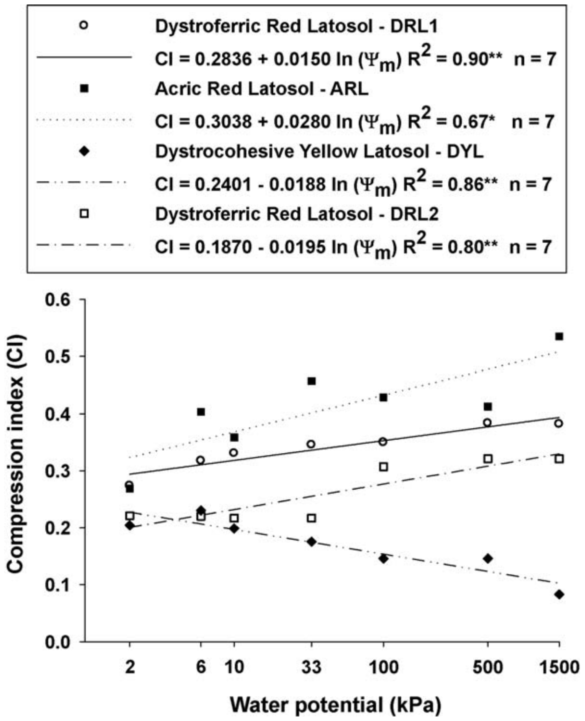


**Fig. 1.** Relationship between compression index and water potential of Latosols.

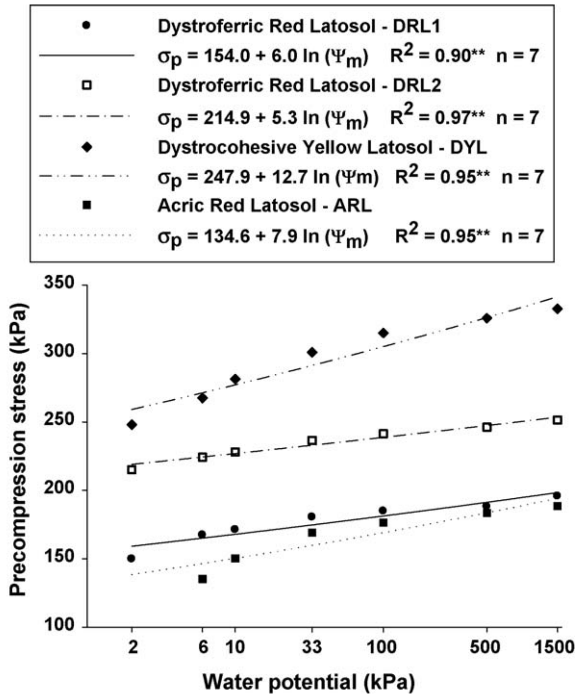


**Fig. 2.** Bearing capacity models for Latosols collected at all sites.

cohesion between the soil particles, occasioned by the gradual increase of the water potential. This helps to explain why soils with high bulk density and low porosity have higher strength at higher water potential. The cohesiveness of the soil particles would only continue to a certain water potential (around 6 kPa) associated with the structure and clay content of the soil (Imhoff et al., 2004; Reatto et al., 2007). When the soil moisture exceeds this point, further addition of water would result in decreased strength and create greater pore water pressure when external stresses are applied.

This general trend was also reported by Sánchez-Girón et al. (2001), which observed a strong dependence of compression index on the soil water potential. However, these results contradict some previous studies, which found the compression index to be moisture independent for most of the studied soils (Larson et al., 1980; O'Sullivan, 1992). In spite of that Larson et al. (1980) reported that as initial moisture content increases, soil compression curves are generally displaced down and to the left in a parallel manner, indicating an increase in susceptibility of soil to compaction. The maximum value of the compression index (Fig. 1) found in this study was CI = 0.53 (Acric Red Latosol) similar to CI = 0.50 found by Larson et al. (1980) in highly weathered soils with 500 g $kg^{-1}$ clay mainly constituted by kaolinite and iron-and Al-oxides equilibrated to 30 kPa of water potential.

Our field experience indicates that the structure of the Brazilian Latosols is closely related to the strength indices, i.e., when we go from granular to blocky structure there is an increase in bulk density and load bearing capacity of these very old tropical soils.

### *3.2. Load bearing capacity*

The load bearing capacity models varied with the different classes of Latosols examined in this study. The model parameters for each site, their coefficient of determination and the level of significance are presented in Fig. 2.

Based on the results comparing the four models, the load bearing capacities follow the order Dystrocohesive Yellow Latosol (DYL) > Dystroferric Red Latosol (DRL2) > Dystroferric Red Latossol (DRL1) > Acric Red Latosol (ARL) (Fig. 2). It is worthy to comment that in the yellow soil the absence of gibbsite (Table 2) and the very low amount of iron oxides (11 g $kg^{-1}$), favors the face-to-face arrangement of kaolinite plates, resulting in a cohesive character and dense aspect of this soil, similar to hardsetting soils (Giarola et al., 2003), contributing for the highest bulk density value (Table 2) and the highest load bearing capacity of this soil.

For the red soils, the load bearing capacities reduce, in the order of changing soil structure from blocky to granular (Fig. 2). For example, in the Dystroferric Red Latosol (DRL2) site where the clay mineralogy is totally kaolinitic (Gb/(Gb + Ka) = 0.00—Table 2), with high amount of iron oxides (227 g $kg^{-1}$) but with no gibbsite, soil structure is blocky with bulk density value of 1.30 Mg $m^{-3}$. On the other hand, the clay mineralogy of the Acric Red Latosol (ARL) and Dystroferric Red Latosol (DRL1) is dominantly gibbsitic (Gb/(Gb + Ka) = 0.54 and 0.45, respectively—Table 2). The gibbsitic soil exhibits a strong well-connected macroporosity (Furian et al., 2001), as a result of the granular structure. This structure influences bulk density values near 1.0 Mg $m^{-3}$ (Table 2), thus lowering the soil strength and increasing the susceptibility to soil compaction. Various studies in Brazil (UFV, 1979; Ferreira et al., 1999a,b; Resende et al., 2005, 2007) showed that in all the studied Latosols, the kaolinite–gibbsite ratio is associated with the soil structure. This structure influences the bulk density and the soil packing state, thus conditioning the soil response to applied stresses.

The higher amounts of organic matter and high activity clays of the temperate region soils compared with tropical soils (Resende et al., 2005, 2007) help to explain the lower values of the precompression stress for the former soils reported by Horn and Fleige (2003) and Peng et al. (2004) compared to the values showed in Fig. 2. However, some researchers (Arvidsson and Keller, 2004; Cavalieri et al., 2008) suggest that the use of different methods to

**Table 3**
Volumetric water retention at different water potentials and pore size distribution of the Latosols studied.

| Soil class | | Water potential (kPa) | | | | | | | MACRO | MICRO |
|---|---|---|---|---|---|---|---|---|---|---|
| | VTP | 2 | 6 | 10 | 33 | 100 | 500 | 1500 | $\phi > 50\ \mu m$ | $\phi < 50\ \mu m$ |
| | $cm^3\ cm^{-3}$ | | | | | | | | | |
| (DRL1) Lavras county, Minas Gerais State | 0.62 | 0.33 | 0.29 | 0.28 | 0.27 | 0.26 | 0.25 | 0.24 | 0.33 | 0.29 |
| (ARL) Uberlândia county, Minas Gerais State | 0.64 | 0.55 | 0.36 | 0.32 | 0.29 | 0.27 | 0.26 | 0.25 | 0.28 | 0.36 |
| (DYL) Aracruz county, Espírito Santo State | 0.36 | 0.29 | 0.26 | 0.24 | 0.21 | 0.19 | 0.18 | 0.17 | 0.10 | 0.26 |
| (DRL2) Santo Ângelo county, Rio Grande do Sul State | 0.54 | 0.53 | 0.51 | 0.50 | 0.48 | 0.47 | 0.46 | 0.44 | 0.03 | 0.51 |

VTP = volumetric total porosity; MACRO = macroporosity, pores with effective diameter greater than 50 μm; MICRO = microporosity, pores with effective diameter smaller than 50 μm.

calculate precompression stress can lead to different results, thus affecting the estimation of the load bearing capacity by this methodology. In the present study we utilize only the spreadsheet developed by Dias Junior and Pierce (1995).

### 3.3. Moisture retention

The moisture retention obtained for the Latosols from different sites are presented in Table 3. Our results showed that the highest water retention at all the water potentials equal or higher than 6 kPa was recorded in the Dystroferric Red Latosol (DRL2) while the lowest one was in the Dystrocohesive Yellow Latosol (DYL). This observation points out the importance of preserving the soil structure in conducting reliable moisture retention experiment and other experiments based on the physical processes in the soil system (Horn and Lebert, 1994), mainly at 6 kPa water potential, where structure influences water retention in Latosols (Mello et al., 2002).

The average values of moisture retained at the different water suctions increase in the direction of increasing clay content. This was similarly observed by Reatto et al. (2007). The Acric Red Latosol (ARL) was observed to specifically retain more water at 2 kPa without any clear explanation for this behavior.

## 4. Conclusions

In this study, the precompression stress of soil samples at different water potential was used to develop the load bearing capacity model, to determine the strength attributes and evaluate compaction susceptibility in the main Latosol classes prevalent in Brazil. The models were developed using undisturbed soil samples collected at the B horizon at the different sites under native vegetation. Differences in the load bearing capacity and compaction susceptibility were found to be influenced by the structure (which is associated with the clay mineralogy) and water potential of the soil under native vegetation.

The study also showed that soil compression index is influenced by water potential and bulk density. Granular structure favors lower values of precompression stress in comparison with blocky structure. Our study has laid a foundation for estimation of compaction susceptibility of Latosols in Brazil.

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