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Shear parameters associated with compaction states and degrees of water saturation in two Hapludox

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The aim of the study was to evaluate the impact of three states of compaction and two degrees of initial water saturation in direct shear parameters in two Hapludox. We studied a Hapludox-LVd (0.55 kg kg^{-1} clay) and a Hapludox-LVdf (0.62 kg kg-1 de argila), in Brazil. We made a map of isolines of soil resistance to of the 0.07-0.12 m layer, which had a higher compaction state and, along with the soil density, we characterized three compaction states which were used as treatments. Statistical analysis consisted of comparing cohesion averages (C) and internal friction angle of the soil (ϕ), in the three states of compaction, degrees of initial water saturation and depths. To analyze the behavior of C and ϕ, depending on the initial density (Dsi) clay content (Arg) and the degree of initial water saturation (Gsi), we generated regressions involving the variables. The states of compaction did not promote significant changes in the values of C, but the depth of 0.07-0.12 m, which concentrated the largest deformation, showed values of C higher than the others. The ϕ did not vary with the Dsi or soil moisture and proved to be the most affected by the clay content of the soil. The C increased with the reduction of Gsi and with increasing Dsi and was more influenced by than Dsi by Gsi, showing that the state compaction or history of tensions already experienced influenced by the soil has more strongly influenced the resistance to shear than the degree of water saturation.

Key words: Cohesion, internal friction angle, compressive behavior, no-tillage system.

INTRODUCTION

The resistance to shear is the mechanical property that directly affects the efficiency of agricultural tools for soil preparation (Voorhees et al., 1978) and represents the property of the soil to bear loads (load-bearing capacity) preserving its stability.

The soil, when subjected to external forces, reacts in different ways according to the characteristics of the tension, distribution form, orientation and magnitude of the tension. Each mode corresponds to a new stress-strain relationship, which can cause compaction, dilatation

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gaps and/or plastic flow with volume change. The theory and processes on solo material is complex because many soils are heterogeneous and discontinuous (Soane and Ouwerkerk, 2010).

The properties that determine the shear resistance of the soil are:

Shape and particle size distribution of the soil, moisture, structure, density, type of clay mineral present and the type and amount of exchangeable cations and the attraction and repulsion forces between particles (McCormack and Wilding, 1979).

The granulometry of the soil greatly influences its shear strength (Horn et al., 1994), for the abundance of fine particles affect the intensity of compaction that the ground reaches, which tends to increase the shear resistance (Voorhees et al., 1978).

The evaluation of direct shear of the soil gives the rupture line of Mohr-Coulomb, where it is possible to determine the cohesion and angle of friction of structured soils (Lebert and Horn, 1991).

With these parameters, the potential of the ground traction can be determined and, thereby, it is possible to determine the effects of the preparation, other management actions and grazing on the soil bearing capacity (Silva et al. 2004).

In practical terms, the shear resistance curve allows knowledge of the resistance of the aggregates and the mass of soil, the first being conditioned by phenomena of molecular cohesion, whereas the soil mass resistance depends on the surface cohesion and friction between particles (Caputo, 1967).

The cohesion and shear resistance of the soil increased significantly with the reduction of the water content (Silva and Carvalho, 2007), but other studies have indicated that these parameters have also been increased by increasing the compaction or degradation of the soil structure (Azevedo, 1999; Iori et al., 2012).

The characteristics of shear resistance determine the development of forces soil-tractor or soil-implement, affecting traction efficiency (Stafford and Tanner, 1983).

For clayey soils, the most effective way to reduce soil compaction requires the use of minimum load and maximum agricultural tire contact area (Blackwell and Soane, 1981).

According to Larson and Gill (1973), the maximum pressure on the soil is between 2 and 3 times the inflation pressure of the tires.

When the internal pressure of the tire is 108 kPa, the pressure on the soil corresponds to 216 to 324 kPa, which is greater than the shear tension of many soils in a water tension of 10 kPa (field capacity).

Understanding the compressive behavior of soils is critical to maintain the structural quality so as not to compromise the growth conditions of crops.

In this sense, this work has been developed to evaluate the impact of three states of compaction and two degrees of initial soil water saturation in the direct Shear parameters in two Hapludox.

MATERIALS AND METHODS

Study areas

The experiments were conducted in two crop areas located in two counties in the state of Rio Grande do Sul, RS, Brazil: the first in Cruz Alta (Latitude: 28°38’19”S and Longitude: 53°36’23”W) and the second in Coronel Barros (Latitude: 28°22’59”S and Longitude: 54°03’56”W). In Cruz Alta, the area for the experiment was planted 14 years ago under no-tillage, with crop rotation in the winter (wheat, oats, turnip) and summer (corn and soybeans), while in Coronel Barros, the area was cultivated 7 years ago under no-tillage with continuous cultivation of wheat in the winter and soybeans in the summer.

Geomorphologically, these areas are located in the plateau of the state of Rio Grande do Sul, and the climate in these regions is classified as Cfalg, according to the Köppen climate system, that is, subtropical humid, without typical drought. The average temperature of the warmest month is above 22°C and the coldest month is higher than 3°C and lowers than 18°C. The average annual rainfall is greater than 1600 mm, with a tendency for increased precipitation in spring and summer.

In Cruz Alta the soil is classified as Hapludox-LVd (0.55 kg kg^{-1} clay) and in Coronel Barros it is a Hapludox-LVdf (0.62 kg kg^{-1} clay), while according to Soil Taxonomy (USDA, 2010). The clay content was determined by the pipette method according to Embrapa (1997).

Determination of the states of soil compaction (EC) In both study areas, prior to performing the collection of soil samples for the determination of shear parameters, three states of soil compaction were identified from obtaining the bulk density (Ds) and penetration resistance (PR) values in the study areas.

To map the different states of compaction, we marked a parcel of 50 × 30 m within the study areas and measures of Ds and RP were performed on a grid of 4 × 2 m within and the cone index was obtained according to ASAE standard R313. To determine the Ds, samples were each area. The RP was determined in the field to a depth of 0.40 m from the surface with the aid of a penetrograph collected with the preserved structure in rings of 5 cm diameter and 5 cm in height, in the layers 0-0.05, 0.07-0.12 and 0.20-0.25 m. Once collected, the samples were transported to the laboratory prepared, weighed, dried at 105°C for 48 h and weighed again. The Ds was calculated according to the method of volumetric ring (EMBRAPA, 1997).

Thus, three ECs were determined in the study areas by means of a map of isolines generated from the RP values of the layer 0.07 to0.12 m (Figure 1), since this layer was the one with the largest PR and Ds values. The values of RP, Ds and clay contents in the soil determined in different ECs are shown in (Table 1).

Sampling and initial water saturation of samples for shear tests

To determine the shear parameters, soil samples were collected in metal castings of 2.0 × 5.0 × 5.0 cm. In each soil investigated were collected three groups of 8 boxes per depth (0.0-0.05; 0.07-0.12 and 0.20-0.25 m) in each state of compaction of the study areas (Figure 2a). Soil samples were collected at two different times: in the area of Cruz Alta, from May to July 2000 (Time 1) and from May to August 2001 (Time 2), and in Coronel Barros, from February to March 2000 (Time 1) and from September to October 2001 (Time 2). The samples were then conducted to the laboratory, prepared, saturated with water for 72 h and each set of four boxes was

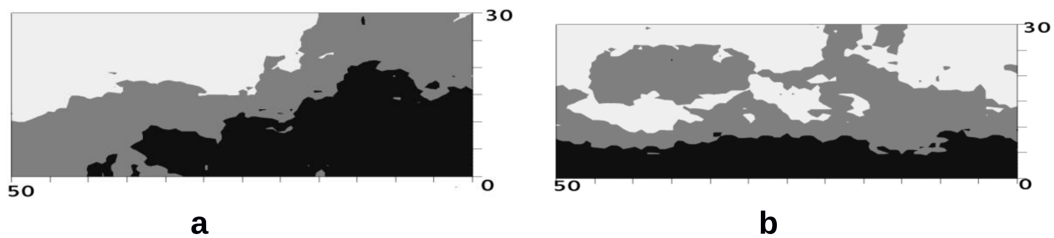

Figure 1. Distribution of soil resistance to penetration, in the layer 0.07-0.12 m, in the LVd (a) and in the LVdf (b). (EC1 = dark color; EC2 = gray color; EC3 = white color). The direction 0-50 m is the line from the edge of the crop, while the direction 0-30 m is from the edge to the center of the crop.

Table 1. Mean values of soil resistance to penetration (Rs), gravimetric soil moisture (Ug) at the time of Rs data collection, soil density (Ds) and clay content.

Compaction state	Rs range	Ug	Ds	Clay
	MPa	kg kg^{-1}	Mg m^{-3}	kg kg^{-1}
		LVd		
EC1	2.76 to 3.2	0.27	1.58	0.56
EC2	2.2 to 2.75	0.26	1.52	0.53
EC3	1.7 to 2.22	0.28	1.45	0.58
		LVdf		
EC1	2.11 to 2.8	0.23	1.55	0.60
EC2	1.6 to 2.1	0.22	1.51	0.65
EC3	0.2 to 1.59	0.21	1.38	0.61

EC, Compaction states: EC1, higher; EC2, intermediate; EC3, lower.

subjected to the stresses of 33 and 300 kPa in a Richards chamber, to characterize different degrees of water saturation (GS) before performing the direct shear tests. These tensions provided, on average, GS values of 63% (GS1) and 58% (GS2) for LVd and 68% (GS1) and 63% (GS2) for LVdf, respectively.

For a better understanding of the behavior of ϕ and C according to the degree of initial water saturation (Gsi), it was necessary to obtain GS values lower than the obtained in the tension of 300 kPa. Therefore, in addition to the samples collected for tensions 33 and 300 kPa, 8 samples were collected per layer for each soil compaction state, which were placed in cardboard boxes with small holes, allowing moisture loss in a slow and homogeneous way. Thus, with the data from the LVd and the LVdf, samples were obtained with GSi < 30%, GSi of 30-60% and GSi>60%.

The total samples for each season was 216. The shear study used 864 soil samples (216 × two times × two locations) for the tensions of 33 and 300 kPa, over 144 samples (8 samples per layer × three layers × three compaction states × two locations) to obtain GS <30% and GS of 30 to 60%, totaling 1008 direct shear tests, with the goal of getting a wide variation of structural conditions and soil moisture.

Direct shear test

After being balanced in different GS, samples were submitted to the direct shear test in a direct shear press, model Solotest (Figure 2b), equipped with a split metal box (Figure 2c) where the samples were inserted with the aid of a wooden tool. The normal pressures used during the test were 34.68, 104.04, 208.08 and 416.16 kPa; the settling time of each load was approximately 5 min and the wind velocity was 0.25 mm min^{-1}. The readings of the tension applied on the samples were performed in a horizontal defletometer, which was coupled to the bipartite box, each 0.20 mm in horizontal displacement until the sample was ruptured (Figure 2d).

Thus, for each soil and moisture condition were obtained four values of shear tension (τ), one for each value of normal tension applied (34.68, 104.04, 208.08 or 416.16 kPa) with which it was possible to adjust an equation similar to Equation (1), whose intercept corresponds to the cohesion (C) and the angle cohesion that corresponds to the coefficient of friction.

$$\tau = C + \sigma \cdot tg\, \phi \qquad (1)$$

Where, τ = shear tension (kPa); C= soil cohesion, which is the shear resistance of a soil in the absence of pressure (kPa); σ = effective normal tension (kPa), and ϕ = angle of internal friction (°). The angle whose tangent corresponds to the angle coefficient of the equation is the internal friction angle (ϕ) (Figure 3).

The average duration of each sample's test was 45 min. The shear resistance parameters, cohesion and internal friction angle, were determined according to the methodology proposed by Lambeand Witman (1979).

Data analysis

The mean values for C and ϕ in different EC and GS for each soil layer were compared using the Student t test at α error level of 5%

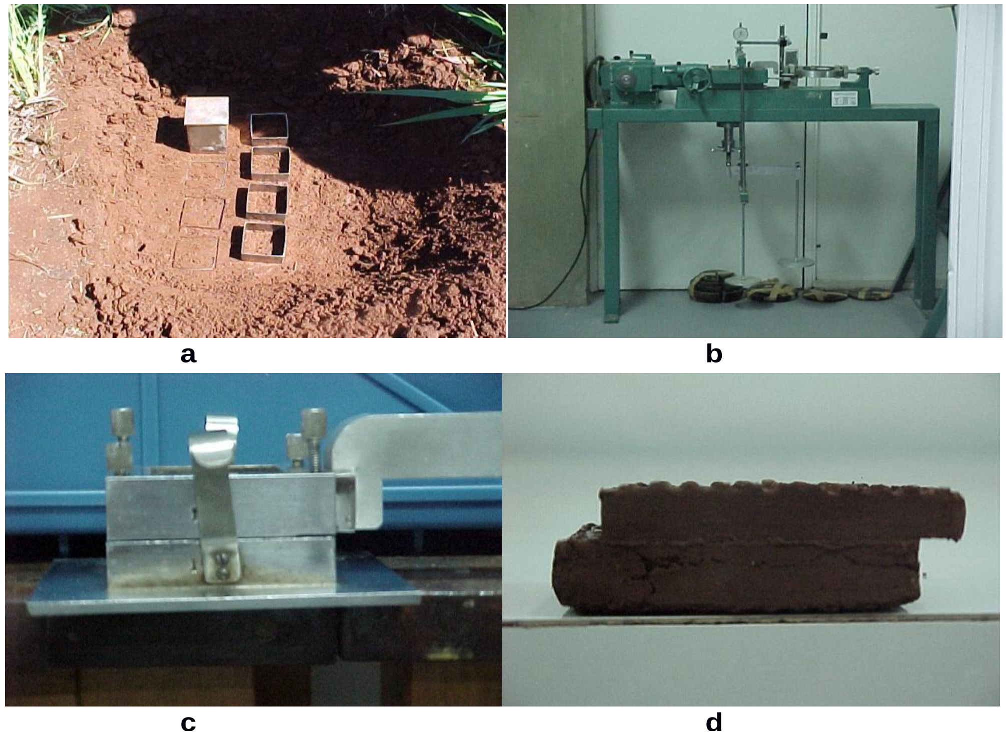

Figure 2. Collection of undeformed soil samples (a), direct shear press (b), bipartite box (c) and soil sample after completion of the shear test (d).

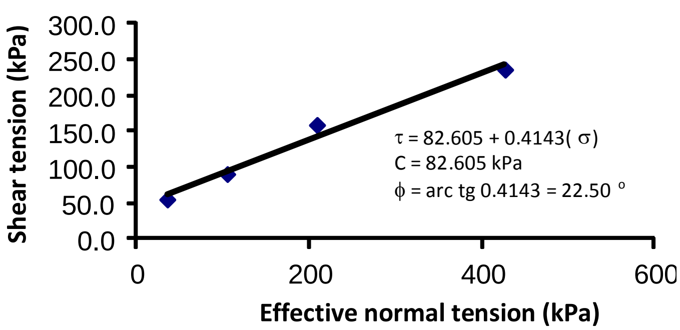

Figure 3. Ratio between shear tension and effective normal tension to the samples and determination of shear parameters: cohesion (C) and internal friction angle (ϕ).

with the help of the Sisvar Software. The behavior of C and ϕ depending on the initial density (Dsi), clay content (Arg) and degree of initial water saturation (Gsi) was also assessed using regressions involving the variables and the analysis of the determination coefficient (R^2).

RESULTS AND DISCUSSION

Cohesion (C)

The mean values of C observed in the samples depending on the CE and GS in 2000 and 2001 for the soils of the study areas are shown in Tables 2 and 3. In general, it was observed that, as the GS decreased (GS1 → GS2), C increased in all layers of the different Ecs of the soils studied.This effect was expected, considering that the cohesive forces manifested more strongly with lower water content in the soil. This result corroborates those presented by Hillel (1980) and Silva and Carvalho (2007), which state that, as the soil moisture increases, a small film of water forms between its particles, facilitating their rearrangement in the soil matrix and decreasing the soil resistance to deformation. This behavior in the two Hapludox is easily visualized in Figure 4.

Table 2. Values of cohesion (C) and internal friction angle (ϕ) determined in different layers, compaction states (EC), degrees of water saturation (GS) in the years 2000 and 2001of the LVd (average of three replicates).

Compaction states	C (kPa)				ϕ (°)			
	2000		2001		2000		2001	
	GS1	GS2	GS1	GS2	GS1	GS2	GS1	GS2
Layer 0-0.05 m								
EC1	24^{a}*	38^{a}	13^{a}	17^{a}	30^{a}	29^{a}	25^{a}	27^{a}
EC2	37^{a}	38^{a}	22^{a}	22^{a}	25^{a}	33^{a}	21b	25^{a}
EC3	33^{a}	49^{a}	16^{a}	24^{a}	25^{a}	27^{a}	26^{a}	24^{a}
Mean	31^{B}	41^{A}	17^{A}	21^{A}	27^{A}	29^{A}	24^{A}	25^{A}
Annual mean	36^{A}		19^{B}		28^{A}		24^{B}	
Layer 0.07-0.12 m								
EC1	79^{a}	93^{a}	52^{a}	66^{ab}	30^{a}	34^{a}	27^{a}	30^{a}
EC2	43^{a}	68^{a}	56^{a}	70^{a}	30^{a}	27^{a}	27^{a}	27^{a}
EC3	44^{a}	77^{a}	40^{a}	56^{b}	26^{a}	27^{a}	28^{a}	29^{a}
Mean	55^{B}	79^{A}	49^{B}	64^{A}	29^{A}	29^{A}	27^{A}	29^{A}
Annual mean	67^{A}		56^{A}		29^{A}		28^{A}	
Layer 0.20-0.25 m								
EC1	59^{a}	61^{a}	42^{a}	53^{a}	27^{a}	30^{a}	23b	27^{a}
EC2	52^{a}	54^{a}	34^{a}	37^{a}	25^{a}	29^{a}	30^{a}	31^{a}
EC3	41^{a}	70^{a}	33^{a}	56^{a}	29^{a}	27^{a}	29^{a}	30^{a}
Mean	51^{B}	61^{A}	36^{B}	49^{A}	27^{A}	29^{A}	27^{A}	29^{A}
Annual mean	56^{A}		42^{A}		28^{A}		28^{A}	

*Means followed by the same letter, lowercase in the column and uppercase in the line do not differ significantly by Student's t test (P<0.05). EC, Compaction states: EC1, higher; EC2, intermediate; EC3, lower.

The compaction states, in general, did not promote significant changes between the values of C in the two Latosols, if we look at the values in each layer. However, when comparing the mean values of C in the 0.07 to 0.12 m layer in relation to the others, it can be verified that these were superior. This is due to the fact that the layer of 0.07 to 0.12 m focuses accumulation of tensions imposed by the tires of machinery and agricultural implements, culminating in a greater deformation and consequently higher values of C. This increase in C associated with the degradation of the structure of layer 0.07 to 0.12 m is in line with results found by Iori et al. (2012) and this tendency to compaction in the top layer (0.07 to 0.15 m) in areas managed under no-tillage system has been shown by other authors (Silva et al., 2000; Stone and Silveira, 2001), being named “no-tillage-compaction” (Reichert et al., 2009).

Although the compaction states have not promoted significant changes between the values of C, it is found that as there was an increased soil density, in both Hapludox, there was an increase in the values of C (Figure 5), the expected result in accordance with the literature (Horn et al., 1994; Silva et al., 2004; Iori et al., 2012).

The annual average values of C, both in LVd and in LVdf, in the three states of compaction, degrees of water saturation and layers did not differ significantly at 5% significance by Student's t test, except for the 0 to 0.05 m layer of the LVd (Tables 2 and 3). The explanation for the absence of a significant difference is the use of the same machines within the two years, which did not provide any increase in pressure, additional to those already experienced by the soil.

Angle of internal friction (ϕ)

The average values of ϕ observed in the samplesaccording to the EC and GS in 2000 and 2001, for soils of the study areas, are shown in Tables 2 and 3. There were no significant statistical differences between the values of ϕ, in both soils, compaction states, initial degree of water saturation of soil and layers evaluated, being a not very variable feature of the ground (changes due to the clay content) and independent of the structural state.

The annual average values of ϕ, both in LVd and in LVdf, from the three states of compaction, degrees of water saturation and layers did not differ significantly at 5% significance by Student's t test. The values found in the literature (Soane and Ouwerkerk, 1994) show that this parameter has low variability and changes with more

Table 3. Values of cohesion (C) and internal friction angle (ϕ) determined in different layers, compaction states (EC), degrees of water saturation (GS) in the years 2000 and 2001of the the LVdf (average of three replicates).

Compaction states	C (kPa)				ϕ (°)			
	2000		2001		2000		2001	
	GS1	GS2	GS1	GS2	GS1	GS2	GS1	GS2
Layer 0-0.05 m								
EC1	43[a]	36[a]	28[a]	23[a]	26[a]	29[a]	25[a]	27a
EC2	9[b]	37[a]	42[a]	46[a]	33[a]	27[a]	23[a]	24a
EC3	36[a]	39[a]	38[a]	42[a]	26[a]	26[a]	23[a]	24a
Mean	**29[A]**	**37[A]**	**36[A]**	**37[A]**	**28[A]**	**27[A]**	**24[A]**	**25[A]**
Annual mean	**33[A]**		**37[A]**		**27[A]**		**24[A]**	
Layer 0.07-0.12 m								
EC1	65[a]	69[a]	43[a]	56[a]	29[a]	29[a]	25[a]	28a
EC2	27[a]	66[a]	48[a]	64[a]	27[a]	28[a]	29[a]	28a
EC3	67[a]	52[a]	48[a]	68[a]	28[a]	29[a]	23[a]	28a
Mean	**53[A]**	**62[A]**	**46[B]**	**63[A]**	**28[A]**	**29[A]**	**26[A]**	**28[A]**
Annual mean	**57[A]**		**54[A]**		**27[A]**		**27[A]**	
Layer 0.20-0.25 m								
EC1	37[a]	45[a]	32[a]	32[b]	23[a]	27[ab]	28[a]	29a
EC2	31[a]	57[a]	38[a]	42[ab]	21[a]	23[b]	26[a]	28a
EC3	46[a]	38[a]	31[a]	55[a]	27[a]	29[a]	24[a]	25a
Mean	**38[A]**	**47[A]**	**34[B]**	**43[A]**	**24[A]**	**26[A]**	**26[A]**	**27[A]**
Annual mean	**42[A]**		**38[A]**		**25[A]**		**25[A]**	

*Means followed by the same letter, lowercase in the column and uppercase in the line do not differ significantly by Student's t test (P<0.05). EC, Compaction states: EC1, higher; EC2, intermediate; EC3, lower.

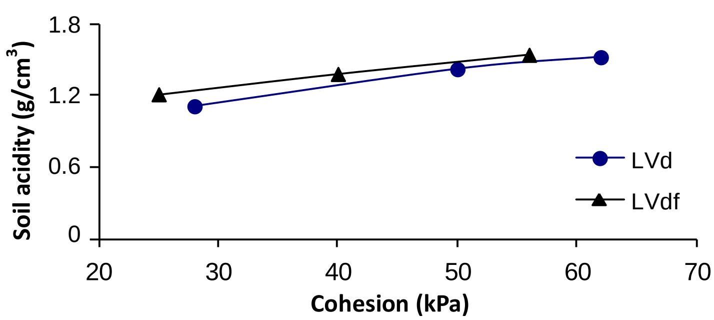

Figure 4. Ratio between soil density and cohesion in the soils of the study areas. General mean values of the three states of compaction, layers and degrees of water saturation.

significant changes in the levels of water and/or soil texture.

Regression with data sets of Hapludox

The regression of the two data sets indicated that soils in the water saturation class Gsi<30% for soil C, the Dsi was responsible for the largest percentage (55%) of variations occurred (Table 4). In this class, the Gsi was responsible for 20% of the variations occurred in the ϕ and when the model included the Dsi, these attributes were responsible for 34% of the variations occurred in ϕ.

In class of Gsi 30-60%, the Dsi was responsible for 35% of the variations occurred in C and for 7% of the variations in soil ϕ. In the class Gsi> 60%, the Dsi was responsible for 31% of the variations in C and for 3.5% of the variations in soil ϕ.

Thus, it was verified that the soil shear parameter that has the greatest influence on the compressive behavior of the soil, C, in the three degrees of water saturation was influenced more by Dsi than the Gsi for both Latosols

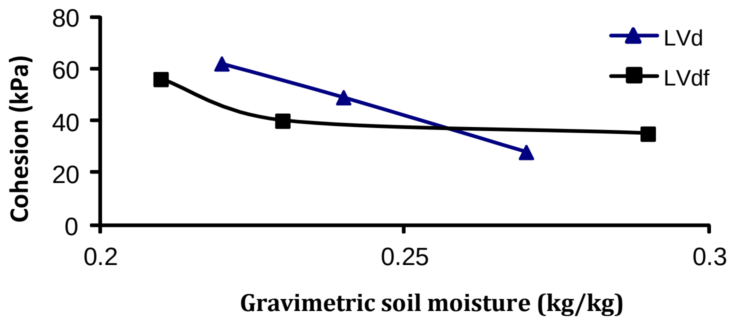

Figure 5. Ratio between cohesion and gravimetric soil moisture in the soils of the study areas. General mean values of the three states of compaction, layers and degrees of water saturation.

Table 4. Coefficient of determination of regression (R2) and prediction equations for shear parameters with data sets of LVd and LVdf in three classes of degrees of initial water saturation.

Atributes	R2
Gsi < 30%	
Dsi	0.550
Dsi + Arg	0.680
Dsi + Arg + Gsi	0.740
C = - 78.94 + 139.72(Dsi) + 108.28(Gsi) - 0.65 (Arg)	
Gsi	0.200
Gsi + Dsi	0.340
ϕ = 60.07 – 57.67(Dsi) – 154.44(Gsi)	
Gsi 30 – 60%	
Dsi	0.350
Dsi + Gsi	0.380
Dsi + Gsi + Arg	0.400
C = - 141.89 + 150.23(Dsi) + 159.88(Gsi) + 0.57(Arg)	
Dsi	0.070
ϕ = 14.97 + 9.77(Dsi)	
Gsi > 60%	
Dsi	0.313
Dsi + Gsi	0.341
Dsi + Gsi + Arg	0.359
C = - 132.45 + 194.80(Dsi) + 144.85(Gsi) - 0.64(Arg)	
Dsi	0.035
Dsi + Arg	0.064
Dsi + Arg + Gsi	0.071
ϕ = 21.08+15.12(Dsi)+ 12.60(Gsi) – 0.18(Arg)	

For the regression analysis, we used the results of 1008 direct shear tests.

studied. This shows that the state of compaction influenced more strongly in shear resistance than the degree of water saturation and therefore in the compressive behavior of these soils.

These results corroborate the results of the literature (Caputo, 1967; Azevedo, 1999), which state that the factors that most influence the shear resistance in unsaturated cohesive soils are: State of density of the soil (or compaction), weakness or stability of the soil structure, drainage conditions and speed of load application.

Conclusions

The states of compaction did not promote significant changes in the values of cohesion (C), but the layer of 0.07 to 0.12 m, which concentrated the largest deformation, showed values of C higher than the others. The internal friction angle (ϕ) did not vary with the initial density of the soil (Dsi) or with soil moisture and proved to be most affected by the clay content of the soil. In both Hapludox, C increased with the reduction of initial degree of water saturation (Gsi) and increased Dsi, and was more influenced by Dsi than by Gsi. Therefore, the compaction state or history of tensions experienced by the soil, influenced more strongly in shear strength than the degree of water saturation and, therefore, in the compressive behavior of these soils.

REFERENCES

Asae R 313. Soil Cone Penetrometer. American Society of Agricultural Engineers, 2950 Niles Rd., Box 29, St. Joseph, 1971 (Reaffirmed 1975).

Azevedo MAA (1999). Contribuição ao estudo geotécnico de solos de Viçosa, MG. 169f. Dissertação (Mestrado em Engenharia Civil) – Universidade Federal de Viçosa, Viçosa.

Blackwell PS, Soane BD (1981). A method of predicting bulk density changes in fields soils resulting from compaction by agricultural traffic. J. Soil. Sci. Oxford. 32:51-65.

Caputo HP (1967). *Mecânica de solos e suas aplicações.* Rio de Janeiro: Ao Livro Técnico, P. 187.

Empresa Brasileira de Pesquisa Agropecuária –Embrapa (1997). Manual de métodos de análises de solo. 2.ed. Rio de Janeiro: Ministério da Agricultura e do Abastecimento, P. 212.

Hillel D (1980). Fundamentals of soil physics. University of Massachusetts. Amherst, Massachusetts, USA. Academic Press, P. 413.

Horn R, Taubner H, Wuttke M (1994). Soil physical properties related to soil structure. Soil Till. Res. Amsterdam 30:187-216.

Iori P, Dias Junior MS, Silva RB (2012). Resistência do solo à penetração e ao cisalhamento em diversos usos do solo em áreas de preservação permanente. Bio. Sci. J. Uberlândia. 28:185-195.

Lambe TW, Whitman RV (1979). *Soil mechanics, SI Version*. New York: J. Wiley & Sons. (Series in soil engineering). P. 553.

Larson WE, Gill WR (1973). Soil physical parameters for designing new tillage systems. 1. Management principles. In: Conservation Tillage, The Proocedings of a National Conference. Ankeny: SCSA, pp. 13-22.

Lebert M, Horn R (1991). A method to predict the mechanical strenght of agricultural soils. Soil Till. Res. Amsterdam 19:275-286.

McCormack DE, Wilding LP (1979). Soil properties influencing strength of Cranfield and Geeburg soils. Soil Sci. Soc. Am. **J**. Madison 43:167-173.

Reichert JM, Suzuki LEAS, Reinert DJ, Horn R, Håkansson I (2009). Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Till. Res. Amsterdam 102:242-254.

Silva VR, Reinert DJ, Reichert JM (2000). Densidade do solo, atributos químicos e sistema radicular do milho afetados pelo pastejo e manejo do solo. R. Bras. Ci. Solo, Viçosa 24:91-199.

Silva RB, Dias Junior MS, Santos FL, Franz CAB (2004). Resistência ao cisalhamento de um Latossolo sob diferentes uso e manejo. R. Bras. Ci. Solo, Viçosa 28:165-173.

Silva AJN, Carvalho FG (2007). Coesão e resistência ao cisalhamento relacionadas a atributos físicos e químicos de um Latossolo amarelo de tabuleito costeiro. R. Bras. Ci. Solo, Viçosa 31:853-862.

Soane BD, Ouwerkerk C van (2010). Soil compaction problems in world agriculture. In: Soane BD, Ouwerkerk C van, ed. *Soil compaction in crop production*. Netherlands: Elsevier, 1994, pp. 01-21.

Soil Survey Staff (USDA) (2010). Keys to Soil Taxonomy, 11th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Stone LR, Silveira PM (2001). Efeitos do sistema de preparo e da rotação de culturas na porosidade e densidade do solo. R. Bras. Ci. Solo, Viçosa 25:395-401.

Stafford JV, Tanner DW (1983). Effect of rate on soil shear strength and soil-metal friction. I. Shear strength. Soil Till. Res. Amsterdam 3:245-260.

Voorhees WB, Senst CG, Nelson WW (1978). Compaction and soil structure modification by wheel traffic in the Northern corn belt. Soil Sci. Soc. Am. J. Madison 42:344-349.