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Abstract

The Brazilian Central Plateau covers about 40% of the Cerrados Biome and represents 24% of the Brazilian territory. The Latosols that correspond to about 40 % of the surface area of the Central Plateau are characterized by a poor horizonation, a weak macrostructure and a strong development of the fine granular structure composed of sub-rounded microaggregates 50 to 300 µm in size. In this study, we analyzed the hydraulic properties of a set of Latosols varying according to their clay content and mineralogy with respect to their location along a regional topossequence across the Brazilian Central Plateau. Ten Latosols (L) were selected on the South American Surface (L1 to L4) and Velhas Surface (L5 to L10) and we studied the properties of their diagnostic horizon

(Bw). We measured their bulk density and particle density, and the soil-water retention properties at -1, -6, -10, -33, -300, and -1500 kPa by using the centrifugation method. We also determined the saturated hydraulic conductivity in the field using the Guelph permeameter procedure. Results showed that the total pore volume (V_p) ranged from 0.460 to 0.819 $cm^3\ g^{-1}$ and 58.2 % of the variance was explained for by the clay content. According to Balbino et al. (2002), V_p was divided into a volume of intra-microaggregates pores (V_{intra}) and inter-microaggregates pores (V_{inter}). Results showed that V_{intra} ranged from 0.090 to 0.234 $cm^3\ g^{-1}$ and V_{inter} from 0.305 to 0.585 $cm^3\ g^{-1}$. Results showed also that V_p explained a proportion of the variance of the water retained that decreased with the water potential. On the other hand, the clay content explained a proportion of that variance that increases when the water potential decreased. The great proportion of variance (90.7 %) explained for by the clay content alone at -1500 kPa showed that there is little variability that can be attributed to clay mineralogy variation. The saturated hydraulic conductivity (K_s) was related to an effective porosity (Φ_e) defined as the volume proportion of pore with equivalent diameter > 300 µm. Finally, our results showed that water retention properties and saturated hydraulic conductivity varied mainly according to the clay content and development of large pores without any close link with the mineralogy of the clay fraction.

Keywords: Structure; Oxisol; Ferralsol; Pedotransfer function, Water retention, Cerrado

1 – Introduction

The Brazilian Central Plateau covers about 40% of the Cerrados Biome and 24% of the whole Brazilian territory (Adámoli et al., 1986). It can be divided into two main geomorphic surfaces: the South American Surface and the Velhas Surface (King, 1956; Lepsch and Buol, 1988; Motta et al., 2002; Marques et al., 2004). The South American Surface corresponds to a landscape that originated from a vast peneplain resulting from erosion between the lower Cretaceous and the middle Tertiary under humid climatic conditions favorable to deep weathering of rocks (Braum, 1971). Because of continent uplift, that peneplain was dissected, thus resulting in a landscape of tablelands 900 to 1,200 m high corresponding to remnants of the South American Surface (Radambrasil, 1984). On the other hand, the Velhas Surface has formed later and corresponds to surfaces connecting the South American Surface to lower portions of the landscape where the rivers flow. The Velhas Surface shows moderate and convex slopes and covers a much smaller surface areas of the Brazilian Central Plateau than the South American Surface.

The Latosols cover about 40% of the Central Plateau surface area (Silva et al., 2005). Most Latosols in the Brazilian Soil Taxonomy (Embrapa, 1999) correspond to Oxisols in the Soil Taxonomy (Soil Survey Staff, 1998) and to Ferralsols in the International Reference Base System (ISSS Working Group R.B., 1998; Reatto et al. 1998). In the Central Plateau, the Latosols can be Red Latosols (Acrustox, ~28%), Yellow Red Latosols (Acrustox, ~10%) and Yellow Latosols (Haplaquox, ~2%) (Silva et al., 2005). The main characteristics of Latosols are a poor differentiation of the horizons, a weak macrostructure and a strong submillimetric granular structure (Embrapa, 1999) resulting in microaggregates 50 to 300 µm in size (Balbino et al., 2001 and 2002; Volland-Tuduri et al., 2004 and 2005) and earlier described as “pseudosand”, “micropeds” and “granules” (Kubiena, 1950; Brewer and Sleeman 1960; Brewer, 1976) or primary particle fraction (Westerhof et al., 1999). The development of that granular structure in Brazilian Latosols was analyzed in numerous studies (e.g. Resende, 1976; Lima, 1988; Ker, 1995; Ferreira et al.,1999a; Schaefer, 2001; Gomes et al., 2004a; Cooper and Vidal-Torrado, 2005; Volland-Tuduri et al., 2004 and 2005). Kaolinite, gibbsite, goethite and hematite were recognized in different proportions in the clay fraction of Latosols. Curi and Franzmeier (1984) analyzed the mineralogy of the clay fraction in a topossequence of Latosols developed in the weathered basalt in Southern Goiás state. They showed that gibbsite was the main mineral in red Latosols located upslope when it was kaolinite and goethite in yellow Latosols located downslope. Ferreira et al. (1999a) studied seven diagnostic horizons (horizon Bw) of Latosols from the Minas Gerais and Espírito Santo states. They showed that kaolinite and goethite were the main minerals in the clay fraction of yellow Latosols when it was gibbsite, hematite and goethite in different proportions in the <2µm fraction of ferric red Latosols and red Latosols. They also concluded that kaolinite and gibbsite were the main minerals responsible for the structure development of the Latosols studied. Ker (1995) studied the clay fraction of 26 diagnostic horizons collected in Latosols located in several Brazilian states. He showed that ferric red Latosols were rich in kaolinite, gibbsite and hematite, the red Latosols in kaolinite and hematite, the yellow red Latosols in kaolinite and goethite, and the yellow Latosols in kaolinite, gibbsite and goethite. Reatto et al. (2000)

studied the diagnostic horizon of 124 Latosols located in the Brazilian Cerrado area and showed that other mineralogical compositions than those recorded by earlier authors were associated to the different types of Latosols. Gomes et al. (2004a) analyzed the clay fraction of 36 diagnostic horizons of Latosols located in the Eastern Goiás and Minas Gerais states. These authors grouped the Latosols studied according to their clay and Fe_2O_3 content and showed a large range of clay mineralogy.

The hydraulic properties of Latosols have been studied by several authors. Macedo and Bryant (1987) studied a hydrosequence of Latosols developed in weathered Tertiary sediments in the Federal District. They showed that the Red Latosols were located on the South American Surface in the well drained central part of the plateau. On the other hand they showed also that the Yellow Red Latosols were located downslope in poorly drained position. Pachepsky et al. (2001) found relationships between the soil water retention and topographic variables and showed that more than 60% of the variation in soil water content at –10 and –33kPa were explained by these relationships. Van den Berg et al. (1997) studied the water retention properties of Latosols in different regions and showed that water release occurs between –5 and –10 kPa such as in sandy soils. Cichota & van Lier (2004) discussed the spatial variability of the water retention properties of loamy Yellow Red Latosols. The water retained at every different potential ranging from –1 to –100 kPa was not closely related to the clay content. Ferreira et al. (1999b) showed that the saturated hydraulic conductivity (K_s) of Latosols increased with the clay content but they did not discuss the variability within every class of Latosols. However they showed for the diagnostic horizon that $3.9\ 10^{-6} < K_s < 2.2\ 10^{-5}$ m.s^{-1} for kaolinitic Latosols except for on diagnostic horizon ($K_s = 1.7\ 10^{-4}$ m.s^{-1}) and $5.5\ 10^{-5} < K_s < 8.4\ 10^{-5}$m.s^{-1} for gibbsitic Latosols. Thus, according to these authors, the kaolinitic Latosols would have smaller K_s than gibbsitic. They recorded also that kaolinitic Latosols had a greater bulk density, a smaller aggregate stability and macroporosity than gibbsitic Latosols. Marques et al. (2002) studied the water retention properties and K_s of the different horizons of clay Yellow Latosol and Red Latosol. They recorded no difference between these two Latosols whatever the horizon studied. Gomes et al. (2004b) showed that the water retention properties in the surface horizons of large range of type of Latosols located in the Eastern Goiás and Minas Gerais states were closely correlated with the clay and organic carbon content. Balbino et al. (2004) studied a clayey Latosol and showed a variation of the water retention properties and unsaturated hydraulic conductivity between native vegetation and pasture. Cooper and Vidal-Torrado (2005) studied a Nitisol and a Latosol in Southeast of Brazil. They showed that the diagnostic horizon of the Nitisol had a strong to moderate subangular blocky structure and smaller K_s than the diagnostic horizon of the Latosol.

Although there is a large range of composition among Brazilian Latosols, the earlier studies did not show any close relationship between the Latosol composition and their hydraulic properties. In this study, we analyzed the hydraulic properties of set of Latosols varying in their particle size distribution and mineralogical composition according to their location in a regional topossequence across the Brazilian Central Plateau. We showed that water retention properties and saturated hydraulic conductivity varied mainly according to the development of the microaggregation with no clear link to the mineralogy of the clay fraction.

2 – Material and Methods

2.1 – Site conditions

According to the Köppen classification, the most representative climate of the Central Plateau is Megatermic or Humid Tropical (Aw) with the subtype savanna. It is characterized by a dry winter (medium temperature of the coldest month > 18°C) and maximum rains in summer. The mean annual rainfall ranges from 1,500 to 2,000 mm, with the highest rainfall in January and the smallest in June, July and August (<50 mm/month). The relative humidity of the air is about 75% between January and April, when it is about 30% during the dry winter (Assad et al., 1993).

2.2 - Soil selection

The Latosols studied were selected according to Reatto et al. (2000) who studied the mineralogical composition of Latosols in the Cerrados Biome. By using a semi-quantitative method based on a sulfuric acid extraction and the soil color (Resende et al., 1987, Resende and Santana, 1988). Reatto et al. (2000) showed that for the data of mineral oxides from sulfuric acid extraction, was used to estimate the values of kaolinite, gibbsite, goethite and hematite, and the two last clay minerals with the integration of the color (hue, value and chrome), according Santana (1984). Besides of the mineralogical variability was realized an arrangement between: class of Latosols, according Brazilian Soil Taxonomy (Embrapa, 1999) and topography surface, and textural class, and parent material.

Ten Latosols (L) were selected along an approximately 350 km long regional toposequence across the South American Surface (L1 to L4) and Velhas Surface (L5 to

L10) (Table 1). The Latosols L5 and L6 were located on the upper Velhas Surface, L7 and L8 on the intermediate Velhas Surface, and L9 and L10 on the lower Velhas Surface. According to Reatto et al. (2000) who studied the mineralogical composition of a large range of Latosols in the Cerrados Biome by using semi-quantitative methods based on sulfuric acid extraction and soil color (Resende et al., 1987; Resende and Santana, 1988), the selected Latosols showed a large range of mineralogical composition (Table 1).

2.3 - Soil characterization

Soils were described according to the field manual of Lemos and Santos (1996) and the Brazilian Soil Taxonomy (Embrapa, 1999). A pit 2–m depth was dug and the top horizon (A), transitional horizons (AB and BA) and diagnostic horizon (Bw) were described. Disturbed samples were collected in every horizon as well as undisturbed samples in triplicate using copper cylinders 100 cm^3 in volume (∅ = 5.1 cm, h = 5 cm).

Basic soil characterization was performed on the air-dried <2-mm material according to the Brazilian standard procedures as described by Embrapa (1997). Thus, the particle size distribution was determined using the pipette method after dispersion with NaOH 1N. The particle density was determined by using 95% hydrated alcohol with 20 g of air-dried soil material in a 50-ml pycnometer. The soil pH was measured in distilled water and 1N KCl using 1:1 mass soil to solution ratio. The cation exchange capacity (CEC) was determined as being the sum of the electric charges of Ca^{2+}, Mg^{2+}, and Al^{3+} extracted with 1N KCl, of K^+ and Na^+ extracted with 0,05N HCl, and of H^+ and Al^{3+} extracted with a tampon solution of $Ca(CH_3COO)_2$ and CH_3COOH at pH 7.0. The organic carbon content was determined by wet oxidation with 0.4N $K_2Cr_2O_7$.

The water retention properties of the horizon Bw were determined for every soil by using the undisturbed samples collected in triplicate. These samples were saturated for 24 h prior the determination of their water retention properties by using the centrifugation method (Freitas Junior and Silva, 1984). A 120-min centrifugation long was used as recommended by Silva and Azevedo (2002). The water content was determined at -1, -6, -10, -33, -300, and -1500 kPa. The sample mass was measured at every water potential and the final water content was determined at -1500 kPa after oven-drying the soil at 105°C. The water content at every potential was then calculated. The bulk density ($g.cm^{-3}$) was calculated using the oven-dry mass of the soil material contained in the 100 cm^3 cylinders. The saturated hydraulic conductivity was determined in the field using the Guelph permeameter procedure (Reynolds and Elrick, 1985). The water infiltration measurements were taken from three bore holes, applying two different constant water heads for each hole. The field saturated hydraulic conductivity was thus measured in the horizon Bw at a depth ranging from 110 to 140 cm according to the soil description.

3 - Results

3.1 – Structure

Field observations revealed a decrease in the development of the sub-angular blocky structure with depth and a strong increase in the development of the very fine granular structure. Dense centimetric nodules with similar composition to the surrounding soil material were recorded in different proportion in the Latosols studied. Nodules were about 20% of the soil volume between 30 and 70 cm depth in L1, L2, L3, L5, L6 and L10, 10% in L8, 5% in L9 and 2% in L4 and L7. Spherical iron concretions <2 mm in diameter were also recorded in L1 and their proportion roughly increased with depth. Most roots were located within the 0-5 cm top layer and their size decreased with depth, roots several centimeters in diameter being very rare below 20 cm depth. Channels a few millimeters in diameter and cavities a few centimeters in size that are related to termite and ant activity were found in the Latosols studied. They were particularly numerous in L7, moderately numerous in L1, L6 and L8 and a few in the other Latosols studied.

The diagnostic horizons (Bw) of the Latosols studied showed a compound weak to moderate medium subangular blocky structure and a strong fine to very fine granular structure (Table 2). Dense nodules were not recorded in the diagnostic horizons (Bw) of L2, L4, L6, L7 and L7. They were between 30 and 40% of the soil volume in L1, about 20% in L5, 10% in L7 and 5% in L3 and L8. Cavities and channels were several millimeters in diameters and few in L1, L4 and L5 when they were numerous in L7. They were very rare in the other diagnostic horizons.

3.2 – Physico-chemical characteristics of the diagnostic horizon Bw

The pH_w ranged from 4.8 to 5.3 and pH_{KCl} from 4.0 to 6.2. The horizons Bw of the Latosols of the South American Surface were more electropositive than the Latosols of the Velhas Surface (Table 3). The organic carbon content of the horizon Bw was close to 0.6 $g.kg^{-1}$ in L2, L5, L7 and L8, close to 0.3 $g.kg^{-1}$ in L1 and L4, and close to 0.02 $g.kg^{-1}$ in L3, L6, L9, and L10. The sum of exchangeable bases (SB) ranged from 0.16 to 0.27 $cmol_c\ kg^{-1}$, except in L10 where it was much greater (0.93 $cmol_c\ Kg^{-1}$). The cation exchange capacity (CEC) ranged from 1.72 to 10.60 $cmol_c kg^{-1}$. The high values of CEC appeared to be related to the high $H^+ + Al^{3+}$ content as observed in L2, L6 and L8.

The horizon Bw studied showed high clay content that ranged from 520 to 780 $g.kg^{-1}$, except for L4 where it was 300 $g.kg^{-1}$. The particle density (D_p) and bulk density (D_b) ranged from 2.64 to 2.88 $g.cm^{-3}$ and from 0.84 to 1.21 $g.cm^{-3}$, respectively and there is no distinction between the horizons Bw collected in Latosols located on the South American Surface and those located on the Velhas Surface (Table 4). The saturated gravimetric water content (W_0) ranged from 0.378 to 0.748 $g.g^{-1}$ and the gravimetric water content at –1500 kPa (W_{1500}) ranged from 0.099 to 0.281 $g.g^{-1}$. The field saturated hydraulic conductivity (K_s) of the diagnostic horizons Bw ranged from 8.64 10^{-6} to 4.18 10^{-5} $m.s^{-1}$ (Table 4).

4 – Discussion

4.1 – Total pore volume and elementary pore volumes

We computed the total pore volume (V_p in cm^3 g^{-1}) by using both the bulk density (D_b) and particle density (D_p) as following:

$$V_p = 1/D_b - 1/D_p$$

Results showed that V_p ranged from 0.460 to 0.819 cm^3 g^{-1} (Tables 4 & 5) and 58.2 % of the variance was explained for by the clay content (Fig. 1). Earlier studies (Balbino et al., 2002; Volland-Tuduri et al., 2004 and 2005; Cooper and Vidal-Torrado, 2005) showed that the total pore volume of microaggregates of the Latosols resulted from the contribution of the pores related to the assemblage of elementary particles inside the microaggregates (intra-microaggregate pores, V_{intra} in cm^3 g^{-1}) and of the pores between the microaggregates (inter-microaggregate pores, V_{inter} in cm^3 g^{-1}). The volume of inter-microaggregates pores resulted from the contribution of the pores related to the assemblage of the microaggregates and of those related to biological activity that are usually greater in these soils than the former (Schaefer, 2001; Barros et al., 2001; Volland-Tuduri et al., 2004 and 2005). Balbino et al. (2002) studied the variation of V_{intra} for a large range of Latosols and showed that it was closely related to the clay content (C) as following:

$$V_{\text{intra}} = 0.0003\ C - 0.0004$$

with C, the clay content ($g.kg^{-1}$). According to that relationship, V_{intra} ranged from 0.090 to 0.234 $cm^3\ g^{-1}$ for the Latosols studied (Table 5). Then we computed V_{inter} using the following relationship:

$$V_{\text{inter}} = V_{\text{p}} - V_{\text{intra}}$$

The recorded V_{inter} ranged from 0.305 to 0.585 $cm^3\ g^{-1}$ (Table 5). That variation of V_{inter} cannot be related to the structure development of the diagnostic horizons Bw studied as described in Table 2. However, the smallest V_{inter} was recorded in L1 where the horizon Bw_2 showed the greatest proportion of dense nodules (Tables 2 & 5).

4.2 – Water retention properties

Our results showed that the percentage of variance of the gravimetric water content explained for by V_{p} decreased with the water potential (Fig. 2). That percentage gradually decreased from 97.9 to 63.6 % when the water potential decreased from –1 to –300 kPa, the percentage of variance explained being a little greater at –1500 kPa (65.1 %) than at –300 kPa. Such a decrease of the closeness of the relationship with the water potential was earlier recorded for other soils (Bruand et al., 1988; Dexter, 2004) and it is related to the decrease in the proportion of V_{p} that retains water when the water potential decreases.

On the other hand, our results showed also that the percentage of variance of the gravimetric water content explained for by the < 2 µm content increased with the absolute value of the water potential (Fig. 3). Indeed, that percentage gradually increased from 56.7 to 90.7 % when the water potential decreased from –1 to –1500 kPa. That increase is related to the decrease in the size of the pores retaining the water when the water potential decreases, the more their pore size being small, the more the pore volume to which they correspond to being closely related to the < 2 µm content (Bruand and Prost, 1987; Bruand et al., 1988).

The proportion of variance remaining unexplained for by the < 2 µm content and its increase with the water potential would result from the contribution to water retention of a volume of pores that increased with the water potential and that was not related to the < 2 µm content but to aggregation development. On the basis of the Jurin's law, water is retained at –1500 kPa in pores with equivalent pore diameter (D_e) ≤ 0.2 µm thus indicating that at this water potential water was retained in pores resulting from the assemblage of the < 2 µm particles and explaining the great percentage of variance explained for by the < 2 µm content at –1500 kPa (90.7%) (Fig. 3f).

4.3 – Saturated hydraulic conductivity

The smallest and greatest averaged K_s and V_{inter} were recorded for L1, respectively 8.64 x 10^{-6}m.s^{-1} and 0.305 cm^3 g^{-1}, and L6, respectively 4.18 x 10^{-5} m.s^{-1} and 0.585 cm^3 g^{-1} (Tables 4 & 5). However, comparison of K_s and V_{inter} led to poor correlation between them probably because V_{inter} includes a large proportion of small pores that only participate marginally to water transfer when the soil is saturated. Ahuja et al. (1989)

related K_s to the effective porosity (Φ_e) defined as the porosity occupied by air at –33 kPa as following:

$$K_s = a(\Phi_e)^b$$

where a and b are constants. That relationship was used by Franzmeier (1991) and Tomasella and Hodnett (1997) for a large range of soils. We computed the porosity occupied by air (Φ_a) at different potentials as following:

$$\Phi_a = (V_p - W_h/\rho_w) \times D_b$$

with ρ_w, the specific mass of water taken as equaled to 1 g cm^{-3}, and h, successively equaled to -1, -6, -10 and -33 kPa. Then we correlated K_s to the different values of Φ_a and showed that the closest correlation was recorded with Φ_a computed for h = -1 kPa (R^2 = 0.558) (Fig. 4). The correlation recorded with Φ_a computed for h = -33 kPa as earlier proposed by Ahuja et al. (1989) was the loosest (R^2 = 0.362). Thus, unlike Φ_e defined by Ahuja et al. (1989) as the porosity occupied by air at -33 kPa (D_e = 10 µm), the effective porosity should be defined as the porosity corresponding to larger pores ($D_e \geq$ 300 µm since occupied by air at -1kPa) for the diagnostic horizons (Bw) of Latosols.

5 – Conclusion

Our results showed that for the diagnostic horizons studied the total pore volume (V_p) ranged from 0.460 to 0.819 cm^3 g^{-1}. They showed also that 58.2 % of the variance of V_p was explained for by the clay content alone although there was a large range of clay mineralogy within the set of diagnostic horizons (Bw) studied.

According to Balbino et al. (2002), V_p was divided into a volume of intra-microaggregates pores (V_{intra}) and inter-microaggregates pores (V_{inter}). Results showed that V_{intra} ranged from 0.090 to 0.234 $cm^3\ g^{-1}$ and V_{inter} from 0.305 to 0.585 $cm^3\ g^{-1}$.

Results showed also that V_p explained a proportion of the variance of the water retained that decreased with the water potential. On the other hand, the clay content explained a proportion of that variance that increases when the water potential decreased. The great proportion of variance (90.7 %) explained for by the clay content alone at -1500 kPa showed that there is little variability that can be attributed to clay mineralogy variation. The saturated hydraulic conductivity (K_s) was related to an effective porosity (Φ_e) defined as the volume proportion of pore with equivalent diameter > 300 µm.

Thus, our results showed that water retention properties and saturated hydraulic conductivity varied mainly according to the clay content and development of large pores without any close link with the mineralogy of the clay fraction.

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References

Adámoli, J., Macedo, J., Azevedo, L.G., Madeira Neto, J., 1986. Caracterização da região dos cerrados. In: Goedert, W.J. (Ed.). Solos dos Cerrados: tecnologias e estratégias de manejo. Empresa Brasileira de Pesquisa Agropecuária/ Nobel, São Paulo, pp.33–74.

Ahuja, L.R., Cassel, D.K., Bruce, R.R., Barnes, B.B., 1989. Evaluation of spatial distribution of hydraulic conductivity using effective porosity data. Soil Science 148, 404–411.

Assad, E.D., Sano, E.E., Masutomo, R., Castro, L.H.R., Silva, F.A.M., 1993. Veranicos na região dos cerrados brasileiros: freqüência e probabilidade de ocorrência. Pesquisa Agropecuária Brasileira 28, 993–1002.

Balbino, L. C., Bruand, A., Brossard, M., Guimarães, M. F. 2001. Comportement de la phase argileuse lors de la dessiccation dans dês Ferralsols microagrégés du Brésil : rôle de la microstructure et de la matière organique. Comptes Rendus de l'Académie des Sciences 332, 673-680.

Balbino, L.C., Bruand, A., Brossard, M., Grimaldi, M., Hajnos, M., Guimarães, M.F. 2002. Changes in porosity and microaggregation in clayey Ferralsols of the Brazilian Cerrado on clearing for pasture. European Journal of Soil Science 53, 219–230.

Balbino, L.C., Bruand, A., Cousin, I., Brossard, M., Quétin, P., Grimaldi, M., 2004. Change in the hydraulic properties of a Brazilian clay Ferralsol on clearing for pasture. Geoderma 120, 297–307.

Barros, E., Curmi, P., Hallaire, V., Chauvel, A., Lavelle, P. 2001. The role of macrofauna in the transformation and reversibility of soil structure of an oxisol in the process of forest to pasture conversion. Geoderma 100, 193-213.

Braum, O.P.G., 1971. Contribuição à geomorfologia do Brasil Central. Revista Brasileira de Geografia 32, 3–39.

Brewer, R., Sleeman, J. R. 1960. Soil structure and fabric: their definition and description. Journal of Soil Science 11, 172-185.

Brewer, R. 1976. Fabric and mineral analysis of soils. New York, Robert E. Krieger. 482p.

Bruand, A., Tessier D., Baize, D. 1988. Contribution à l'étude des propriétés de rétention en eau des sols argileux : importance de la prise en compte de l'organisation de la phase argileuse. Comptes Rendus de l'Académie des Sciences 307, 1937–1941.

Bruand, A., Prost, R. 1987. Effect of water content on the fabric of a soil material: an experimental approach. Journal of Soil Science 38, 461-472.

Ciachota, R., van Lier, Q de J. 2004. Análise da variabilidade espacial de pontos amostrais da curva de retenção da água no solo. Revista Brasileira de Ciência do Solo 28, 585-596.

Cooper, M., Vidal-Torrado, P., 2005. Caracterização morfológica, micromorfológica e físico-hídrica de solos com horizonte B nítico. Revista Brasileira de Ciência do Solo 29, 581–595.

Curi, N., Franzmeier, D., 1984. Topossequence of Oxisols from Central Plateau of Brazil. Soil Science Society of America Journal 48, 341–346.

Dexter, A.R., 2004. Soil physical quality Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120, 201–214.

Embrapa, 1997. Manual de métodos de análise de solo. 2ed. rev. atual. Empresa Brasileira de Pesquisa Agropecuária, Rio de Janeiro, 212 pp.

Embrapa, 1999. Sistema Brasileiro de Classificação de Solos. Empresa Brasileira de Pesquisa Agropecuária, Rio de Janeiro, 412 pp.

Ferreira, M.M., Fernandes, B., Curi, N., 1999a. Mineralogia da fração argila e estrutura de latossolos da região sudeste do Brasil. Revista Brasileira de Ciência do Solo 23, 507–514.

Ferreira, M.M., Fernandes, B. Curi, N., 1999b. Influência da mineralogia da fração argila nas propriedades físicas de latossolos da região sudeste do Brasil. Revista Brasileira de Ciência do Solo 23, 515–524.

Franzmeier, D.P., 1991. Estimation of hydraulic conductivity from effective porosity data for some Indiana soils. Soil Science Society of America Journal 55, 1801–1803.

Freitas Júnior, E., Silva, E.M., 1984. Uso da centrífuga para determinação da curva de retenção de água do solo, em uma única operação. Pesquisa Agropecuária Brasileira 19, 1423–1428.

Gomes, J.B.V., Curi, N., Schulze, D.G., Marques, J.J.G.S.M., Ker, J.C., Motta, P.E.F., 2004a. Mineralogia, morfologia e análise microscópica de solos do Bioma Cerrado. Revista Brasileira de Ciência do Solo 28, 679–694.

Gomes, J.B.V., Curi, N., Motta, P.E.F., Ker, J.C., Marques, J.J.G.S.M., Schulze, D.G., 2004b. Análise de componentes principais de atributos físicos, químicos e mineralógicos de solos do Bioma Cerrado. Revista Brasileira de Ciência do Solo 28, 137–153.

ISSS Working Group R.B. 1998. World Reference Base for Soil Resources: Introduction. J.A. Deckers, F.O. Nachtergaele and O.C. Spaargaren (Eds), First Edition. International Society of Soil Science (ISSS), International Soil Reference and

Information Centre (ISRIC) and Food and Agriculture Organization of United Nations (FAO). Acco, Leuven. 88 pp.

Ker, J., 1995. Mineralogia, sorção e dessorção de fosfato, magnetização e elementos traços de Latossolos do Brasil. Ph. D. Thesis. Universidade de Viçosa, Viçosa-MG, 181 pp.

King, L.C., 1956. A geomorfologia do Brasil Central. Revista Brasileira de Geografia 18(02): 3-39.

Kubiena, M. L. 1950. Zur micromorphologie der braunen and roten tropenboden. Transactions of the 4th International Congress of Soil Science, Amsterdam, 1: 304-307.

Lemos, R. C., Santos, R. D. 1996. Manual de descrição e coleta de solo no campo. 3 ed. Campinas, Sociedade Brasileira de Ciência do Solo, 84 pp.

Lepsch, I. F., Buol, S. W. 1988. Oxisol-Landscape relationships in Brazil. In: Proceedings of the Eighth International Soil Classification Workshop. Classification, Characterization and Utilization of Oxisols. Part 1: Papers. (Beinroth, F. H., Camargo, M. N., Eswaran, H., Eds). Rio de Janeiro-RJ, 174-189 p.

Lima, P. C. 1988. Micromorfologia de "horizonte B" de latossolos do Sudeste e Sul do Brasil. In: Anais da III Reunião de Classificação, Correlação de Solos e Interpretação da Aptidão Agrícola. Rio de Janeiro - RJ, EMBRAPA-SNLCS/SBCS. Documentos, 12: 391-411.

Macedo, J., Bryant, R.B., 1987. Morphology, mineralogy, and genesis of a hydrosequence of oxisols in Brazil. Soil Science Society of America Journal 51, 690-698.

Marques, J.D., Libardi, P.L., Vanlier, Q., Jong, V.L. 2002. Relação entre horizontes pedológicos e propriedades hidráulicas entre dois Latossolos. Revista Brasileira de Ciência do Solo 26, 567–577.

Marques, J. J., Schulge, D. G., Curi, N., Merttzman, S. A. 2004. Major element geochemistry and geomorphic relationships in Brazilian Cerrado soils. Geoderma 119, 179-195.

Motta, P. E. F., Carvalho Filho, A., Ker, J. C., Pereira, N. R., Carvalho Junior, W., Blancaneaux, P. 2002. Relações solo-superfície geomórfica e evolução da paisagem em uma área do Planalto Central Brasileiro. Pesquisa Agropecuária Brasileira 37, 869-878.

Pachepsky, Ya. A., Timlin, D. J., Rawls, W. J. Soil water retention as related to topographic variables. Soil Science Society American Journal 65, 1785-1795.

Radambrasil, 1984. Levantamentos de recursos naturais, Folha SD. 23. Brasília, Ministério de Minas e Energia - Secretaria Geral. 19, 654 pp.

Reatto, A., Correia, J.R., Spera, S.T. 1998. Solos do Bioma Cerrado: aspectos pedológicos. In: Sano, S.M., ALmeida, S.P. (Eds). Cerrado: ambiente e flora. Empresa Brasileira de Pesquisa Agropecuária, Planaltina-DF, pp. 47 - 88.

Reatto, A., Martins, E.S., Guimarães, E.M., Spera, S.T., Correia, J.R,. 2000. Variabilidade mineralógica de latossolos da área da Embrapa Cerrados em relação aos do Bioma Cerrado. Boletim de Pesquisa Embrapa Cerrados 20, 1-29.

Reynolds, W. D., Elrick, D. E. 1985. In situ measurement of field-saturated hydraulic conductivity, sortivity, and the α-parameter using the Guelph permeameter. Soil Science 140, 292-302.

Resende, M. 1976. Mineralogy, chemistry, morphology and geomorphology of some soils of Central Plateau of Brazil. Ph. D. Thesis. Purdue University, West Lafayette, 237p.

Resende, M., Bahia Filho, A.F.C., Braga, J.M., 1987. Mineralogia da argila de latossolos a partir do teor total de óxidos do ataque sulfúrico. Revista Brasileira de Ciência do Solo 11,17-23.

Resende, M., Santana, D.P., 1988. Uso das Relações Ki e Kr na estimativa da mineralogia para classificação dos Latossolos. In: Anais da 3. Reunião de Classificação, Correlação de Solos e Interpretação de Aptidão Agrícola. EMBRAPA-SNLCS/SECS, Rio de Janeiro, pp. 225–229.

Ribeiro J.F., Walter B.M.T., 1998. Fitofisionomias do Bioma Cerrado. In: Sano, S.M., ALmeida, S.P. (Eds). Cerrado: ambiente e flora. Empresa Brasileira de Pesquisa Agropecuária, Planaltina-DF, pp 89–166.

Santana, D.P., 1984. Soil formation in a toposequence of oxisols from Patos de Minas region, Minas Gerais, State, Brasil. Ph. D. Thesis. Purdue University, West Lafayette, 129p.

Schaefer, C. E. R. 2001. Brazilian latosols and their B horizon microstructure as long-term biotic constructs. Australian Journal Soil Research 39, 909-926.

Silva, E.M., Azevedo, J.A., 2002. Influência do período de centrifugação na curva de retenção de água em solos de Cerrado. Pesquisa Agropecuária Brasileira 37, 1487–1494.

Silva, A.V., Farias, M.F., Reatto A., Martins, E.S., Brossard, M., Becquer, T., Oliveira, O.R., 2005. Caracterização e distribuição das principais classes pedológicas do

Planalto Central Brasileiro. In: Anais do XXV Congresso Brasileiro de Ciência do Solo. SBCS, Recife-PE, CD-ROM.

Soil Survey Staff, 1998. Keys to Soil Taxonomy. 8 ed. United States Department of Agriculture, Natural Resources Conservation Service, Washington. 326 pp.

Tomasella, J., Hodnett, M.G., 1997. Estimating unsaturated hydraulic conductivity of Brazilian soils using soil-water retention data. Soil Science 162, 703–712.

Van den Berg, M., Klamt E., Van Reeuwijk, L.P., Sombroek, W.G., 1997. Pedotransfer functions for the estimation of moisture retention characteristics of Ferralsols and related soils. Geoderma 78, 161–180.

Vollant-Tuduri, N., Brossard, M., Bruand, A., Garreau, H. 2004. Direct analysis of microaggregates shrinkage for drying: Application to microaggregates from a Brazilian clayed Ferralsol. Comptes Rendus de l'Académie des Sciences 336, 1017–1024.

Vollant-Tuduri, N., Bruand, A., Brossard, M., Balbino L. C., Oliveira, M. I. L., Martins, E. S. 2005. Mass proportion of migroaggregates and bulky density in a Brazilian clayed Oxisol. Soil Science Society American Journal 69, 1559–1564.

Westerhof, R., Buurman, P., van Griethuysen, C., Ayarza, M., Vilela, L., Zech, W. 1999. Aggregation studied by laser diffraction in relation to plowing and liming in the Cerrado region in Brazil Geoderma 90, 277–290.

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Table 1
General characteristics of the Latosols (L) studied

Latosols	Geographical Coordinates	Geomorphic Surface	Soil type	Altitude	Geology	Lithology	Parent Material	<2 µm mineralogy	Vegetation
L1	S066°60'77'' W81°60'187'	South America	Red Latosol (Rhodic Acrustox)	1,050 m	Metamorphic Rocks- Complex Goiano – (Anápolis - Itauçu) and metaclastic rocks – Group Araxá - Superior Precambrian	Granulite	Mafic granulite	gibbsite/hematite	Subcaducifolic Tropical Florest (Floresta Tropical Subcaducifólia)
L2	S15°37'127'' W47°45'576'	South America	Red Latosol (Typic Acrustox)	1,200 m	Clastic rocks - Paranoá Group - Superior Precambrian	Sandy Metarithimite	Lateritic crusts and saprolite Sandy Metarithimite	gibbsite/hematite	Typical Savannas (Cerrado Típico)
L3	S15°36'919'' W47°45'78''	South America	Yellow Latosol (Xanthic Acrustox)	1,190 m	Clastic rocks - Paranoá Group - Superior Precambrian	Sandy Metarithimite	Lateritic crusts and saprolite Sandy Metarithimite	gibbsite/goethite	Typical Savannas (Cerrado Típico)
L4	S15°36'320'' W47°44'148'	South America	Plinthic Yellow Latosol (Plinthic Acrustox)	1,180 m	Clastic rocks - Paranoá Group - Superior Precambrian	Quartzite	Lateritic crusts and saprolite Quartzite	gibbsite/goethite	Typical Savannas (Cerrado Típico)
L5	S15°36'502'' W47°42'813''	Velhas, superior level	Red Latosol (Typic Acrustox)	920 m	Clastic rocks - Paranoá Group - Superior Precambrian	Clayed Metarithimite	Colluvial Sediment	kaolinite/hematite	Xeromorphic Tropical Florest (Cerradão)
L6	S15°31'450'' W47°41'903	Velhas, superior level	Red Latosol (Rhodic Acrustox)	880 m	Pelitic rocks - Paranoá Group - Superior Precambrian	Metapelite	Lateritic crusts and saprolite Metapelite	kaolinite/hematite	Subcaducifolic Tropical Florest (Floresta Tropical Subcaducifólia)
L7	S15°13'24,2'' W47°42'14,7'	Velhas, intermediate level	Red-Yellow Latosol (Typic Acrustox)	820 m	Pelitic rocks - Paranoá Group - Superior Precambrian	Metapelite	Colluvial Sediment	kaolinite/goethite	Dense Savannas (Cerrado Denso)
L8	S15°13'23,3'' W47°42'5,2''	Velhas, intermediate level	Red Latosol (Rhodic Acrustox)	805 m	Pelitic rocks - Paranoá Group Superior Precambrian	Metapelite	Colluvial Sediment	kaolinite/hematite	Dense Savannas (Cerrado Denso)
L9	S15°11'183'' W47°43'680''	Velhas, inferior level	Red Latosol (Rhodic Acrustox)	785 m	Pelitic rocks and limestone - Paranoá Group Superior Precambrian	Metapelite and limestone	Saprolite Metapelite and limestone	kaolinite/hematite	Dense Savannas (Cerrado Denso)
L10	S15°14'080'' W47°46'372'	Velhas, inferior level	Red Latosol (Rhodic Acrustox)	760 m	Limestone and lacustrine sediment of Terciary	Lacustrine limestrone	Colluvial Sediment	kaolinite/hematite	Dense Savannas (Cerrado Denso)

Geographical Coordinates: measured with a Global Positioning System (GPS); Altitude: measured with an altimeter, vegetation classified according to Ribeiro and Walter (1998).

Table 2
Morphological characteristics of the diagnostic horizons (Bw) selected in the Latosols (L) studied

Latosol	Horizon	Depth cm	Matrix Munsell Color dry	Matrix Munsell Color wet	Compound Structure	Nodules	Root channels	Insects channels and cavities
L1	Bw_2	100 - 160	2,5YR 4/8	2,5YR 3/6	1mSBK and 2fSBK and 1f-mGR and 3f-vfGR	(+++)vf-fDN	(+)fCH	no
L2	Bw_2	115/120 - 200+	5YR 5/6	2,5 YR 4/8	1cSBK and 3f-vfGR	no	no	no
L3	Bw_2	130 - 180	10YR 6/6	10YR 6/6	2-1cSBK and 3f-vfGR	(+-)fCN	no	no
L4	Bw_1	60 - 110	10YR7/8	10YR 5/8	1cSBK and 1f-mSBK and 2f-vfGR	no	(+-)fCH	no
L5	Bw_1	57/90 - 90/120	5YR 5/8	2,5YR 3/6	2mSBK and 3-2fSBK and 3-2fGR	(++)fDN	(+)fCH	(+)f-mCV
L6	Bw_2	140 - 200+	2,5YR 4/8	10R 3/6	1mSBK and 3f-vfGR	no	no	no
L7	Bw_2	96/110 - 200+	5YR 5/6	5YR 5/9	2-1m-fSBK and 3f-vfGR	(+)vfDN	no	(++++)vf-f CHCV
L8	Bw_2	95 - 200+	2,5YR 4/8	2,5YR 3/6	2-1m-fSBK and 3f-vfGR	(+-)vfDN	no	(+)vf-f CHCV
L9	Bw_2	100/110 - 180	2,5YR 4/6	2,5YR 3/6	1mSBK and 3f-vfGR	no	no	no
L10	Bw2	100 - 140	2,5YR 4/6	10R 4/8	2-1c-mSBK and 2c-mGR and 3f-vfGR	no	no	no

Structure description: (grade – size – type). Grade: 1 – weak; 2 – moderate; 3 – strong. Size of granular structure: vf – very fine (< 1mm); f = fine (1-2mm); m = medium (2-5mm); c = coarse (5-10mm); vc = very coarse (>10mm). Size of subangular blocky: vf – very fine (< 5mm); f = fine (5-10mm); m = medium (10-20mm); c = coarse (20-50mm); vc = very coarse (>50mm). Type: GR = granular; SBK = subangular blocky. Nodules description: (grade – size – type). Grade: (++++) = very strong; (+++) = strong; (++) = moderate; (+) = weak; (+-) = very weak; no = not observed. Size similar of subangular blocky. Type: DN = dispersed nodules; CN = concentrated nodules. Biological Activity description: (grade – size – type). Grade and size similar of nodules. Type: CH = channels; CV = cavities

Table 3
Chemical characteristics of the diagnostic horizons (Bw) of the Latosols (L) studied

Latosol	Horizon	pH_w	pH_{KCl}	OC	$Ca^{2+} + Mg^{2+}$	K^+	Na^+	Al^{+3}	$H^+ + Al^{3+}$	SB	CEC
				($g.Kg^{-1}$)	($cmol_c\ kg^{-1}$)						
L1	Bw_2	5.3	6.2	0.34	0.25	0.01	0.00	0.00	1.74	0.26	2.00
L2	Bw_2	5.3	6.2	0.61	0.16	0.00	0.00	0.00	10.44	0.16	10.60
L3	Bw_2	5.2	5.8	0.02	0.17	0.00	0.00	0.00	1.58	0.17	1.75
L4	Bw_1	5.2	5.7	0.34	0.24	0.00	0.00	0.00	1.48	0.24	1.72
L5	Bw_1	4.8	4.0	0.62	0.23	0.04	0.00	0.29	2.92	0.27	3.19
L6	Bw_2	4.8	5.5	0.02	0.18	0.01	0.00	0.00	9.80	0.19	9.99
L7	Bw_2	4.8	4.9	0.59	0.21	0.01	0.00	0.01	2.84	0.22	3.06
L8	Bw_2	4.9	4.2	0.61	0.20	0.01	0.00	0.18	8.84	0.21	9.05
L9	Bw_2	5.0	4.0	0.01	0.23	0.02	0.00	0.32	2.86	0.25	3.11
L10	Bw_2	5.2	4.3	0.02	0.91	0.02	0.00	0.09	4.66	0.93	5.59

OC = Organic carbon. SB = Sum of exchange bases ($Ca^{2+} + Mg^{2+} + K^+ + Na^+$). CEC = Cation exchange capacity (SB + $H^+ + Al^{3+}$). BS = Bases saturation (SB/CEC) x100.

Table 4

Physical characteristics of the diagnostic horizons (Bw) of the Latosols (L) studied

Latosol	Horizon	Particle size distribution (µm) 50-2000	2-50	< 2	Density D_p	D_b	Gravimetric water content W_0	W_1	W_6	W_{10}	W_{33}	W_{300}	W_{1500}	K_s
		(g.kg^{-1})			(g.cm^{-3})		(g.g^{-1})							(m.s^{-1})
L1	Bw_2	440	40	520	2.73	1.21	0.392	0.384	0.290	0.267	0.221	0.188	0.169	8.64×10^{-6}
L2	Bw_2	250	140	610	2.76	0.90	0.664	0.621	0.395	0.341	0.292	0.251	0.231	3.36×10^{-5}
L3	Bw_2	160	90	750	2.72	0.88	0.640	0.609	0.422	0.367	0.301	0.264	0.245	3.53×10^{-5}
L4	Bw_1	690	10	300	2.64	1.18	0.378	0.349	0.227	0.194	0.144	0.112	0.099	3.98×10^{-5}
L5	Bw_1	300	150	550	2.76	1.02	0.531	0.516	0.377	0.325	0.272	0.228	0.202	1.52×10^{-5}
L6	Bw_2	130	90	780	2.65	0.83	0.748	0.678	0.418	0.382	0.326	0.291	0.272	4.18×10^{-5}
L7	Bw_2	160	140	700	2.76	0.96	0.615	0.569	0.391	0.364	0.327	0.302	0.281	2.65×10^{-5}
L8	Bw_2	170	70	760	2.88	0.98	0.638	0.582	0.375	0.341	0.296	0.268	0.246	2.56×10^{-5}
L9	Bw_2	170	80	750	2.80	1.06	0.487	0.459	0.381	0.340	0.298	0.268	0.248	2.97×10^{-5}
L10	Bw_2	180	70	750	2.76	0.88	0.680	0.649	0.456	0.391	0.323	0.277	0.252	1.69×10^{-5}

D_p = Particle density. D_b = Bulk density. W_h = water content in g.g^{-1} at a potential of –h in kPa. *Ks* = saturated hydraulic conductivity.

Table 5
Total pore volume and elementary pore volumes of the diagnostic horizons (Bw) of the Latosols (L) studied

Latosol	Horizon	*V*p	V_{intra}	V_{inter}
			(cm^3g^{-1})	
L1	Bw_2	0.460	0.156	0.305
L2	Bw_2	0.739	0.183	0.556
L3	Bw_2	0.771	0.225	0.547
L4	Bw_1	0.463	0.090	0.373
L5	Bw_1	0.618	0.165	0.453
L6	Bw_2	0.819	0.234	0.585
L7	Bw_2	0.682	0.210	0.472
L8	Bw_2	0.667	0.228	0.439
L9	Bw_2	0.584	0.225	0.359
L10	Bw_2	0.765	0.225	0.540

*V*p, total volume of pores; V_{intra}, volume of intra-microaggregate pores, V_{inter}, volume of inter-microaggregates pores.

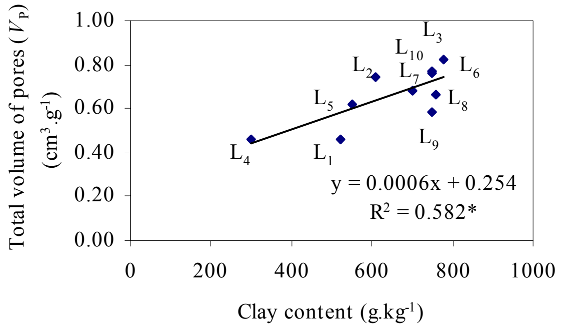

Fig.1. Volume of Total Pores (V_P) according to the clay content of the diagnostic horizons (Bw) for the Latosols (L) studied. (*: P = 0.05, significant at p > 0.05 level of probability).

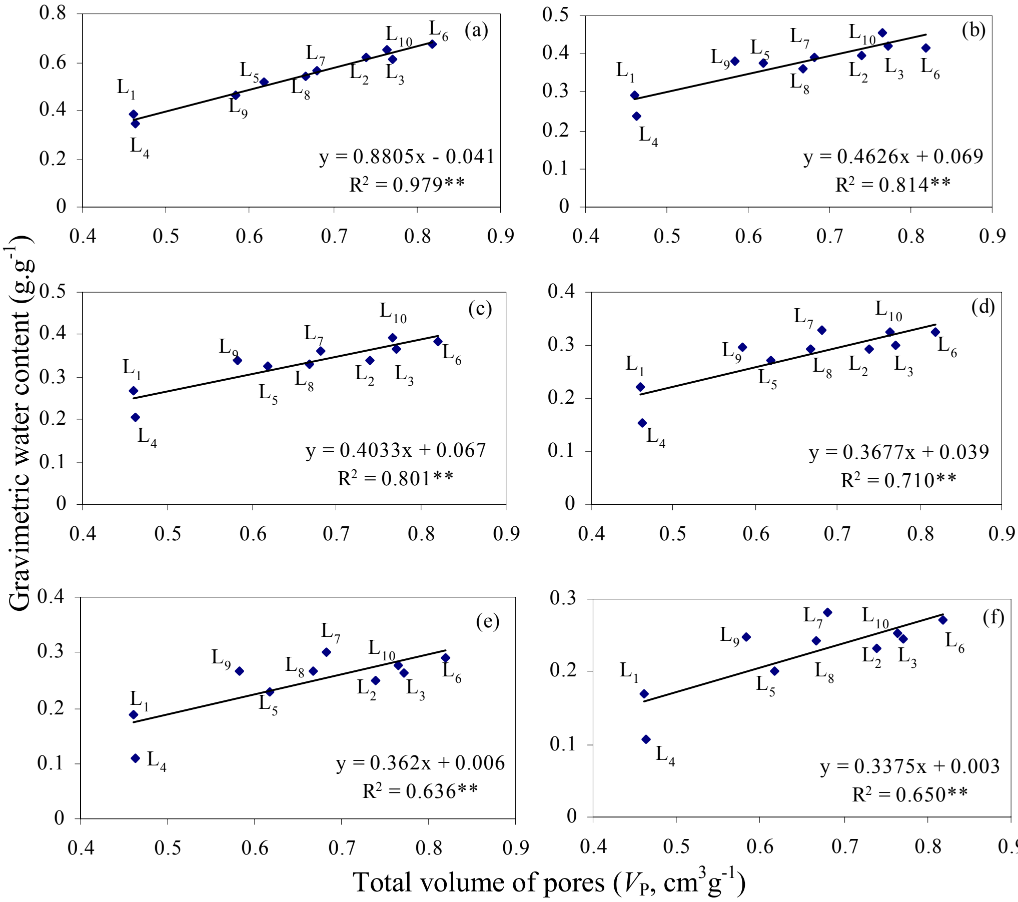

Fig.2 - Gravimetric water content at (a) -1kPa, (b) -6kPa, (c) -10kPa, (d) -33kPa, (e) -300kPa, (f) -1500kPa according to the total volume of pores (V_P) of the diagnostic horizons (Bw) for the Latosols (L) studied. (**: P = 0.01, significant at p > 0.01 level of probability).

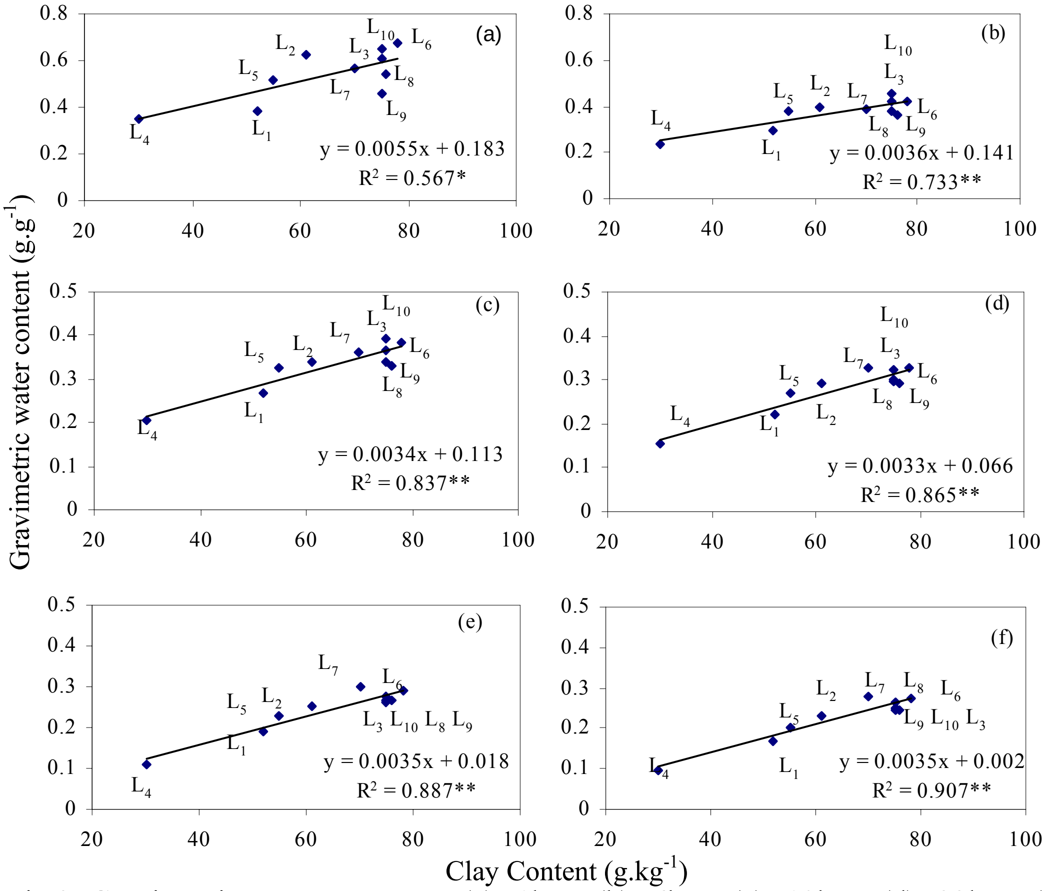

Fig.3. Gravimetric water content at (a) -1kPa, (b) -6kPa, (c) -10kPa, (d) -33kPa, (e) -300kPa, (f) .1500kPa according to the clay content of the diagnostic horizons (Bw) for the Latosols (L) studied. (**: P = 0.01, significant at p > 0.01 level of probability), (*: P = 0.05, significant at p > 0.05 level of probability).

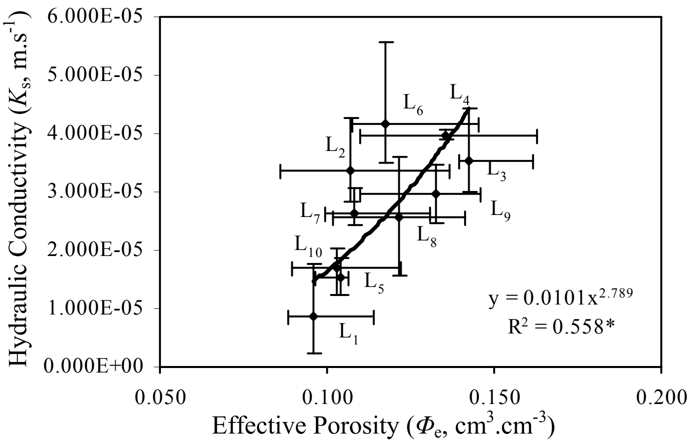

Fig.4. Saturated hydraulic conductivity (K_s) according to the effective porosity (Φ_e) of the diagnostic horizons (Bw) for the Latosols (L) studied. (*: P = 0.05, significant at p > 0.05 level of probability).