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PHYSICAL-HYDRAULIC ATTRIBUTES AS INDICATORS OF FUNCTIONALITY OF SOIL PORES UNDER DIFFERENT COMPACTION LEVELS[1]

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ABSTRACT – Compaction modifies the structural arrangement and essential functions of soil pores. In this context, the objective of this study was to evaluate the impact of different compaction levels in an *Argissolo Amarelo* (Ultisol) on the physical-hydraulic attributes that indicate the functionality of soil pores. The experiment was conducted using 0.05 x 0.05 m soil cylinders with 4 compaction levels (CL): 61, 71, 82 and 92%, and at each CL, the pore-size distribution, intrinsic soil air permeability (K_{air}), pore continuity index N, soil water characteristic curve and cumulative pore-size frequency were quantified under a completely randomized design. The increase in CL did not impact the amount of micropores, but reduced the amount of macropores to values lower than the minimum required from the CL of 82%. The increase in CL caused reductions in N index, K_{air} and aeration porosity, but with different amplitude depending on the CL and the water tension in the soil. CL above 61% reduced the water content at the tension range between 0 and 6 kPa and, as a consequence, increased the percentage of aeration pores, besides promoting greater water retention within the range between 10 and 1500 kPa. The evaluation of the physical-hydraulic attributes of the *Argissolo Amarelo* (Ultisol) revealed that the increase in the compaction level altered soil structure, reduced and formed pores that were poorly continuous and less permeable to air flow and, despite the higher water retention at the higher tensions, promoted lower available moisture content.

Keywords: Soil structure. Pore function. Soil physical quality.

ATRIBUTOS FISICO-HIDRICOS COMO INDICADORES DA FUNCIONALIDADE DOS POROS DO SOLO SOB DIFERENTES NIVEIS DE COMPACTAÇÃO

RESUMO – A compactação modifica o arranjo estrutural e as funções essenciais dos poros do solo. O trabalho teve como objetivo avaliar o impacto de diferentes graus de compactação em um Argissolo Amarelo sobre os atributos físicos-hídricos indicadores da funcionalidade dos poros. Foram utilizados cilindros de solo 0.05 x 0.05 m em 4 graus de compactação (GC): 61, 71, 82 e 92%, e em cada GC, foi quantificado, sob um delineamento inteiramente aleatorizado, a distribuição de poros por tamanho, permeabilidade intrínseca do solo ao ar (K_{ar}), índice N de continuidade de poros, curva caraterística da água no solo e frequência acumulada de poros. O incremento no GC não causou impacto na quantidade de microporos, mas diminuiu a quantidade de macroporos para valores menores que o mínimo requerido a partir do GC de 82%. O aumento no CG provocou redução no índice N, K_{ar} e porosidade de aeração, porém com amplitude diferente dependendo do GC e da tensão da água no solo. Os GC acima de 61% reduziram o conteúdo de água na faixa de tensão entre 0 até 6 kPa e, como consequência, aumentaram a porcentagem de poros de areação; enquanto na faixa entre 10 e 1500 kPa proporcionaram maior retenção de água. A avaliação dos atributos físicos-hídricos do Argissolo Amarelo revelou que o incremento na compactação alterou a estrutura do solo, reduziu e formou poros pouco contínuos, e menos permeável ao fluxo de ar; e apesar da maior retenção de água nas tensões mais elevadas, promoveu menor conteúdo de umidade disponível.

Palavras-chave: Estrutura do solo. Função dos poros. Qualidade física do solo.

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INTRODUCTION

The compaction process is one of the main responsible for changes in soil physical conditions and, consequently, a limiting factor for the establishment and development of crops (SHAH et al., 2017; KELLER et al. 2017; TIAN et al., 2019). Motivated by anthropic actions, compaction promotes the rearrangement of soil constituents, and as a result greater proximity between solid particles and increase in mass per unit of volume, reduction of total porosity and variation in pore size distribution (SIVARAJAN et al., 2018; LIMA et al., 2020; LIMA et al., 2022; HOLTHUSEN et al., 2018).

In the perception of soil physical quality, changes in soil structural arrangement can reduce pore functionality, thereby maintaining physical-hydraulic processes essential to plant growth, especially water and air fluxes (ANDOGNINI et al., 2020).

In order to know the main impacts of compaction on soil physical quality, many studies have considered the characterization of attributes that express the mass/volume ratio, such as density and porosity. However, in the understanding of functionality, more than that, soil physical quality should be evaluated through attributes that indicate its efficiency in performing essential functions (MENTGES et al., 2016; MENEZES et al., 2018).

In this aspect, the use of attributes related to processes that vary in space and time, such as the pore-size distribution, intrinsic soil air permeability as a function of water content, pore continuity indices and the characteristic curves of water in the soil and pore space in the soil responsible for aeration with soil drying (RODRIGUES; SILVA; GIAROLA, 2011; DÖRNER et al., 2022).

In this context, this study was based on the following hypotheses: i) the physical interpretation of pore functions is dependent on the compaction level; and ii) the magnitude of compaction effects is greater on attributes related to the air conduction function of soil pores. Thus, the objective was to know the impact of different compaction levels on an *Argissolo Amarelo* (Ultisol) on the functionality of pores through the evaluation of geometric aspects and water retention.

MATERIAL AND METHODS

Soil collection and analyses

Soil samples were collected from an *ARGISSOLO AMARELO* (ULTISOL) located in the Hydraulics Sector at the Federal University of Ceará - Pici Campus, Fortaleza-CE, Brazil (Figure 1).

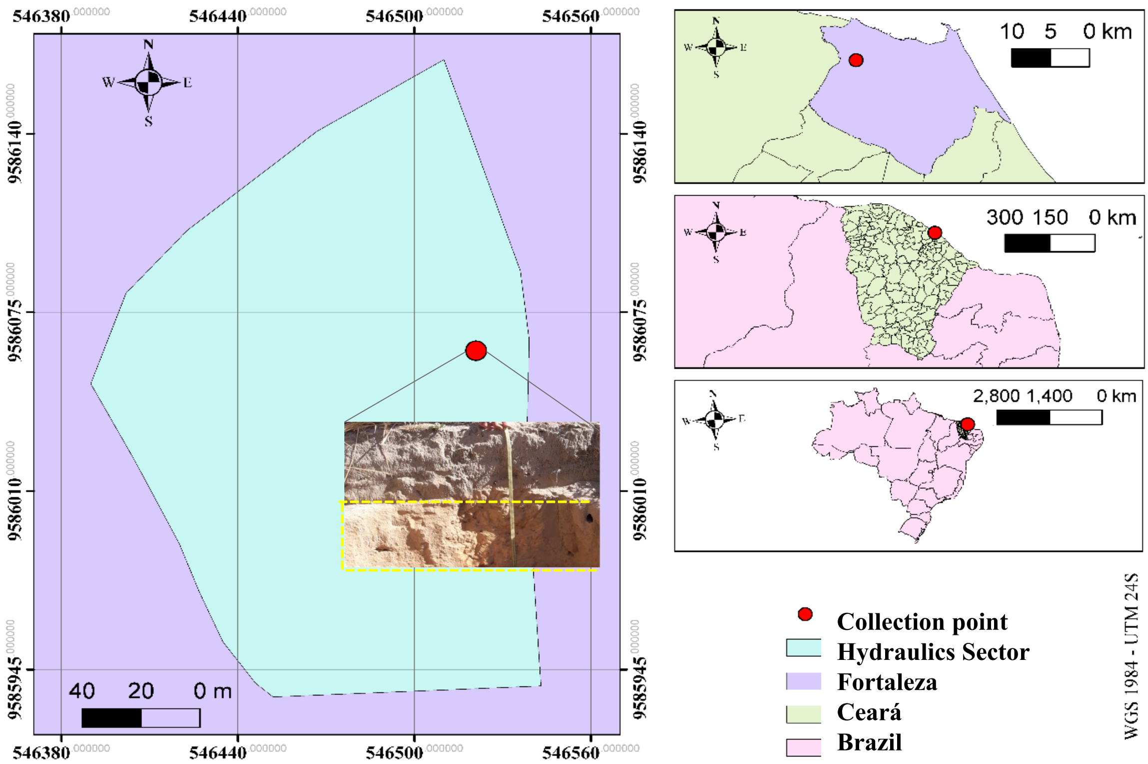

Figure 1. Location of the soil collection point.

Before the collection, morphological characterization of the soil was performed and, after verification, it was decided to collect samples in the 0.40-0.90 m layer, formed by medium-textured material, which made it possible to define a wider range of values for the soil compaction state. Subsequently, the samples were air dried, passed through a 2 mm mesh sieve to obtain the air-dried fine earth (ADFE) and used for characterization (Table 1) and for preparation of specimens.

For physical characterization (Table 1), particle size was determined based on the method described by Gee and Or (2002). Smaller particles such as silt and clay were separated by sedimentation, following Stokes' Law. The sand was separated by sieving and fractionated according to the particle-size classification of the United States Department of Agriculture (USDA, 1972). For chemical characterization of the soil (Table 1), the analyses were carried out according to the methodology described by EMBRAPA (2011).

Table 1. Physical and chemical characteristics of the soil used.

Grain distribution								Texture		
Sand fractionation										
VC	C	M	F	VF	Total	Silt	clay			
	-------------------------------- g kg^{-1} -----------------------------							sandy clay loam		
23	55	157	249	82	566	115	319			
Chemical characteristics										
---g dm^{-3}---		--------------- $cmol_c$ kg^{-1} ----------------						-------$cmol_c$ kg^{-1}----		
pH H_2O	Corg	Na^+	Ca^{2+}	Mg^{2+}	K^+	Al^{3+}	H^+	SB	CTC	V%
5.0	4.0	0.01	0.5	0.4	0.11	0.9	1.51	1.02	3.43	29.74

Sand: VC: very coarse =< 2.0-1.0 mm; C: coarse =< 1.0-0.5 mm; M: medium =< 0.5-0.25 mm; F: fine =< 0.25-0.105 mm; VF: very fine =< 0.105- 0.053.

The experimental units were composed of specimens made in 0.05 x 0.05 m metal cylinders filled with an amount of ADFE and moistened with masses of water previously calculated to reach 4 density levels (DL), namely: 1.2, 1.4, 1.6 and 1.8 Mg m^{-3}, corresponding to compaction levels (CL) of 61, 71, 82 and 92%, respectively. The CLs correspond to the values between the actual soil density and the maximum density of the compaction curve obtained by the Proctor test, as indicated in NBR 7182 (ABNT, 1986).

At the end of the test, density values were determined for gravimetric moisture values (u). A second-degree polynomial equation (DL= $-159.96u^2 + 39.474u - 0.4727$; R^2: 0.95) was fitted to the data and, from this, it was possible to calculate the mass of water necessary for moisture homogenization to ensure the preparation of the experimental units with each CL.

The preparation was carried out using a hydraulic press with working capacity of up to 15 tons. Compaction was applied using an iron piece with a diameter slightly smaller than that of the cylinder.

After preparation, the experimental units referring to each CL were slowly saturated by capillarity and, after saturation, were taken to the tension table to apply the tensions of 2, 4, 6, 10 kPa and, after that, to Richards' pressure plate apparatus to empty the pores at the tensions of 33, 100, 300, 700 and 1500 kPa (KLUTE, 1986).

With the data of moisture after equilibrium of the water content in the soil pores with the applied tensions, the soil water retention characteristic curves (SWRCC) were constructed for each CL. The model proposed by Van Genuchten (1980) (Equation 1) was applied to fit the curve, with estimation of only the parameters alpha, m and n. Table Curve 2D Trial Version, 5.1 was used for this procedure.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^n]^m} \quad (1)$$

where: q corresponds to the water content (cm^3 cm^{-3}); qr and qs are, respectively, residual volumetric moisture (equal to volumetric moisture at the permanent wilting point) and saturation volumetric moisture (total porosity, cm^3 cm^{-3}); ψ is the matric potential of soil water (kPa); a is a scaling factor of ψ (m^3); m and n are model fitting parameters related to the shape of the curve (MUALEM, 1976).

The volumetric water contents at saturation and in equilibrium with the tension of 6 kPa, a value related to the emptying of pores with diameter greater than 50 µm, were considered to obtain total porosity and microporosity, respectively.

Macroporosity was calculated by subtracting the value of microporosity from the total porosity (DONAGEMA et al., 2011).

From the relationship between the logarithm of the tensions applied with the quotient between volumetric moisture and total porosity, the cumulative pore-size frequency was obtained for each compaction level.

In the samples in equilibrium for moisture at tensions of 2, 4, 6, 10, 33 and 100 kPa, the values of pressure reduction over time were obtained according to the decreasing pressure method (KIRKHAM, 1946; SILVEIRA et al., 2011), for subsequent determination of the intrinsic soil air permeability (K_{air}) by calculating the permeability coefficient (Equation 2). Permear v.1.0 software, developed by Silveira et al. (2011), was used to record the decrease in pressure over time.

$$K_{air} = \frac{L\eta V}{AP_{atm}} \times |S| \qquad (2)$$

where: K_{air} is the air permeability coefficient (m²), V is the volume of air passing through the cylinder (m³), h is the dynamic viscosity of the air (Pa.s), L is the height of the volumetric ring (m), (A) cross-section area of the soil sample (m²), P_{atm} is local atmospheric pressure (Pa) and S is the angular coefficient of the linear regression of pressure (pressure ln) as a function of time.

The pore continuity index N was also determined, and for this, the relationship between the intrinsic soil air permeability and aeration porosity was established by the equation suggested by Kozeny-Carman, similar to that given by Ahuja et al. (1984), according to Equation 3.

$$K_{air} = M_{\varepsilon air^N} \qquad (3)$$

where: M and N are empirical constants. The exponent N, for Kozeny-Carman and Ahuja et al. (1984), is considered a pore continuity index. Equation 4 fitted to the logarithmic form (base 10 log) is equivalent to the form below.

$$logK_{air} = logM + NLog_{\varepsilon air} \qquad (4)$$

The values of M and N were obtained from the linear regression of the log ε_{air} versus log K_{air}. The intercept of the linear line with the abscissa on the graph that relates air permeability to the aeration porosity can be used as a measure of blocked porosity (εb) (Equation 5). It is considered as a quantity of pores that are blocked and do not contribute to the air flow, with K_{air} equal to 0.

$$\varepsilon_b = 10^{(-\log M)/N} \qquad (5)$$

where: N is the slope of the equation, M is intercept of the linear line with the abscissa on the graph that relates to log K_{air} in which log ε_{air}= 0; and the intercept with axis log ε_{air} where log K_{air} = 0 is the (ε_b).

Data analysis

The variables were analyzed in a completely randomized design with five replicates. For the intrinsic soil air permeability, a 4 × 6 × 5 factorial scheme (four compaction levels, six tensions and five replicates) was used. The data were subjected to the Shapiro-Wilk test to check the assumptions of normality, to the F test for analysis of variance, and to Tukey test for comparison of means, all at 5% probability level. The statistical program SISVAR was used for data analysis (FERREIRA, 2014).

RESULTS AND DISCUSSION

The increase in the compaction levels significantly reduced macroporosity, and the reduction was greater as the density approached its maximum, with the CL of 82% leading to less than 10% macropores. For microporosity, there was no change with the increase in CL (Table 2).

Table 2. Comparison of means for microporosity (Mi) and macroporosity (Ma) data obtained under different compaction levels.

Porosity (m³ m⁻³)	Compaction levels (%)			
	61	71	82	92
Ma	0.205 a	0.145 b	0.068 c	0.014 d
Mi	0.278 a	0.274 a	0.267 a	0.240 a

These results were due to the rearrangement caused by the compaction process, which forces the primary particles that compose the soil mass to settle in the space occupied by air, thereby increasing the soil mass per unit of volume and reducing total porosity, but with a greater impact on the amount of macropores than on micropores, agreeing with the results presented by Lima et al. (2020) and Lima et al. (2022).

Macropores are considered the pores

responsible for the free circulation of air in the soil, as water drainage is facilitated, and for promoting the maintenance of the minimum porosity of 10%, considered as limiting for normal respiration of roots and development of plants. Thus, it can be observed that the variations in CL can compromise the soil aeration state, a factor of direct influence on crop yield (KELLER et al., 2017).

It must be pointed out that, although the diameter of soil pores is not the only factor controlling the aeration process, the predominance of pores with small diameters can drastically reduce air renewal in the soil (BRAGA et al., 2015). Romero et al. (2014), in a study with soil physical quality indicators performed with samples of two *Latossolos* (Oxisols), observed a direct relationship in attributes such as macroporosity and microporosity with the increase of compaction.

The relationship between K_{air} and the tensions applied at all CLs defined the logarithmic regression model (Figure 2), with increments from the tension of 2 kPa, and more significantly for the range between 2 and 10 kPa. Considering that the increase in tension reduced water content in the whole portion of total porosity, consequently increasing the portion occupied by air, this justifies the higher K_{air}.

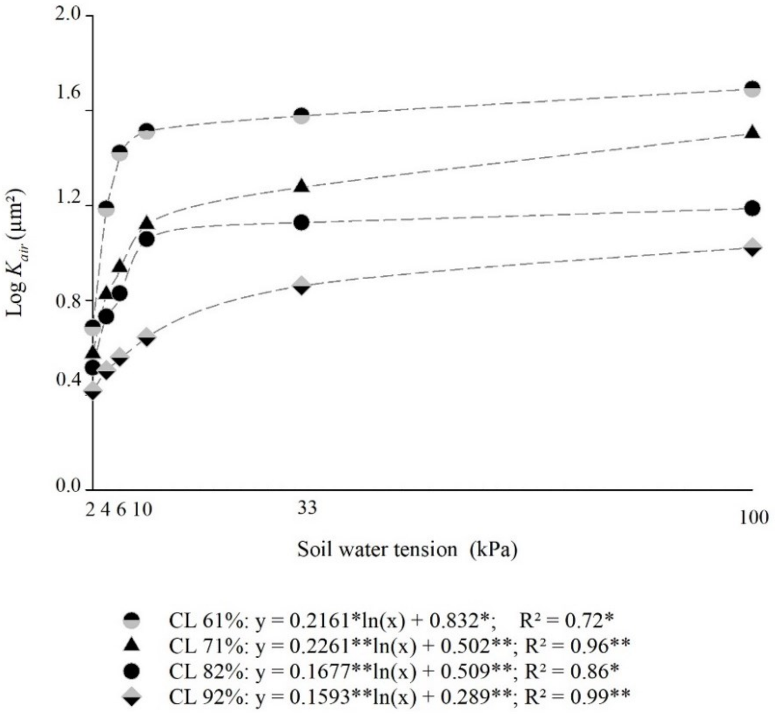

Figure 2. Relationship between intrinsic soil air permeability (K_{air}) and soil water tension in samples under different compaction levels. **and * significant at 1 and 5% probability levels, respectively.

In addition to the dependence on water exit, the movement of air in the soil also depends on factors related to soil structure, such as pore size (NEIRA et al., 2015). Pores of larger diameters were the first to be emptied at low tensions, which led to an increase in K_{air} for the range up to 10 kPa (Figure 2). Similar results were found by Menezes et al. (2018) in a study to evaluate pore functionality in horizons of soils of the Coastal Tablelands of the state of Ceará with and without natural compaction.

From Figure 3, it is possible to observe that the increases in CL, regardless of the applied tension, led to reduction in the value of K_{air} and a greater proximity between the means for CLs of 71% and 82%. As previously addressed, the rearrangement of individual particles caused a reduction in total porosity, especially in macropores (Table 2), increase in the value of density, and thereby the formation of a more cohesive structure (LIMA et al., 2020; LIMA et al., 2022), which affected other aspects of the pore space morphology, such as smaller area available to air flow (K_{air}). In the study conducted by Braga et al. (2015), compaction, represented by different values of soil density, also caused reduction in K_{air}.

Figure 3 shows that the highest compaction level (92%) at all tensions applied, despite not fully blocking the air flow, caused the lowest K_{air}. The mathematical determination of K_{air} considers the relationship between the amount of air that crosses a soil sample by convective flow as a function of time (RODRIGUES; SILVA; GIAROLA, 2011) and, as macropores are more efficient in this process, the volumetric reduction of these pores under CL of 92% (Table 2) led to the formation of paths of greater resistance to air flow, reducing the values of

K_{air}. Holthusen et al. (2018) also found that the air conduction function of soil pores was reduced due to the effects of compaction on soil porosity.

The positive linear relationships for the variation of K_{air} as a function of the aeration porosity (ε_{air}) obtained for all CLs at all tensions (Figure 4) confirm that, in fact, the reduction in soil water content with increasing tension increased the volume of pores occupied by air (Figure 2), as well as the area available for its conduction, as also highlighted by Rodrigues, Silva, and Giarola (2011).

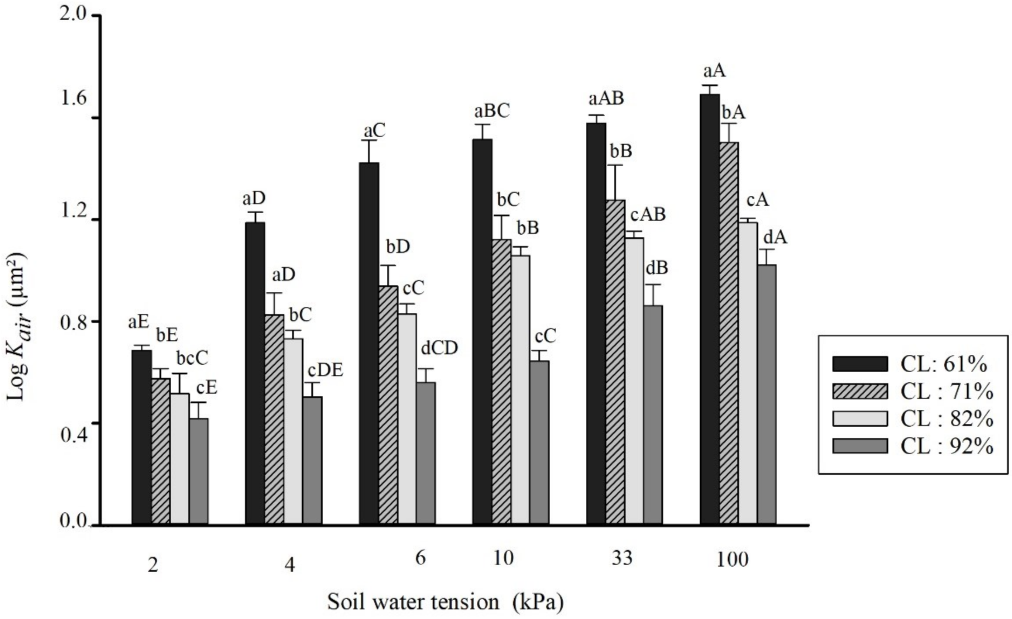

Figure 3. Means and standard deviations for the values of intrinsic soil air permeability in samples subjected to tensions of 2, 4, 6, 10, 33 and 100 kPa at four compaction levels. Means followed by the same lowercase letter in each group and the same uppercase letter between the groups do not differ by Tukey test at 5% significance level.

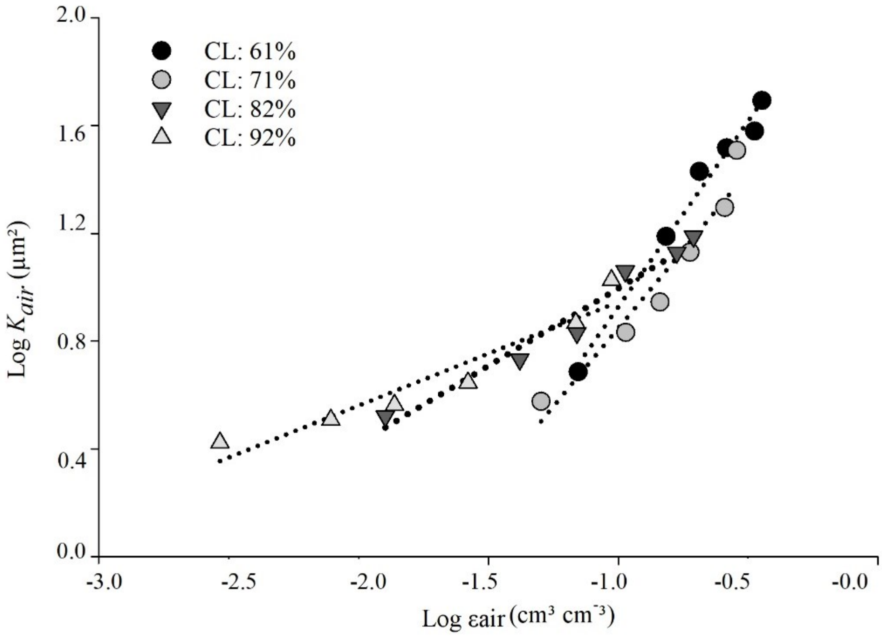

Figure 4. Linear relationship between Log K_{air} and Log ε_{air} in soil samples under different compaction levels.

There has been consensus on using the aeration porosity value of 10% (Log ε_{air} = -1.0 m³ m⁻³) suggested by Grable and Siemer (1968) as the minimum necessary to supply oxygen for normal respiration of plant roots. At this critical porosity, the compaction levels of 61 and 71% resulted in higher values of K_{air} compared to soil samples with CL of 82 and 92%. For these two, it was also observed that the minimum value of aeration porosity was only reached in moisture values corresponding to the tensions of 6 kPa (CL: 82%) and 10 kPa (CL: 92%).

From the management point of view, the results presented presuppose that, under higher moisture conditions (low tensions), soil pores under CL of 82 and 92% will have less contribution to the flow of gases, which presumably can be a limiting factor for the development of plants due to the low aeration of the root system. On the other hand, for conditions under which the soil is drier (high tensions), these CLs can hinder the growth of plant roots and their exploration due to the increased mechanical resistance of the soil to penetration, as reported by Grzesiak et al. (2014) and Chen, Weil, and Hill (2014).

Despite the potential limitations that higher CLs can cause to plants, from the physical point of view, the fact that they did not have Log K_{air} = 0 (Figure 4) reinforces that K_{air} is not dependent only on the attributes that define the amounts and proportions of physical masses, such as density and porosities, but also on those that define structural arrangement of pores, such as continuity, connectivity and tortuosity (FU et al., 2019; KUNCORO et al., 2014; RODRIGUES; SILVA; GIAROLA, 2011).

The parameters of the regression equation obtained through the relationship in Figure 4 are presented in Table 3. The pore continuity index N, which reflects the increase in K_{air} with the increase in ε_{air}, shows that the increase in CL made the pores less continuous, corroborating the lower K_{air}. This information shows that, even if the soil pores are filled by a reasonable amount of air, they may have their air conduction function restricted (DÖRNER et al., 2022). Mentges et al. (2016) stated, among other things, that the deformation caused by compaction in soil under no-tillage reduced air flow and attributed it to lower pore continuity.

Table 3. Parameters of the regression equation log K_{air} = log M + N log β and blocked porosity (εb) for 4 compaction levels.

CL (%)	Log M	N	R²	εb
	-----------µm²-----------			%
61	2.305	1.378	0.98	2.126
71	2.009	1.161	0.94	1.861
82	1.572	0.576	0.94	0.283
92	1.331	0.385	0.92	0.035

Pore continuity is the result of the structural configuration of the soil, which in turn differs depending on the particle-size distribution (MENTGES et al., 2016). Thus, the high percentages of sand in the medium and fine fractions may have intensified the effects of compaction and contributed to the lower pore continuity (Table 3). The fine fractions of sand promote a more compact arrangement of the soil (LUCIANO et al., 2012), leading to changes in geometric variables, for instance the formation of more tortuous and less continuous pores.

As for blocked porosity (εb) (Table 3), it is observed that the increase in CL led to the lowest values of εb. Although the interpretation of these results seem to suggest a possible contradiction, they should be understood in terms of pore volume, that is, as the CL increased there was a reduction in the total volume of pores and, consequently, a reduction in the volume of pores that could be blocked.

It is worth pointing out that the increase in CL led to more restrictive conditions to air flow in the soil, as indicated by the reduction of macroporosity, K_{air} and the presence of less continuous pores (Tables 2 and 3 and Figure 3). Therefore, the low amount of pores that were not connected and that do not contribute to air flow (Table 3) was proportionally more relevant for CLs at which the pore volume was lower (82 and 92%). This particularity results mainly in reduction in the diffusion of atmospheric air into the soil, which, among other things, may lead to deficit of O_2 in the root zone, affect normal root respiration and cause negative effects on plants (TIAN et al., 2019).

Regarding soil water retention curves, it is observed that the changes in density and its integrated effects led to different slopes (Figure 5). For the tension range resulting from the emptying of macropores (0 to 6 kPa), the highest CLs (82 and 92%) led to lower water retention, tending to converge to the range in which the micropores prevail. Andognini et al. (2020) found similar behavior when analyzing the effect of different compaction levels on soil physical properties.

The phenomena responsible for retention, capillarity, more relevant at low tensions, and adsorption, more relevant with soil drying, are totally dependent on the interaction between the soil matrix and the solution retained in it. Thus, the higher CLs, for having led to greater proximity of solid particles and reduction in macroporosity, resulted in a larger surface area for interaction with water, hence causing a predominance of retention over drainage at the lowest tensions (Figure 5).

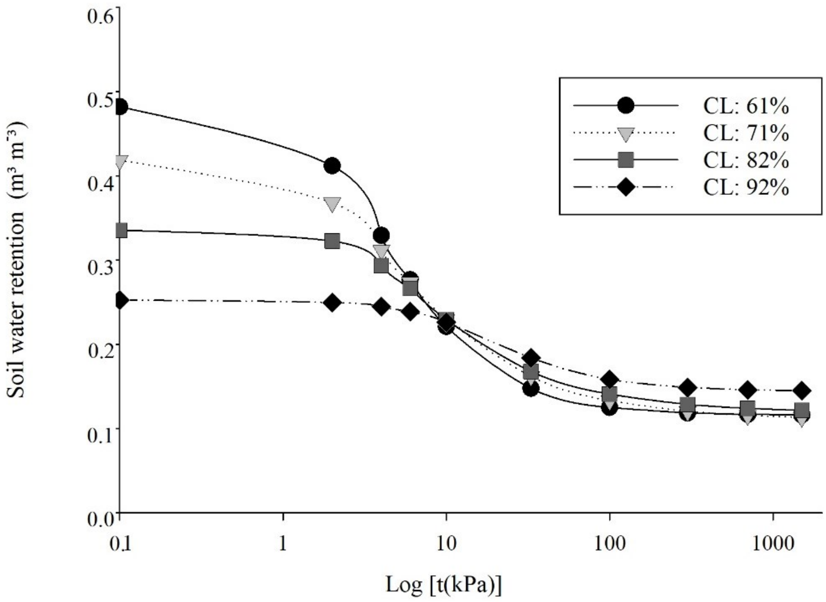

Figure 5. Soil water retention characteristic curves for 4 compaction levels.

However, despite this increase in moisture retention, it is possible to observe a reduction in the available water to be used by plants as the CL approaches its maximum (92%), only 0.01 m^3 m^{-3} of moisture, which can compromise essential processes to plant growth and reduce yield (SHAH et al., 2017).

These results may at first indicate lower limitations to soil aeration. However, as already addressed, the higher compaction levels, due to geometric changes in pores, can hinder aeration even when the soil is subjected to low tensions. Moreover, in the tension range within which adsorption is a prevalent process, the more cohesive condition of the soil formed by the increase in compaction can potentiate possible mechanical impediments to root growth caused by increased resistance to root penetration (SIVARAJAN et al., 2018; PEIXOTO et al., 2019).

According to Figure 6, which shows the cumulative pore-size frequency and indicates which fraction of their volume is occupied by air with the increase in tension and drying of the soil, it is found that for the tension range between 6 and 10 kPa, the highest compaction level (92%) led to a quantity of air-filled pores ranging from 5.4 to 10.4%, while for the lowest compaction level (61%) the variation for this same tension range was from 42 to 54%.

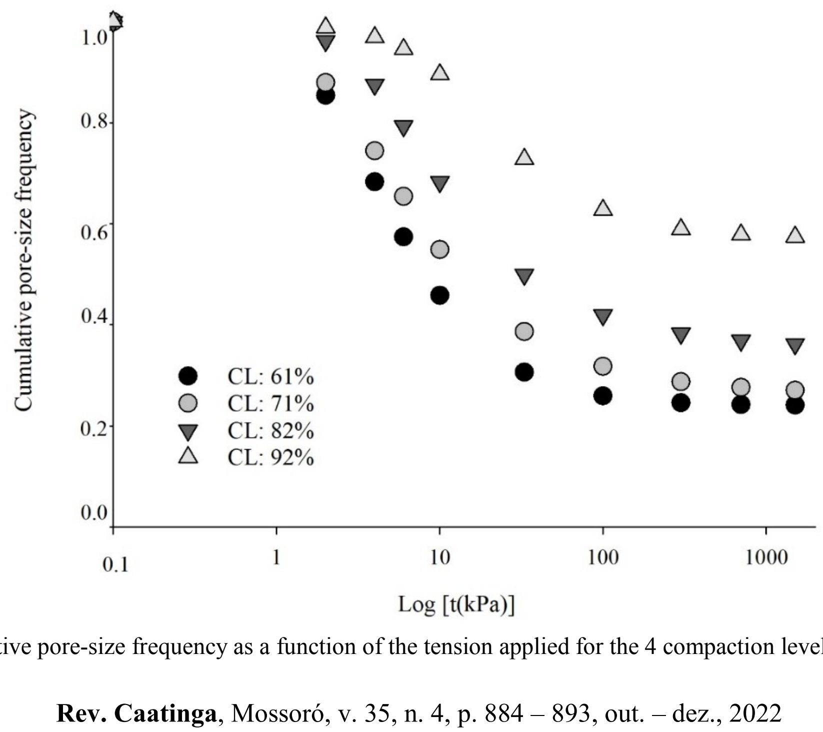

Figure 6. Cumulative pore-size frequency as a function of the tension applied for the 4 compaction levels

As the range of tensions between 6 and 10 kPa is usually associated with field capacity, hence a desirable hydraulic condition of the soil for many plant species, the variation in the amount of air -filled pores presented in Figure 6 confirms that the increase in compaction directly interferes in the space responsible air flow in the soil.

CONCLUSIONS

The evaluation of the physical-hydraulic attributes revealed that the increase in the compaction level in the *Argissolo Amarelo* (Ultisol) altered the structure and functionality of the pores due to the reduction in the amount of macropores, formed poorly continuous pores with lower air permeability and smaller space for aeration. In addition, it resulted in higher water retention at higher tensions, but lower available water content close to the maximum density, which mainly impacts the maintenance of air flow in the soil. Thus, the increase in compaction levels above 61% can create a more restrictive physical environment for plant growth.

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