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Soil compressibility and penetrability of an Oxisol from southern Brazil, as affected by long-term tillage systems $\stackrel{\approx}{\sim}$

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Abstract

The precompression stress value defines the transition from the reloading curve to the virgin compression line in the stress-strain curve, which can be used to quantify the highest load or the most intense predrying previously applied to the soil. Thus, in soils with well-defined structured soil horizons, each layer can be characterized by such mechanical strength. Penetration resistance measurements, on the other hand, can be used to determine total soil strength profiles in the field. The effect of long-term tillage systems on physical and mechanical properties was determined in undisturbed and remolded samples collected at 5 and 15 cm depth, 6 months after applying no-till (NT), chisel plow (CP), and conventional tillage (CT) treatments, along with the application of mineral fertilizer and poultry litter. The compressibility tests were performed under confined conditions, with normal loads varying from 10 to 400 kPa after a defined predrying to -6 or -30 kPa. Penetration resistance was determined in the field, after seeding, in three positions: seeding row (SR), untrafficked interrow (UI), and recently trafficked interrow (TI). No-till system showed greater soil resistance to deformation than tilled treatments, as determined by the higher precompression stress and lower coefficient of compressibility. When original soil structure was destroyed (remolded samples), smaller differences were found. The application of extra organic matter (poultry litter) resulted in a reduction of precompression stress in undisturbed samples. Penetration resistance profiles showed greater differences among tillage treatments in the upper layer of the untrafficked interrow, where NT system showed the higher values. Smaller differences were found in the seeding row (with lower values) and in recently trafficked interrow (with higher values), showing that even traffic with a light tractor after soil tillage reduced drastically the effect of previous tillage by loosening up the soil. On the other hand, the tool used to cut the soil and to open the furrow for seeding, incorporated in the direct seeding machine, was sufficient to realleviate surface soil compaction.

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1. Introduction

The mass of various machines used in agricultural operations has increased by a factor of 3–4 during the last

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three decades, while the number of field operations can be greater than 10 per year (Horn, 1995). As a consequence, increasing interest in surface and subsoil compaction has been focused in order to protect the soil against detrimental effects on physical, chemical, and biological soil properties and processes in deeper layers, which cannot be easily realleviated by tillage implements or inexpensive practices (Håkansson and Reeder, 1994).

From basic soil mechanics, the normal stress on any plane is, in general, the sum of the stresses transmitted

 $^{^{\}diamond}$ Chapter of the Ph.D. thesis of the first author.

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by solid particles (effective) and the pressure of the fluid in the void space (neutral). The effective stress (σ') for saturated soils is given by the expression proposed by Terzaghi:

$$\sigma' = \sigma - u \tag{1}$$

where σ denotes total normal stress and *u* denotes fluid pressure in the pore space.

In unsaturated soils, air and water in the pore space also affect the stress transmission (Bishop, 1961). Thus, the corresponding expression for the effective stress in all situations is defined as:

$$\sigma' = \sigma - u_{\rm a} + \chi (u_{\rm a} - u_{\rm w}) \tag{2}$$

where u_a denotes pressure in the gas and vapor phase and u_w denotes pressure in the pore water. The values of the χ parameter are unity for saturated soils, when the equation is reduced to a two-phase system as proposed by Terzaghi, and zero for dry soils (pF 7). The intermediate values will depend primarily on the saturation degree (Bishop, 1961). Another special case arises when u_a is equal to atmospheric pressure, which reduces the effective stress equation to (Skempton, 1961)

$$\sigma' = \sigma - \chi(u_{\rm w}) \tag{3}$$

Especially for long-term loading, this equilibration will occur between internal and external pore air pressures in uniaxial confined test. Although this type of equation is well-known since many decades, the calculation of the effective stress is mostly not considered in the calculation of the precompression stress because neither the pore water pressure changes during the stress application were determined, nor values of the χ factor were calculated. Depending on soil type and processing conditions, saturation degree and χ factor present different behavior, but in overall terms the relation can be considered as being 1:1 in high saturation degree (Horn and Baumgartl, 1999).

The simultaneous registration of soil settlement and pore water pressure during stress-strain tests under confined conditions allows studying the relationship between soil deformation and water suction during soil compressibility determination in a multi-step device. Fazekas and Horn (2005) found that increasing time of each loading step increased soil settlement and reduced pore water pressure and precompression stress values. Longer time intervals allowed the remaining water to redistribute in the whole soil sample and result in a new equilibrium state of pore water pressure (since part of water can be lost during the test) in the reduced pore volume and new pore size configuration. It can be also concluded from their findings that the more negative the pore water pressure, the higher is the effective stress, which in itself shows a clear dependency to the loading time and the corresponding stresses applied.

In soils with markedly differentiated soil horizons or layers, each layer has a well-defined mechanical strength value which can be quantified by its precompression stress. If the applied stress does not exceed this value, the soil horizon reacts elastically, while exceeding it results in further plastic deformation (Horn et al., 1995). Furthermore, deeper soil horizons will be also subjected to an additional soil compaction as long as their internal strength is smaller than the remaining stress applied. Soil tillage systems affect mechanical behavior of soil layers. Horn (1986, 2004) determined that soils under a longterm conservation tillage induced changes in physical properties compared with conventionally tilled soils, being more resistant and thus less susceptible to deformation. Differences in precompression stress, shear strength, and hydraulic conductivity were found at 10-15 cm after approximately 3 years, at 30–35 cm after 5–6 years, and at 55-60 cm the same trend started after around 7 years (Horn, 2004). He also concluded that, under climatic conditions prevailing in northern Germany, better functioning pore systems can be obtained under a continuously applied system of conservation tillage, but these findings could only be maintained if during all tillage operations the internal soil strength is never exceeded by the applied mechanical stress.

Penetration resistance measurements can be used to determine total soil strength profiles in the field, being suitable in detecting strength and structural discontinuities associated with wheel tracks and size of structural units (Lowery and Morrison, 2002). Since this determination is highly influenced by soil water content and suction, measurements in the field should be done preferably when soil water content is uniform in the whole profile, i.e. when the water content is at field capacity, which is obtained 3-5 days after a rainfall with high precipitation. Shafiq et al. (1994) determined that penetration resistance increased with the increase in degree of compaction and this increase was more pronounced when compaction was induced at higher antecedent soil water contents. Greater penetration resistance was found in upper layers in no-till compared with conventional tillage systems (Burch et al., 1986; Francis et al., 1987) and chisel plow (Stewart and Vyn, 1994). When additional load (12 Mg axle load) was applied before tillage, significant differences in penetration resistance were restricted to depths of less than 35 cm in any of the tillage system (Stewart and Vyn, 1994). Genro et al. (2004) found higher penetration

resistance at about 10 cm depth in no-till system, and lower values were found above and below this depth. This determination was highly depended on soil water content, and restrictive values to root growth were found only when the soil was dry.

Several studies were performed in order to establish relations among soil properties and strength, but few of them were performed with undisturbed samples considering no-till system, especially in soils with high clay and oxides content, like in tropical areas. This, in turn, will be important to better understand the effects of soil amendments and tillage on states of compaction which is helpful to guide soil and plant management. Thus, the objective of this paper was to study the relations between soil physical and mechanical properties in different soil tillage systems, including no-till system in an Oxisol located in southern Brazil, under subtropical climate.

2. Material and methods

2.1. Experimental design and treatments

Field and laboratory analyses were performed in 2004 on an experiment which was installed in 1994 at the Epagri Experimental Station of Campos Novos, Santa Catarina, Brazil (27°24′S, 51°13′W, 970 m.a.s.l.), on a Typic Haplorthox, a Nitossolo Vermelho in Brazilian classification (Embrapa, 1999), with high clay, medium organic matter, and high base saturation at soil surface (Table 1).

Before the experiment installation, the field was used for crop production for more than 20 years under a conventional tillage system (primary disking plow plus two secondary disking). The main treatments were a combination of residue management and soil tillage, but only those treatments where residues were maintained in the field (on the surface/no-till, semi-incorporated/ chisel plow, and incorporated/conventional tillage) were analyzed and described in this paper. In addition, the effect of fertilizer application locally used by the farmers (like mineral fertilizer and poultry litter) and soil strength and pore functions were investigated. The experimental design corresponds to subdivided random blocks with three replications, with the tillage treatments and nutrients sources as tested variables.

The crops were seeded in a 3-year crop rotation, including crops for grain production in the spring/ summer season and cover crops in autumn/winter season, according to the sequence: triticale or rye/ soybean/common vetch/corn/black oat/black bean. A tractor with approximately 4.0 Mg and four-wheel drive was used to perform the primary tillage operations (i.e. primary disking plow and chisel plow) and a tractor with approximately 2.9 Mg and two-wheel drive was used to perform the secondary tillage operations (i.e. secondary disking) and seeding. Only soybean and triticale were harvested with a combine harvester with a mass of about 10 Mg.

2.2. Soil compressibility

Stress-strain curves were determined using undisturbed samples (10 cm diameter and 3 cm height) taken at two depths: 5 cm (3.5-6.5 cm layer) and 15 cm (13.5–16.5 cm layer), and collected in the untrafficked interrow of poultry litter and mineral fertilizer treatments, 6 months after the last tillage. Samples were saturated and equilibrated at -6 kPa pore water pressure on sand boxes. The compressibility test was performed under confined conditions in a multi-step apparatus with normal loads of 10, 20, 30, 50, 80, 120, 200, 300, and 400 kPa. Height changes and changes in pore water pressure were recorded automatically. Each load was applied either for 30 or 120 min (three replications each) before the following load was added. In order to determine the effect of soil aggregation on soil compressibility, also remolded samples were equilibrated at -6 and -30 kPa pore water pressure (three replications each) and thereafter stressed for 30 min, with identical normal loads as previously described.

Effective stress at the end of each load applied was calculated using Eq. (3), considering the χ factor identical

Table 1

General physical and chemical characterization of the analyzed soil profile at experimental site at the beginning of the experiment

Horizon	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	OC (%)	pН	$S (\text{cmol}_{c} \text{L}^{-1})$	$T (\mathrm{cmol}_{\mathrm{c}} \mathrm{L}^{-1})$
Ар	0–23	70.6	27.1	2.4	1.84	7.0	13.18	14.28
BĂ	23-38	74.5	24.2	1.3	1.55	6.4	8.65	11.95
Bt1	38-62	81.5	17.7	0.8	1.26	5.3	2.23	12.73
Bt2	62-88	82.1	17.5	0.4	0.86	5.3	1.83	10.63
Bw	88 to >134	76.7	22.4	0.9	0.40	4.9	0.53	10.13

OC: organic carbon; S: sum of basic cations; T: cation exchange capacity at pH 7.

to the saturation degree, since the values of saturation degree were always higher than $0.6 \text{ cm}^3 \text{ cm}^{-3}$ at the beginning of the test. In this range of saturation degree the relation between χ factor and saturation degree is near to 1:1 (Horn and Baumgartl, 1999). The precompression stress value, which defines the transition from the reloading curve to the virgin compression line (or the highest load previously supported by the soil), was calculated mathematically using parameters of van Genuchten equation originally developed for soil water retention curve, but modified by Baumgartl and Köck (2004) for the mechanical analysis. Additionally, the compressibility coefficient was calculated using two points of the virgin compression line, using the relation $\Delta e/\Delta \log \sigma'$, where e is the void ratio and σ' is the effective stress.

2.3. Penetration resistance

Cone index was determined under in situ conditions 1 week after seeding and 3-5 days after a rainfall, when the soil water content was nearly at field capacity, using a digital handheld cone penetrometer $(30^{\circ} \text{ cone tip angle}, 10 \text{ mm diameter})$. Measurements were taken in increments of 1.5 cm, from the soil surface down to 60 cm depth, with a penetration velocity of about 1 m min^{-1} . This determination was performed in all nutrient sources treatments at three positions in each plot, namely seeding row (SR), untrafficked interrow (UI), and recently trafficked interrow (TI). The recent traffic corresponded to two passes of the tractor of about 2.9 Mg during the seeding procedure. Due to soil surface irregularity in the field, statistical analysis of penetration resistance was performed using moving average values considering three depths increments, plotted in the middle point of the corresponding layer.

2.4. Statistical analysis

Statistical analysis was performed using the Statistical Analysis System (SAS, 1989), and includes ANOVA test for physical and mechanical analysis for variances among soil tillage, nutrient sources, and depth. Means differences were compared using the Tukey test (P < 0.05).

3. Results and discussion

There were statistical differences among the three tillage systems and between the two depths for all physical and mechanical parameters analyzed (Table 2). Precompression stress was the only one which showed statistical differences between nutrient sources, without interaction between tillage and depth. The time interval of 30 and 120 min between loads did not affect significantly mechanical parameters determined in the compressibility test. No-till system, as opposite to tillage treatments which broke and mobilized the soil, showed higher bulk density and lower total porosity and air filled porosity, based on higher water saturation at -6 kPa suction (Table 3). The latter are related to the fact that in this system the soil had not been tilled for 10 years, and the natural settlement and soil compaction due to the machinery traffic took place. This higher compaction degree resulted in higher soil resistance, as shown by the lower compressibility coefficient and higher precompression stress (Tables 3 and 4), which is an estimation of the highest load previously supported by the soil.

Except for precompression stress, there was a significant interaction between tillage and depth (Table 2) and greater differences in soil physical parameters were observed for the upper layer (Table 3). No-till showed the greatest bulk density at sampling

Table 2

Analysis of variance (ANOVA) for soil physical and mechanical parameters determined in three replications of undisturbed samples collected in three soil tillage systems, two nutrient sources and two depths, and equilibrated at -6 kPa suction

Sources of variation	BD	TP	S6	$\sigma_{ m p}$	Cc	R (%)
Soil tillage (ST)	**	36.36	**	**	水水	**
Nutrient source (NS)	ns	ns	ns	**	ns	ns
$ST \times NS$	ns **	ns **	ns **	ns **	ns **	ns **
$ST \times depth$	**	**	**	ns	36.34	*
Load time				ns	ns	ns

BD: bulk density; TP: total porosity; S6: saturation degree at -6 kPa suction; σ_n : precompression stress; C_c : compressibility coefficient; R: percent of rebound related to original settlement. ns: not significant.

P < 0.05.

** P < 0.01.

108

Table 3

Depth (cm)	Soil tillage	BD (g cm ^{-3})	TP ($cm^3 cm^{-3}$)	S6 $(cm^3 cm^{-3})$	$C_{ m c}$	R (%)
5	No-till	1.19a	0.52b	0.85a	-0.27a	33.3a
	Chisel plow	1.02b	0.59a	0.66b	-0.50b	19.4b
	Conventional tillage	1.03b	0.59a	0.67b	-0.47b	18.6b
15	No-till	1.23a	0.51a	0.86a	-0.24a	34.4a
	Chisel plow	1.17ab	0.54a	0.83a	-0.31ab	27.3b
	Conventional tillage	1.16b	0.54a	0.83a	-0.32b	26.7b

Statistical analysis of soil physical and mechanical parameters in undisturbed samples collected in two depths of three soil management systems

BD: bulk density; TP: total porosity; S6: saturation degree at -6 kPa suction; C_c : compressibility coefficient; R: percent of rebound related to final settlement. Means followed by the same letter in a given column for each depth are not statistically different (Tukey, P < 0.05).

time and, consequently, lower total porosity and air filled porosity, as shown by the higher saturation degree at -6 kPa. The same trend was observed at 15 cm depth, but statistical difference was observed only for bulk density. These results are in agreement with those obtained in other studies (Fernandes et al., 1983; Derpsch et al., 1991; Hubbard et al., 1994) and are due to the fact that in the no-till system only part of soil surface is disturbed at seeding row, while the interrow area remains identical to the former period. When the soil is plowed, however, the soil volume at first has a smaller bulk density until it will be restressed by the application of a higher load than the former soil strength state. In this study, the time interval between tillage and soil sampling was not long enough to promote natural soil settlement due to wetting and drving cycles that could eliminate this effect, since the differences in bulk density were statistically significant between no-till and tilled treatments in both depths at sampling time.

Soil mechanical parameters were directly related to bulk density or compaction state. The higher the bulk density, the higher the precompression stress (r = 0.54, P < 0.001) and the percent rebound (r = 0.86,

Table 4

Precompression stress of undisturbed samples collected in two depths of the three soil tillage systems and two nutrient sources, equilibrated at -6 kPa suction

Treatment	Precompression stress (kPa)		
	5 cm	15 cm	Average
Soil tillage			
No-till	76	105	90a
Chisel plow	54	78	66b
Conventional tillage	55	88	71b
Nutrient source			
Mineral fertilizer	68	98	83a
Poultry litter	55	82	68b
Average	61b	90a	

Means followed by the same letter in a given column or row are not statistically different (Tukey, P < 0.05).

P < 0.001), and the lower is the compressibility coefficient (r = -0.95, P < 0.001). After 10 years of different treatments and 6 months after the last tillage, notill showed greater soil strength at both depths compared with the tilled sites. This behavior can be explained by the smaller proportion of soil mobilization in the no-till plot, which results in natural soil strength increase and soil compaction due to the previous machinery traffic. The greater precompression stress observed in the no-till system caused greater soil strength and smaller additional plastic deformation, as can be confirmed by the higher percent rebound and lower compressibility coefficient observed in this treatment. It means that not only the precompression stress value changed, but also the slope of the virgin compression line, changing the pattern of the whole stress-strain relationship curve (Fig. 1). The latter implies that when compaction occurs, the soil reaches to a new state of compaction susceptibility, which can increase even more if higher compaction states are achieved in separated and following events, increasing soil strength. If this compaction occurs in surface layer, it can avoid stress transmission and soil compaction in deeper soil layers. However, this resistance needs to be lower than the limit to root elongation and to allow proper pore size distribution for water and air flux through this layer. On the other hand, this higher soil strength should not be used as a justification to increase the mass of the machines used in agricultural operations, which, in turn, would cause additional compaction state even in deeper layers.

Less differences were observed among soil tillage treatments when the compressibility test was performed with remolded samples (Table 5), suggesting that remolding eliminates mostly the effect of direct strength increase due to soil age hardening and soil aggregation, which, in turn, implies an increased σ_p of about four times. The latter is an important fact as it is well known that soil physical degradation clearly reduces aggregation and soil mobilization reduces both soil hardening and aggregation.



Fig. 1. Void ratio (*e*) and pore water pressure (pwp) changes as a result of applied sequential (multi-step) stresses in undisturbed samples collected at two depths of three soil management systems (NT: no-till; CP: chisel plow; CT: conventional tillage), and equilibrated at -6 kPa suction (averaged across time intervals).

The application of poultry litter compared to mineral fertilizer resulted in lower precompression stress values. This behavior can be explained by the effect of organic matter on some physical properties, as the application of about 3 Mg annually of additional dry-organic material must result in reduced bulk density values. These results, combined with the fact that there were no significant differences in physical properties due to nutrient sources, emphasize the likelihood of direct effect of organic matter in reducing soil ability to support loads. No differences in precompression stress were observed between poultry litter and mineral fertilizers in remolded samples, suggesting that the effect is greater in macroaggregates (undisturbed samples) than in microaggregates (remolded samples). Furthermore, we have to point out that the interaction between Fe content and organic matter applied is not solved with respect to the expected strength increase for those Oxisols.

Table 5

Precompression stress of remolded samples, originally collected in three soil tillage systems (average of two nutrient sources), and equilibrated at -6 and -30 kPa suction

	Precompre	a)	
	-6 kPa	-30 kPa	Average
Soil tillage			
No-till	19	52	35a
Chisel plow	17	43	30a
Conventional tillage	17	48	32a
Average	18b	48a	

Means followed by the same letter in a given column or row are not statistically different (Tukey, P < 0.05).

Soil tillage systems showed different behavior in terms of settlement and pore water pressure changes during the compressibility test (Fig. 1). At 5 cm depth, the conventional tillage and the chisel plow system presented much higher void ratio values at the small applied stresses on the elastic deformation curve, due to the smaller bulk density, but the void ratio values reduced drastically after the precompression stress was exceeded (i.e. in the virgin compression load range). Differences between the soil tillage systems were smaller at 15 cm depth, but showed the same trend.

Pore water pressure started almost at the same value (near -6 kPa, as equilibrated on sand boxes) for all tillage systems and sampling depths, but showed different behavior during the test. In no-till system, pore water pressure became only a little more negative at lower loads and increased if stresses greater than 30 kPa were applied. This behavior is an expression for the higher soil strength (=rigidity) of the pore system, or lower soil strain at this small stress applied. It is also supported by the nearly constant pore size distribution at the stress applied. In tilled treatments, the pore rigidity was less pronounced as the pore water pressure became much more negative at 5 cm depth (i.e. the coarser and air-filled pores were compressed and became partly water resaturated), and increased only after 100 kPa normal stress. At 15 cm depth there were only small differences in pore water pressure among the tillage treatments. These differences are related to the rearrangement of the pore size distribution due to the stresses applied, which is dependent on soil deformation and includes a reduction of macropores and an increase in mesopores. The reduction in pore water pressure was



Fig. 2. Pore water pressure (pwp) at the end of each sequential load applied in two time intervals (30 and 120 min) in a multi-step device, using undisturbed samples collected at two depths of three soil management systems (NT: no-till; CP: chisel plow; CT: conventional tillage) and equilibrated at -6 kPa suction.

more pronounced with increasing time of loading (Fig. 2), since greater time allowed more complete water redistribution inside the whole sample toward an internal water steady state. The readings by the tensiometer at the bottom of the stressed soil sample define only the average of changes in the pore water pressure value inside the whole soil sample, since the tensiometer was installed statically in the middle of the soil sample. We cannot define the maximum pore water pressure changes near the stress plate nor can we differentiate the height dependent changes in the hydraulic conductivity inside the soil sample at present.

A similar relationship between loading time and pore water pressure was obtained by Fazekas and Horn (2005) in remolded samples with a given initial bulk density of 1.4 g cm⁻³, and an initial pore water pressure of -6 kPa suction. They showed that the differences were the greater the longer the samples were stressed (from 10 up to 240 min). In the present study 30 min time interval between loads was not long enough to reach complete water redistribution inside the whole sample after soil deformation, since by loading for 120 min the curves changed significantly. The corresponding changes, as a function of loading time and stress applied, reveal pronounced differences among the various treatments, especially at 5 cm depth (Fig. 2), implying the important role of pore size distribution on pore water pressure during soil settlement process. These changes, however, did not result in statistically significant differences in soil mechanical parameters determined in the compressibility test (Table 2) when the time intervals of 30 and 120 min between loads were compared.

Cone penetrometer resistance profiles determined at three positions showed treatment dependent strength differences (Fig. 3). Penetration resistance in any position or depth was not greater than 2 MPa for the soil water content conditions at the time of penetration resistance determination. This value is defined as the upper limit for unrestricted root penetration (Taylor et al., 1966; Tavares et al., 2001). It means that, if light machinery is used to perform tillage and seeding operations, the formation of compacted layers with strength higher than the root penetration ability in this soil is not expected. In the notill system, there were statistically significant differences among positions only in the upper 10-12 cm layer, because the small chisel used in the planter to open the seeding furrow promoted soil mobilization and reduced the penetration resistance. Below 15 cm, all sampled positions showed almost the same resistance. Recent traffic promoted additional compaction in a thin, surface layer (<5 cm) in no-till system. Chisel plow showed greater penetration resistance values at the recently trafficked interrow down to deeper layers (40 cm), as a result of two passes of a light tractor (2.9 Mg). The conventional tillage (primary plus two secondary disking), on the other hand, resulted in greatest strength at about 20 cm depth (plow-pan layer).

The effect of the traffic on soil strength deeper down the soil profile, observed in the chisel plow treatment, can be explained both by the absence of surface layer with higher soil strength reducing stress propagation to deeper layers, and by the soil homogenisation due to chiseling, which results in a higher concentration factor as was determined in soils with smaller mechanical strength





Fig. 3. Cone penetrometer resistance profiles determined 1 week after seeding in three soil tillage systems (NT: no-till; CP: chisel plow; CT: conventional tillage) and three row positions (SR: seeding row; UI: untrafficked interrow; TI: recently trafficked interrow). Horizontal bars indicate least significant difference values (Tukey test); continuous bars indicate differences at P < 0.05.

(Horn, 1995). The concentration factor determines the three-dimensional stress distribution pattern below the stress point, and can also be used to quantify the stresses distribution along a vertical line under the tire. At a given pore water pressure, the greater the concentration factor, the narrower and deeper the distribution of stress isolines along the vertical line (Soehne, 1958).

Analyzing the soil tillage systems for each sampled position, the lower penetration resistance values were found under the seeding row and in the untrafficked interrow (Fig. 3). In the seeding row, the chisel plowed soil had lower penetration resistance values at a depth of 15–25 cm than the other systems. No-till showed higher cone penetrometer resistance down to 40 cm depth at untrafficked interrow. Since the volumetric water content was similar among tillage treatments in depths sampled at time of the penetration resistance determination (Fig. 4), higher soil strength can be related to differences in bulk density (Fig. 4) in the upper layers, but not near 30 cm depth, where bulk density was similar among



Fig. 4. Volumetric water content (*u*) and bulk density (bd) at three depths of three tillage systems (NT: no-till; CP: chisel plow; CT: conventional tillage), in samples collected in untrafficked interrow at time of the penetration resistance determination.

tillage treatments and cone penetrometer resistance was higher at untrafficked interrow in no-till treatment.

The high soil strength in the surface layer of the notill treatment can be related to the management (i.e. traffic) history of the last 10 years, while in deeper layers the greater values can be explained by residual effect of previous tillage system. At the recently trafficked interrow, there is a statistically significant difference only at approximately 10 cm depth, showing that irrespective of the present soil strength after plowing, the present stress application always results in an additional soil deformation when the stresses applied exceed the internal soil strength, defined as precompression stress.

The results confirm the necessity of avoiding traffic after plowing the soil in order to avoid the reformation of the former strength condition. On the other hand, a superficial compacted layer created by cumulative traffic of light machinery in no-till system can be easily realleviated at seeding row if the planter has an appropriate tool to cut the soil even below this layer, as can be seen in penetration resistance profiles at this position.

4. Conclusions

No-till system showed higher soil resistance to deformation, as determined by the compressibility parameters at both depths (5 and 15 cm). The precompression stress, compressibility coefficient, and penetration resistance were related to bulk density and soil porosity. The variations in pore water pressure during soil stress–strain tests were closely associated to variation in total porosity and to length in time of load application. The addition of extra organic matter (poultry litter) resulted in reduced precompression stress values and higher compressibility coefficient and elasticity (rebound) in undisturbed samples, implying higher susceptibility to compaction. The penetration resistance profile was a good indicator of spatial variation in soil strength, both horizontally (seeding row, untrafficked interrow, and recently trafficked interrow) and vertically (different soil depths).

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