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Mechanical parameters of a constructed soil under different machinery traffic intensities in South of Brazil

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ABSTRACT: Intense machinery traffic tends to degrade the soil physical quality. With the purpose of finding critical values of physical parameters and viable alternatives to minimize soil degradation, this study aimed to evaluate the effects of different traffic intensities on physical parameters of a constructed soil in Candiota, Rio Grande do Sul state, Brazil. Bulk density (Bd), porosity, saturated soil hydraulic conductivity, penetration resistance (PR) and soil compression parameters were evaluated. Different traffic events (TE) were simulated during the soil construction process of an opencast coal mining area with a crawler tractor: zero (TE0), one (TE1), three (TE3), five (TE5) and eight (TE8) passes of the tractor. Immediately after the topographic recomposition and on the traffic track of the crawler tractor, disturbed and undisturbed soil samples were collected from the 0.00 to 0.10 and 0.10 to 0.20 m layers. Hydraulic conductivity, penetration resistance and soil compressibility parameters were sensitive to detect alterations in the constructed soil under different traffic events. PR values were higher than those considered as the critical limit (2000 kPa) in all layers and traffic intensities. Minimizing the traffic machinery intensities can be an effective alternative to mitigate compaction of constructed soils. More studies are necessary to obtain viable alternatives for adequate crop development in these areas.

Key words: bulk density; degree of compactness; penetration resistance; soil compressibility; soil porosity

Parâmetros mecânicos de um solo construído sob intensidades de tráfego no Sul do Brasil

RESUMO: O intenso tráfego de máquinas tem alterado a qualidade física do solo. Com o propósito de encontrar limites críticos de parâmetros físicos e alternativas viáveis para minimizar a degradação do solo, objetivou-se avaliar o efeito de diferentes eventos de tráfego em parâmetros físicos de um solo construído em Candiota, RS. Foi avaliada a densidade (Ds), a porosidade, a condutividade hidráulica de solo saturado (Ks), a resistência à penetração (RP) e parâmetros compressivos do solo. Diferentes eventos de tráfego foram simulados durante o processo de reconstrução de um solo construído em área de mineração com trator de esteira: zero (ET0), um (ET1), três (ET3), cinco (ET5) e oito (ET8) passadas de trator. Imediatamente após a recomposição topográfica e após o trafego de trator de esteira (linha) foram coletadas amostras com estrutura alterada e inalterada nas camadas de 0,00 a 0,10 m e 0,10 a 0,20 m. A condutividade hidráulica de solo saturado, a resistência á penetração e os parâmetros compressivos foram sensíveis para detectar alterações em solos construídos submetidos a diferentes intensidades de trafego. Em todas as intensidades de tráfego, a RP foi mais alta daquela considerada critica (2000 kPa) ao adequado crescimento de culturas. A minimização da intensidade do tráfego de máquinas pode ser efetiva alternativa para mitigar a compactação de solos construídos. Estudos adicionais são necessários para obtenção de viáveis alternativas que forneçam condições adequadas para o desenvolvimento de culturas nestas áreas.

Palavras-chave: densidade do solo; grau de compactação; resistência a penetração; compressibilidade do solo; porosidade do solo

Introduction

The soil construction process in opencast coal mining areas is mainly characterized by the traffic of heavy machinery with formation of soil aggregates by compression (Stumpf et al.; 2016, Wang et al., 2016), which hinders the development of plant species (Stumpf et al., 2014b). Excessive traffic is the main reason of soil compaction in coal mining areas (Pauletto et al., 2016), which is caused by mechanical forces, mainly when the applied load is higher than the load-bearing capacity.

Physical quality indicators have been used to evaluate the compaction of constructed soils. In opencast coal mining areas impacted by heavy machinery, Lima et al. (2012) showed changes in bulk density and porosity, corroborating results by Reis et al. (2014), Miola et al. (2015) and Stumpf et al. (2016). Stumpf et al. (2014a, b) also observed effects of heavy machinery in aggregation and degree of compactness.

Similarly, changes in bulk density, soil porosity, saturated soil hydraulic conductivity, soil organic carbon and penetration resistance due to machinery traffic in agricultural areas were verified (Reichert et al., 2016; Pires et al., 2017). In these areas, values at a magnitude potentially able to restrict plant root growth were usually found by performing penetration resistance evaluation (Keller et al., 2015; Mishra et al., 2015).

The compressive behavior of soils is essential to predict alterations that might occur in the soil structure when submitted to stress caused by agricultural implements. The preconsolidation pressured has been widely accepted and explored as an indicator of the history of stress to which the soil was submitted in the past and of its load support capacity while the compression index is used as an indicator of soil susceptibility to compaction (Keller et al., 2011; Somavilla et al., 2017). Preconsolidation pressure and penetration resistance are effective alternatives to evaluate and identify soil compaction (Neiva Junior et al., 2015). Additionally, the degree of compactness expresses the soil compaction related with a reference value (Reichert et al., 2009).

Considering the possibility of indicating adequate management for crop development in constructed soils after mining, this study aimed to evaluate the effects of different machinery traffic intensities on mechanical parameters (soil strength and compressibility) of a constructed soil in a coal mining area from southern Brazil.

Material and Methods

The study was carried out in an opencast coal mining area located in the municipality of Candiota, Rio Grande do Sul state (31,55° S and 53,67° W), Brazil. The climate is of Cfa climatic type according to Köppen's classification, considered humid subtropical.

The soil studied in 2011 had recently been constructed during the topographic recomposition of the mined area. This process involved the placement of overburden spoils to fill the excavation produced by the previous strip, which were leveled by bulldozers for topographic recomposition. Next, the B horizon removed from the natural soil was deposited on these overburden spoils, as topsoil, thus creating a constructed soil. Before excavation, the soil was classified as Alfisol (USDA, 2010).

The mean contents of clay, sand, silt (clayed textural class), dispersed clay in water, soil particle density (Gee & Bauder, 1986) and the total organic carbon (TOC) are given in Table 1. TOC was quantified using dry combustion with a Perkin Elmer elemental analyzer.

In the study area, a crawler tractor and trucks had already been utilized to homogenize and distribute the topsoil deposited on the overburden spoils for soil construction.

After the soil construction, different traffic events were simulated using a crawler tractor D8T (Caterpillar®). The traffic events tested were zero (TE0), one (TE1), three (TE3), five (TE5) and eight (TE8) passes of the tractor, totaling five treatments.

The crawler tractor utilized had the following characteristics: total weight 38 Mg, power 259 kW, track length 3.20 m, track width 0.56 m, track-soil contact area 3.6 m² and soil pressure applied 103.5 kPa.

Before (TE0) and after (TE1, TE3, TE3 and TE8) traffic events and in the traffic track of the tractor, disturbed soil samples (five treatments x four blocks x two layers x one replicate = 40 samples) and undisturbed samples (five treatments x four blocks x two layers x three replicates = 120 samples) were collected from the 0.00 to 0.10 and 0.10 to 0.20 m layers. These soil samples were collected with steel cylinders of 0.05 m diameter and 0.03 m height to evaluate macroporosity (Ma), microporosity (Mi), total porosity (TP), bulk density (Bd), saturated soil hydraulic conductivity (Ks) and soil compressive parameters (preconsolidation pressure, compression index and degree of compactness).

All undisturbed soil samples were saturated by capillarity for 24 h and then equilibrated at a tension of 6 kPa to evaluated Ma and Mi using a tension table. Subsequently, the same soil samples were equilibrated at a tension of 10 kPa using pressure plates (Klute, 1986). After reaching equilibrium, each sample was weighed and subjected to uniaxial compression test in an automatic consolidometer, Model CNTA-IHM/BR, in which successive and static

Table 1. Mean contents of clay, sand, silt, dispersed clay in water (DCW), total organic carbon (TOC) and soil particle density (Pd) in the 0.00 to 0.10 m and 0.10 to 0.20 m layers of a constructed soil under different traffic events in a coal mining area in Candiota, RS, Brazil.

Variables	0.00 to 0.10 m	0.10 to 0.20 m
Clay (g kg^{-1})	450.0	487.2
Sand (g kg^{-1})	341.0	254.0
Silt (g kg^{-1})	209.0	258.8
DCW (g kg^{-1})	89.0	68.0
TOC (g kg^{-1})	9.1	8.9
Pd (Mg m^{-3})	2.70	2.61

pressures of 25, 50, 100, 200, 400, 800 and 1600 kPa were applied. The displacement at each applied pressure was recorded (Krümmelbein et al., 2008; Silva et al., 2015). Then, the soil samples were oven dried at 105 ºC for 24 h for TP and Bd calculation (Blake & Hartge, 1986).

Soil compression curves were obtained by relating the applied pressure (x-axis, log_{10}) *versus* Bd (y-axis), obtaining the compression index (CI) and the preconsolidation pressure (σp) (Dias Junior & Pierce, 1995). To exclude the effect of initial soil compaction, parameters were normalized by dividing the Bd after each applied load by the initial bulk density.

The soil degree of compactness was calculated according to Reichert et al. (2009) using the bulk density at 200 (DC_{200}) and 1600 kPa (DC_{1600}) load as reference. The Ks was measured with a constant head permeameter (Klute, 1965). The soil penetration resistance (PR) was determined at field after topographic recomposition in the traffic track using an electronic penetrometer (penetrolog Soil Track) with automatic data acquisition system. For each traffic event, the PR was measured in the 0.00 to 0.10 and 0.10 to 0.20 m layers (five treatments x four blocks x five replicates = 100 evaluations). At the time of soil sampling and PR evaluation, the gravimetric soil water content reached 140 g kg^{-1} (0.00 to 0.10 m) and 150 g kg^{-1} (0.10 to 0.20 m).

The mean values obtained for each variable evaluated were submitted to analysis of variance (Anova) and when presenting significant difference they were compared using the Duncan test ($p \leq 0.05$) with the statistic software R (R Core Team, 2014).

Results and Discussion

Figure 1 shows the uniaxial compression curves (y axis: bulk density; x axis: log P applied to the soil) under different traffic events, varying from 25 to 1600 kPa applied loads.

Traffic events presented significantly similar mean values as those of the soil bulk density (Bd) from 0 (TE0) to eight

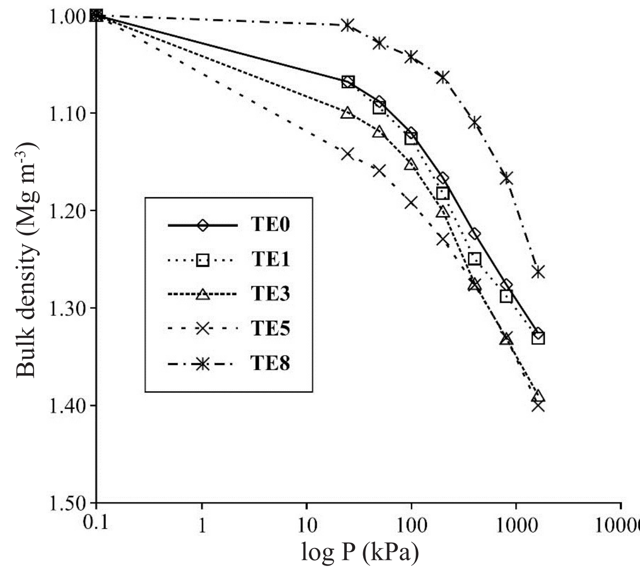

Figure 1. Normalized soil compression curves (bulk density, Bd, as a function of the applied load logarithm, log P), equilibrated at 10 kPa, of a constructed soil under (TE): zero (TE0), one (TE1), three (TE3), five (TE5) and eight (TE8) traffic events in the 0.00 to 0.10m layer, in a coal mining area in Candiota, RS, Brazil.

traffic events (TE8) (Figure 1 and Table 1), showing similar values of soil deformation and susceptibility to compaction and different values of preconsolidation pressure (Table 3) along the applied load (Figure 1).

The Bd values in the 0.10 to 0.20 m layer, increased from TE3 to TE8 (Table 2). According to Reichert et al. (2003), values of approximately 1.45 Mg m^{-3} for soils with 450 g kg^{-1} of clay hampered root development. Thus, in general considering values of Bd, restrictive conditions for root development were found after TE3 (Table 2) in the soil layers evaluated.

Although the compaction caused by machinery traffic is considered to reduce mainly Ma values, in this study, differences were not found in Ma, Mi and Tp (Table 2). The Ma

Table 2. Mean values of bulk density (Bd), macroporosity (Ma), microporosity (Mi), total porosity (TP), saturated soil hydraulic conductivity (Ks) and penetration resistance (PR) in the 0.00 to 0.10 m and 0.10 to 0.20 m layers of a constructed soil under different traffic events in a coal mining area in Candiota, RS, Brazil.

Traffic events[1]	Bd ($Mg\ m^{-3}$)	Ma	Mi	TP	Ks ($mm\ h^{-1}$)	PR (kPa)
			%			
			0.00 to 0.10 m			
TE0	1.32 a	14.40 a	32.31 a	46.71 a	46.30 a	2820 c
TE1	1.40 a	10.46 a	34.05 a	44.51 a	46.03 a	4560 b
TE3	1.47 a	9.77 a	34.06 a	43.83 a	42.07 a	6000 a
TE5	1.50 a	9.60 a	34.18 a	43.77 a	37.67 b	6370 a
TE8	1.46 a	9.48 a	34.24 a	43.72 a	36.79 b	5690 a
			0.10 to 0.20 m			
TE0	1.29 b	14.29 a	32.23 a	46.02 a	97.48 a	5320 b
TE1	1.36 ab	11.16 a	34.31 a	45.47 a	94.38 a	9560 a
TE3	1.46 a	9.18 a	34.39 a	43.57 a	93.05 a	1094 c
TE5	1.47 a	8.74 a	34.44 a	43.18 a	52.73 b	1132 c
TE8	1.48 a	8.57 a	34.61 a	43.17 a	36.74 c	9000 a

Numbers followed by the same letters in the column are not different by Duncan test ($p \leq 0.05$).
[1]TE0: zero, TE1: one, TE3: three, TE5: five and TE8: eight traffic events.

value is restrictive to plant development when it is lower than 0.10 m^3 m^{-3} (Reichert et al., 2009) because the oxygen supply is inadequate. Therefore, limitations associated to soil aeration can be expected from TE3 in the soil layers evaluated. Shäffer et al. (2007) found that two passes of a combine harvester with total weight of 9.8 Mg along the same tracks caused only weak compaction effects, mainly reducing porosity. In contrast, after 10 passes, deep ruts were formed, and porosity was drastically reduced down to the subsoil of a restored soil after the period of restricted cultivation.

According to Soracco et al. (2015), pressures produced by higher number of traffic events, decrease Ks. The Ks was 50% greater in the 0.00 to 0.10 m layer. This fact occurs due to the higher compressive effect of the machinery traffic during the soil construction mainly in the topsoil. For both 0.00 to 0.10 and 0.10 to 0.20 m layers, the Ks was greater in TE0, TE1 and TE3. However, from TE5, the Ks decreased in the 0.10 to 0.20 m soil layer due to the higher transmission of total load of the machinery utilized which caused compaction in deeper layers. According to O'Neal (1952) and Klute (1965), in general, Ks can be classified as moderate (20 to 62.5 mm h^{-1}) in the superficial layer (0.00 to 0.10 m). In the 0.10 to 0.20 m layer, except for TE5 and TE8 (Ks moderate), the Ks was classified as moderately fast (62.5 to 125 mm h^{-1}). Therefore, Ks was more sensitive to different intensities of machine traffic unlike the other soil parameters evaluated (Bd, Ma and Tp).

The gravimetric soil water content (at field) was considered homogeneous in all traffic events and soil layers, including TE0. PR was higher than the critical value for root development (2 MPa) reported by Lima et al. (2012) and Lima et al. (2016), using values established by Taylor et al. (1966) for agricultural soils. However, according to Dexter & Watts (2000), soil compaction is more prejudicial when the agricultural soil is dry because in higher water content values, roots can grow under PR values greater than 4.0 MPa. However, there is no critical PR value for crop development in mined soils considering different water content values.

According to Soracco et al. (2015), traffic led to persistent changes in all the dynamic indicators (saturated hydraulic conductivity and penetration resistance) The static indicators (Bd, Ma and Tp) did not vary significantly when the traffic events were compared. Results showed that dynamic indicators are more sensitive to the effects of compaction and that, in the future static indicators should not be used as compaction indicators without being complemented by dynamic indicators. Thus, variables as Ks and PR may detect changes that would remain undetected if using Bd, TP and Ma mainly when the machinery passes do not exert high energy of compaction.

The constructed soil preconsolidation pressure was dependent on the initial structural condition of the soil. Soane et al. (1981) reported that σp values lower than 100 kPa in agricultural soils are indicated for an effective control of soil compaction. Agricultural machinery can exert pressures ranging from 70 to 350 kPa, while transport vehicles might exert pressures of up to 600 kPa (Soane, 1986; Kanali et al., 1997). Considering these pressure values applied by vehicles, the variation in preconsolidation pressure suggests that the soil studied has been subject to excessively loads (177 a 390 kPa) and values greater than 100 kPa (Table 3).

Lima et al. (2012) pointed out that cover crops decreased the preconsolidation pressure of constructed soils after coal mining in Southern Brazil. Greatest soil reclamation was obtained with the *H. altissima* cover crop, where the lowest degree of soil compactness and soil load capacity were observed. After 6 years of cover crop establishment on constructed soils, *H. altissima* offered a promising solution for soil rehabilitation after coal mining.

Since small changes in soil physical properties might happen when the applied load is lower than the preconsolidation pressure, great care should be taken in terms of selecting tillage timing and the correct vehicles and agricultural machinery to prevent excessive compaction (Imhoff et al. 2004).

Analysing initial Bd (Table 2) and Bdσp (Table 3) values, in general, the constructed soil evaluated did not present

Table 3. Mean values of preconsolidation pressure (σp), compression index (CI), bulk density at preconsolidation pressure (Bdσp), degree of compactness at 200 kPa (DC200) and at 1600 kPa (DC_{1600}) pressures in the 0.00 to 0.10 m and 0.10 to 0.20 m layers of a constructed soil under different traffic events in a coal mining area in Candiota, RS, Brazil.

Traffic events[1]	σp (kPa)	CI	Bdσp ($Mg\ m^{-3}$)	DC_{200}	DC_{1600}
			0.00 to 0.10 m		
TE0	177 b	0.27 a	1.37 c	87 a	72 a
TE1	231 ab	0.27 a	1.40 bc	87 a	71 a
TE3	214 ab	0.27 a	1.53 ab	87 a	73 a
TE5	298 a	0.27 a	1.59 a	90 a	80 a
TE8	322 a	0.27 a	1.51 ab	96 a	84 a
			0.10 to 0.20 m		
TE0	284 a	0.37 a	1.44 bc	90 b	73 b
TE1	320 a	0.31 ab	1.33 c	88 b	76 b
TE3	342 a	0.31 ab	1.53 ab	93 ab	78 b
TE5	308 a	0.29 ab	1.56 a	95 ab	83 ab
TE8	390 a	0.24 b	1.56 a	99 a	91 a

Numbers followed by the same letters in the column are not different by Duncan test (p ≤ 0.05).
[1]TE0: zero, TE1: one, TE3: three, TE5: five and TE8: eight traffic events.

problems related to load-bearing capacity in different traffic events, i.e. in all conditions Bd<. Bdσp. The Bdσp value represents the highest pressure that should be exerted on the ground without causing additional compaction or irreversible soil degradation. Furthermore, in the 0.10 to 0.20 m layer, the CI presented differences between TE0 (0.37) and TE8 (0.24), indicating TE8 reduced soil susceptibility to compaction because the soil was already compacted up to certain levels by the accumulation of pressures applied during machinery traffic.

The traffic events did not influence DC_{200} and DC_{1600} values in the 0.00 to 0.10 m layer while in 0.10 to 0.20 m layer higher DC_{200} and DC_{1600} values were observed when the traffic events were increased (Table 3). Soil compressive parameters, exceeding load-bearing capacity or preconsolidation pressure, showed significant changes mainly in the 0.10 to 0.20 m layer. The values of degree compactness (DC_{200} and DC_{1600}) were similar to those obtained by Lima et al. (2012) in constructed soil.

The uniaxial load was promising to determine reference bulk density for mined soils, with values of degree of compactness always below 100%. The pedotransfer functions may be established to estimate the former based on the latter. The reference bulk density (200 and 1600 kPa) values may be considered just as bulk density values seldom exceeded in the field soils, but they make it possible to establish critical degree of compactness (DC) values.

Soil management systems that generate a low degree of soil compactness can be more efficient for soil recovery, but, on the other hand, can render soils more susceptible to compaction. The advantage of using DC is that different soils may be compared, while the use of critical bulk density may result in an inaccurate comparison between soils. Advances in establishing critical values of degree of compactness for crop growth and yield have been made. The degree of compactness is an efficient parameter to identify soil compaction affecting crops, but there are still unanswered questions, mainly related to reference bulk density such as the effects of clay mineralogy and organic matter content. The effect of compaction on ecological properties such as macroporosity and hydraulic conductivity must also be further intensely considered (Reichert et al., 2009).

Minimizing the traffic machinery intensity can possibly be an effective alternative to mitigate soil compaction Alternative agricultural systems such as controlled traffic and conditions of adequate soil water content may need to be adopted for a more sustainable management on a clay soil (Chan et al., 2005). More studies are necessary to obtain viable alternatives to provide correct conditions for plant development in constructed soils of coal mining areas.

Conclusions

Hydraulic conductivity, penetration resistance and soil compressibility parameters were sensitive to detect alterations in the constructed soil under different traffic events.

Minimizing the traffic machinery intensities can be an effective alternative to mitigate compaction of constructed soils.

Machine specifications, traffic intensity, number of passes and monitoring of water content in constructed soils (at field) provide important information when soil compaction is evaluated in coal mining areas.

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