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# Limiting physical properties of Technosols formed by the Fundão dam failure, Minas Gerais, Brazil

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**ABSTRACT:** Physical properties of the Technosols formed by the tailings deposition may constitute a physical barrier that limits water movement and plant development due to the properties received from those sediments. This study aimed to evaluate the physical quality of the Technosols formed by the deposition of sediments displaced by the Fundão Dam failure, Mariana, Minas Gerais State, Brazil, based on the evaluation of physical properties and Load Bearing Capacity Models (LBCM). For that, three areas under different vegetation types were selected: eucalyptus (Euc), forest with human-assisted revegetation (RF), and forest with native vegetation (NF). Three sampling subareas were demarcated in each area: non-impacted areas (Ni), and Technosols formed in directly impacted areas (Di), and partially impacted areas (Pi). Undisturbed samples were collected in two layers and subjected to the uniaxial compression test after equilibration at five matric potentials. Soil compression curves and LBCM were determined. Soil bulk density (BD), total porosity (TP), organic matter (OM), granulometry, and particle density (PD) were also determined. Clay content was less significant, and the silt and very fine sand content was significantly higher in the Technosols, generating an increase in BD and reduction in TP. Technosols generally exhibited greater load-bearing capacity due to higher pre-consolidation pressure values attained by these soils due to the lower clay and OM contents. High resistance of these soils is one limitation for revegetation of the areas evaluated, being necessary management practices to improve physical properties of the Technosols.

**Keywords:** tailings deposition, soil physical quality, load-bearing capacity models, pre-consolidation pressures, Technosols.

## INTRODUCTION

Mining activity is highly technified and generates wealth for a country. However, despite all the technology involved, the environmental impact from rupture of tailings retention structures leads to enormous environmental and social damage to the population, as occurred in Mariana (2015) and Brumadinho (2019) in Minas Gerais, Brazil (Schaefer et al., 2016; Carmo et al., 2017; Armstrong et al., 2019).

In Mariana, the tailings led to considerable environmental damage that involved displacement of 50 million $m^3$ of sediments, affecting not only the waters of the Doce River, but also around 457.6 ha of forest (Marta-Almeida et al., 2016; Omachi et al., 2018). Permanent deposition of tailings of variable depth on the soils in native ecosystems and systems under agricultural production produced environmental damage, as well as associated economic and social damage.

Deposition of tailings along the edges of the Doce River basin, the thickness of these tailings, and the impossibility of removing them are sufficient indicators to classify the soils under study as Technosols (Huot et al., 2012, 2015; Asensio et al., 2013), a concept introduced in 2006 by the World Reference Base for Soil Resources (WRB-FAO) (IUSS Working Group WRB, 2006). According to this classification system, Technosols are soils constituted in the upper 1.00 m by 20 % or more (in volume) of material of human origin, whose properties and pedogenesis are dominated by their technical origin.

In a similar manner, in 2001, discussions began regarding the need to consider the limitations of the Soil Taxonomy Classification System for classifying soils impacted by human activity, producing revision and modification of the system in 2014 (Soil Survey Staff, 2014) to thus ensuring adequate classification and survey of altered soils and transported by humans (Wilding and Ahrens, 2002; Echevarria and Morel, 2015).

Technosols are found worldwide where human activities have led to artificial soil formation, sealing of original soils, or extraction of materials (Isric, 2023). They are generically defined as soils with indications of pedogenetic development, whose properties and functions were defined by human action (Séré et al., 2010; Oliveira Filho and Pereira, 2023). These soils may occur in urban, industrial, traffic, mining, and military areas (Leguédois et al., 2016). Thus, mining generates large surfaces of degraded Technosols with an annual production of soil material of about 21 Gt $yr^{-1}$ (Hayes et al., 2014; Leguédois et al., 2015).

Although the information available on Technosoils is scarce and recent, interest in monitoring and evaluation has grown. Studies have shown that the properties of this Technosol formed by tailings deposition are completely different from original soils in their physical, chemical, and biological properties (Schaefer et al., 2015; Guerra et al., 2017; Batista et al., 2020; Couto et al., 2021), limiting the adoption of soil use and management practices.

In relation to soil physical properties, the behavior of these waste materials is quite different from those of conventional soils (Radhika et al., 2020). Some studies have indicated the predominance of sand and silt fractions in the tailings (Silva et al., 2006, 2015). This can cause a physical barrier that limits water movement and the capacity for plant development. Therefore, it is extremely necessary to evaluate soil physical quality, which will contribute to understanding the processes involved (Stefanoski et al., 2013; Rabot et al., 2018).

Physical parameters used to evaluate soil physical quality include load-bearing capacity, analyzed by models (Karlen, 2004; Kondo and Dias Junior, 2014). Load-bearing capacity is defined as the capacity of the soil structure to resist induced stresses without irreversible changes in the three-dimensional arrangement of the constituent soil particles (Alakukku et al., 2003; Tassinari et al., 2021).

This study aimed to create and compare load-bearing capacity models for Technosols formed by iron mine tailings deposition from the Fundão Dam, seeking to identify the most restrictive conditions for plant development in accordance with soil use, the impact level of the tailings, and the soil layer. We hypothesize that the Technosols formed from the tailings will have greater physical restrictions than original soils.

## MATERIALS AND METHODS

Study area is located in southeast Brazil, in the state of Minas Gerais (Figure 1a), in the municipality of Mariana (Figure 1b). The soils of this area were affected by the rupture of the Fundão dam located along the banks of the Gualaxo do Norte River nearly four years after the deposition of the tailings. Three types of areas reflecting diverse vegetation (Figures 1c and 1d), considering their distance from the dam and, consequently, the displacement of the tailings, were chosen for study: an area of planted eucalyptus with human-assisted revegetation (Euc) located 25 km from the dam by the river channel; an area of forest with human-assisted revegetation through sowing of herbaceous plants (RF) located 38 km from the dam; and an area of forest with native vegetation (NF) whose tailings moved 43 km downstream (Figure 1d).

In each type of vegetation, three sampling areas with different levels of impact were demarcated: areas not impacted or without tailings located at the top of the landscape (Ni); and two areas with Technosols: areas partially impacted (Pi) by the rupture of the Fundão Dam, with deposition of tailings up to 0.40 m in depth, located on the slope; and areas with deposition of tailings up to 1.00 m depth, or directly impacted areas (Di), located at the bottom. The location of these areas in the landscape is shown in figure 2.

In each sampling area, five points were selected at random for collection of undisturbed samples in two layers: 0.00-0.03 and 0.10-0.13 m. The 0.00-0.03 m layer was chosen as the layer most subject to changes by biological activities, and the 0.10-0.13 m layer was chosen to represent the greater mechanical resistance in field analyses, which may limit root system development.

Undisturbed samples were taken using an Uhland sampler with 6.4 cm diameter and 2.5 cm height rings. Samples were wrapped in plastic film and treated with paraffin wax to preserve their structure. These undisturbed samples were initially prepared by removing excess soil from the cylinders, saturated by capillarity, and placed in a Richards extractor, where they drained under the potentials (ψ) -10, -33, -100, -500, and -1500 kPa, and their weight was determined after equilibrium at each potential (Klute, 1986). After that, these samples were subjected to the uniaxial compression test (Dias Junior and Martins, 2017), applying pressure through compressed air. Pressures applied to the samples were 25, 50, 100, 200, 400, 800, and 1600 kPa. Each pressure was applied until 90 % of maximum deformation was achieved. Soil compression curves were created with these data, where the pre-consolidation pressures (σp) were determined. Potentials were represented on the abscissa (x) axis, and the pre-consolidation pressures (σp) were represented on the ordinate (y) axis to obtain the load-bearing capacity models (Dias Junior et al., 2005) using the Sigma Plot 14 software. These points were fitted to a regression of the $\sigma p = a\Psi m^b$ type, in which σp is the pre-consolidation pressure, Ψm is the matrix potential, and the a and b are parameters that represent empirical parameters obtained from fitting the model (Severiano et al., 2013). Regressions were fitted through the R software, version 4.0.3 (R Core Team, 2020), which was applied to the models of pre-consolidation pressure of the soil samples. Estimated soil equations were statistically compared using the Snedecor and Cochran (1989) test for linear models, which includes a data homogeneity test (F test), the angular coefficient (b), and the significance of the linear coefficient (a) of the equation.

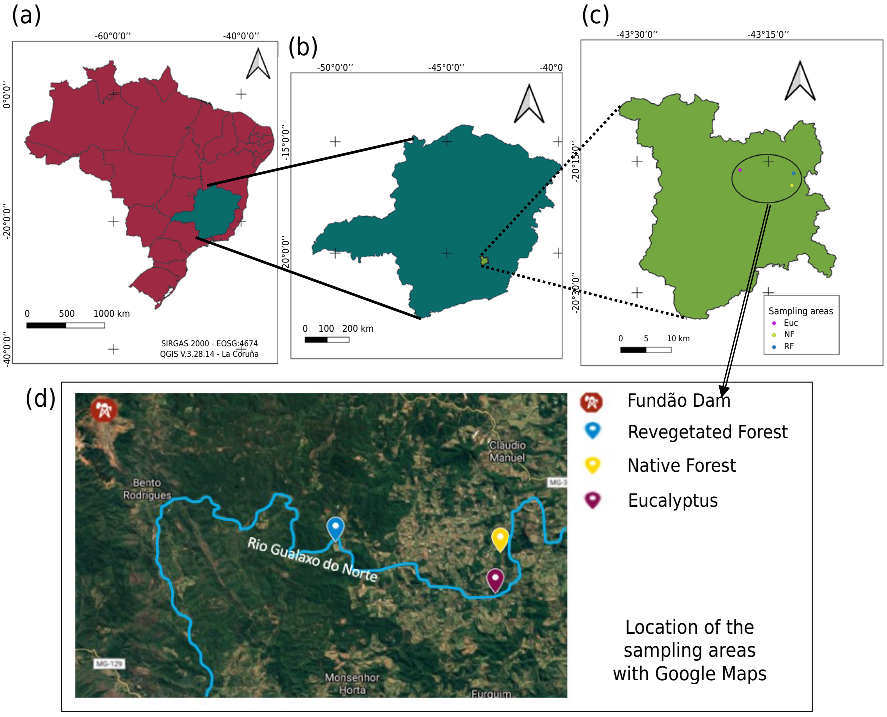


**Figure 1.** Location of the areas of interest (a) state of Minas Gerais (MG), municipality of Mariana (b), area under study (c), sampling areas and their location in relation to the Fundão Dam (d).

After to performe the tests, samples samples were dried in a laboratory oven at 105 °C for 24 h to determine soil bulk density (BD) (Almeida et al., 2017). Total porosity (TP) was determined by the expression: TP = (1-BD/PD), in which: BD is soil bulk density and PD is particle density (Viana et al., 2017).

Material excess removed from the rings was used as disturbed samples. They were air-dried, passed through a 2.0 mm sieve, and used in the following analyses: organic matter (OM) (Cantarella et al., 2001); granulometry by the pipette method, with fractionation of sand to determine the very fine (VF), fine, media, coarse, and very coarse sand fractions (Donagemma et al., 2017); and particle density by the volumetric flask method (Viana et al., 2017).

A completely randomized experimental design was set up to statistically analyze the results to BD, PD, TP, clay, silt, sand, and sand fractions. Before proceeding with the analysis, a transformation that maximizes the likelihood of the normal model was selected for each variable (Box and Cox, 1982). On the other hand, when factors and/or interactions were detected with significant effects in ANOVA, comparisons of means were conducted using the Scott-Knott test ($p<0.01$).

## RESULTS

### Characterization and physical properties of the soils

Soils under study belong, in general, to the medium texture group, but the original soils are classified in the sandy clay loam texture, while the Technosols range from loam to sandy loam texture.

Particle size distribution in the studied soils is shown in figure 3. Soils are clustered according to the results of the Scott-Knott test ($p<0.01$) and classified in an ascending manner. Soils with the highest values for each trait or property are always in the first groups. Thus, the clay contents were highly variable, generating seven groups (Figure 3a). For this trait, the lowest values correspond to Di and Pi (clustered in “d”,

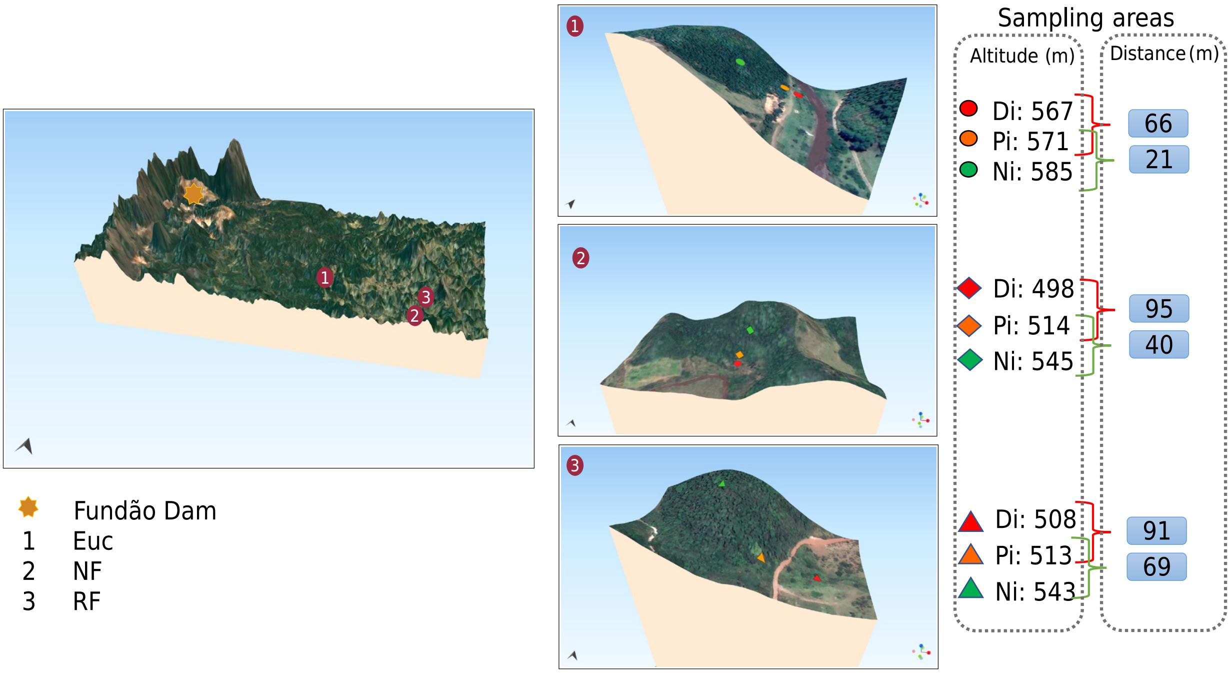


**Figure 2.** Elevation maps indicating the location of the three vegetation types (1. Euc: eucalyptus; 2. NF: native forest; 3. RF: revegetated forest), the sampling areas with different impact levels (Di: directly impacted; Pi: partially impacted; and Ni: not impacted), distance between them, and their altitude.

"e", "f" and "g") with clay from 45 to 105 g kg$^{-1}$. These soils also obtained the highest values for silt (419-480 g kg$^{-1}$) grouped in "a", in contrast with the Ni soils ("b" and "c" groups), which had silt from 165 to 280 g kg$^{-1}$ (Figure 3b).

In contrast, the soils were separated into only two groups regarding the total sand content, with impacted and non-impacted soils in both groups (Figure 3c). In addition, the results for very fine sand (VFS) are similar to silt (Figure 3d). For the Ni soils, the values ranged from 33 to 65 g kg$^{-1}$ (group "c"), whereas for the Technosols, the values were from 189 to 279 g kg$^{-1}$ (groups "a" and "b"), exhibiting significantly higher values.

The PD (Figure 4) were highly variable in the soils studied, generating seven groups. In the first five are the areas under the Technosols (Di and Pi), which have PD from 2.78 to 2.94 Mg m$^{-3}$, compared to the Ni soils, which had PD from 2.40 to 2.60 Mg m$^{-3}$. The highest PD corresponded to the soils under RF, with PD of 2.94 Mg m$^{-3}$ in the two layers evaluated. On the other hand, soil bulk density (BD) in the 18 conditions analyzed exhibited four homogeneous groups (Figure 5a), with the highest BD corresponding to the Technosols, with values from 1.59 to 1.88 Mg m$^{-3}$ (clustered in "a" and "b"). Regarding total porosity (TP), the soils were clustered in three homogeneous groups; in this case, the Technosols were clustered in "b" and "c", with TP from 0.33 to 0.43 m$^3$ m$^{-3}$, significantly lower than in original soils (Figure 5b).

In the case of OM, the results obtained show highly variable in the soils under study, giving rise to eight groups (Figure 6). In general, the OM was greater in the soils without tailings and clustered in "a", "b", "c", "d", and "e" (12.3 to 26.3 g kg$^{-1}$). In Di and Pi, OM was 2.7 to 8.9 g kg$^{-1}$. Thus, in Ni in the three vegetations evaluated, the OM values were higher in the surface layer than in the subsurface layer in the following sequence: NF > Euc > RF, with values from 17.8 to 26 g kg$^{-1}$ in the surface layer and from 12.3 to 19.5 g kg$^{-1}$ in the subsurface layer. Technosols showed the same trend, except for RFPi, which had higher OM contents in the subsurface layer. In Pi and Di, the OM values were variable both in the uses and in the layers evaluated, with values from 2.7 to 8.9 g kg$^{-1}$.

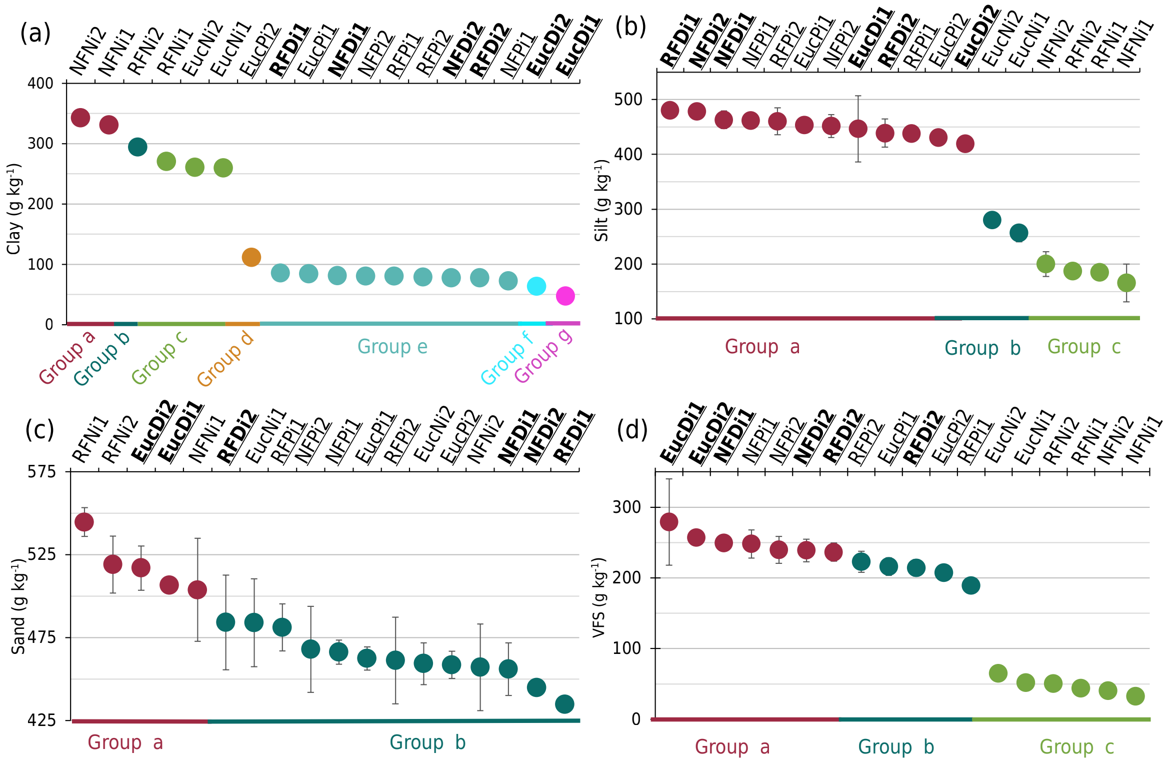


**Figure 3.** Clay (a), silt (b), total sand (c), and very fine sand (VFS) (d) contents clustered by the Scott-Knott test at 1 %, in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Vegetation type: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Impact level: Ni (not impacted), Pi (partially impacted), Di (directly impacted). Evaluated layers: 1 (surface layer: 0.00-0.03 m), 2 (subsurface layer: 0.10-0.13 m).

Results of the correlation between clay content and BD, PD, TP, and OM are shown in figure 7. For all traits evaluated, the clay content played a fundamental role in their clustering or segregation. Thus, Ni have the greatest clay contents, with less restrictive or limiting values for the parameters evaluated, whereas in the soils with lower clay contents (Technosols), the properties evaluated were impacted, generating more restrictive or limiting values for them.

## Load-bearing capacity of the soils

In comparison of the LBCM from soil surface layers (0.00-0.03 m), no differences were observed between the Di and Pi soils under different vegetation types evaluated (Table 1), and they were clustered in a single model. In Ni, soils also did not differ between different vegetation types; therefore, they were clustered in a single model. Consequently, two models were obtained for the surface layer of the nine conditions studied (Figure 8a).

In the 0.10-0.13 m layer, as in the surface layer, there were no significant differences between angular coefficients and linear coefficients of the Di and Pi soils under different vegetation types, and these LBCM were clustered in a single model, as shown in table 2. The same occurred with the LBCM of the Ni soils, which did not differ significantly and were clustered in a single model. Thus, two LBCM were obtained for the subsurface layer, as shown in figure 8b.

In the LBCM of the surface layer obtained after clustering (Figure 8a), the value of the estimated “a” parameter was 82.0 in the A1 model that clusters the original soils, and 137.9 in the A2 model that clusters the Technosols. In the same way, the value of “b” parameter was from 0.91 to 0.12, respectively (Figure 8a).

The “A1” and “A2” models have an $R^2$ of 0.91 and 0.62, indicating their good fit, considering that the fitting parameters had highly significant results, with values lower than 0.01. The A2 model has pre-consolidation pressures (PCP) of around 325 kPa under a matric

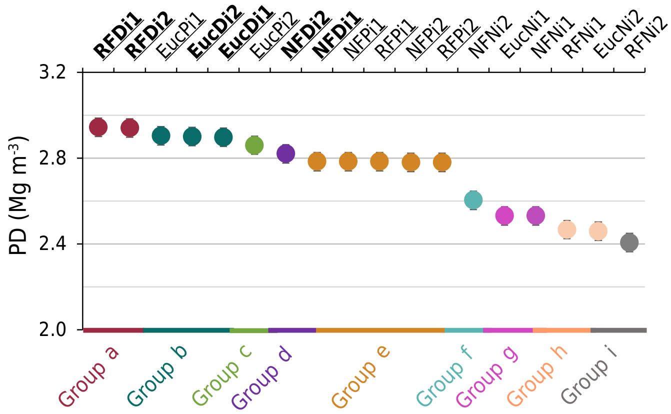


**Figure 4.** Particle density (PD), clustered by the Scott-Knott test at 1 %, in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Type of vegetation: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). Evaluated layers: 1 (surface layer – 0.00-0.03 m), 2 (subsurface layer – 0.10-0.13 m).

potential of -1,500 kPa, whereas the A1 model has values of 220 kPa at the same potential. In contrast, the coefficients of determination ($R^2$) of the B1 and B2 models were 0.87 and 0.83, respectively, and significant at 1 %, showing the good fit of the models (Figure 8b). For these models, the a and b parameters had values of 67.0 and 80.1 (a parameter), and 0.23 and 0.21 (b parameter). For the B1 model, the pre-consolidation pressure was below 350 kPa at the matric potential of -1,500 kPa, and for the B2 model, it was above 350 kPa at the same potential.

Table 3 presents the comparison of the LBCM for the 0.00-0.03 and 0.10-0.13 m layers. Four final models were obtained, since there were significant differences upon making a comparison with the linear model test of Snedecor and Cochran (1989), regardless of the layer or the level of impact compared. Since these models were not clustered, they conserved the values of the “a” and “b” coefficients, as the $R^2$ already indicated (Figure 9).

## DISCUSSION

### Soil characteristics and physical properties

Textural variability of the studied soils was determined by the deposition of material coming from the dam with high silt and very fine sand content, and low clay content. For the total sand values, only two groups were differentiated. Thus, our research shows that as a consequence of the low coarse sand contents in the tailings that gave rise to the Technosols, the values of this particle size do not represent a criterion of differentiation among them and the Ni soils, whereas the finer sands represent a criterion of differentiation.

In this respect, Silva et al. (2015) described the particle size composition of this sediment as consisting of around 90 % sand and silt and only 10 % clay, compacted, and with low porosity and absence of structure. This information corroborates that of Silva et al. (2006); in similar tailings, they observed contents of around 54 g $kg^{-1}$ coarse sand, 729 g $kg^{-1}$ fine sand, 122 g $kg^{-1}$ silt, and less than 100 g $kg^{-1}$ clay. This information regarding the characteristics of the tailings explains the granulometry of the Technosols evaluated in this study, coinciding with the results of Silva et al. (2021a); their research showed that the silt contents in the soils impacted by the dam had a general effect on the physical properties of these soils. Similarly, in their research on Technosols formed by mining, Kozłowski et al. (2023), characterized the texture of these soils as sandy loam because the sand fractions were greater than 50 % and the clays were less than 20 %.

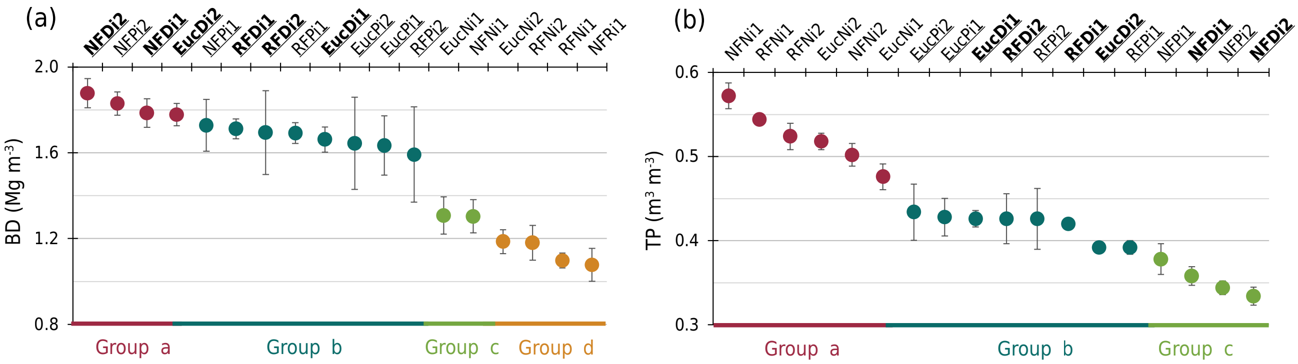


**Figure 5.** Soil bulk density (BD) (a) and total porosity (TP) (b), clustered by the Scott-Knott test at 1 %, in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Vegetation type: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). Evaluated layers: 1 (surface layer – 0.00-0.03 m), 2 (subsurface layer – 0.10-0.13 m).

Clay content in Technosols can also be explained by the nature of the parental material already described because, as mentioned, the newly-formed soils have characteristics received from the sediment of origin, whereas the higher contents of this size of particles in the original soils is a product of the differentiated pedogenesis that occurred in them.

Changes in granulometry can also explain the PD, which changes the physical composition and probably the mineralogical composition of the soils because of the origin of the tailings deposited. High PD in the profile of Technosolos formed from mining tailings was found in recent research (Kaczmarek et al., 2021; Shishkov et al., 2022) and was attributed to the characteristics of the origin material. In this sense, Santos et al. (2019) and Couto et al. (2021) found a predominance of iron oxides in locations impacted by the Fundão Dam. These minerals are typical of tailings dams in the iron mining processes and can explain the PD results. For example, Hematite has a PD of 5.3 Mg $m^{-3}$ (Chen et al., 2019), explaining the higher particle density in the Technosols compared to the original soils with significantly greater clay content (Figure 7a).

Our results for BD coincide with those of Schaefer et al. (2015), Silva et al. (2016, 2021a) and Couto et al. (2021), who evaluated depositions of tailings coming from mining, always obtaining higher BD compared to the BD in the soils without tailings. Similarly, Radhika et al. (2020) found that Technosoils produced by mining, like those in this research, presented BD above 1.7 Mg $dm^{-3}$, with little variability in the profile. These increases may also be related to the lower clay and high silt and sand contents, as already discussed (Figure 7b), the soils with highest clay contents (non-impacted soils) have the lowest BD, while the Technosols, both those formed by partial impact and those formed by direct impact of the tailings, have the highest bulk densities.

However, it is noteworthy that the BD (and consequently lower TP) in these soils may have increased beyond the densification of the tailings over the period of pedogenesis that occurred in the four years after their deposition, in accordance with the principles proposed by Ferreira (2010). In other words, their compaction may have increased by the pedogenetic process of densification brought about in this case by the quantity of silt (content >400 g $kg^{-1}$) and very fine sand (content >200 g $kg^{-1}$) particles. Deposition of the non-consolidated material generated remodeling of the topography at the base of the lowlands, in the floodplains, and in the colluvial areas, coinciding with the areas sampled in this study.

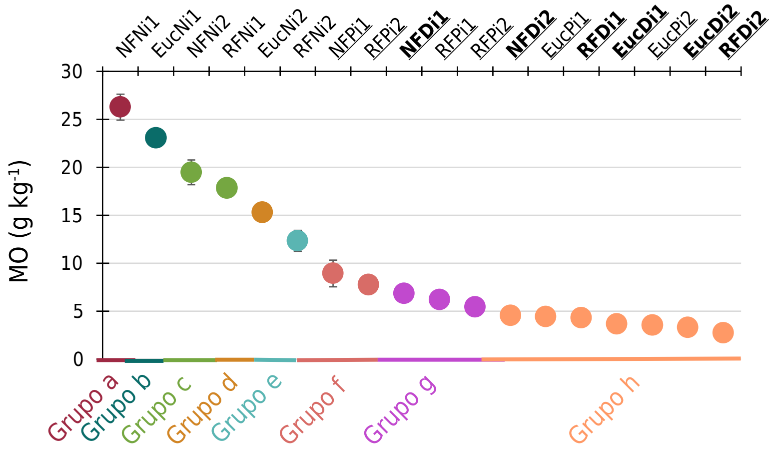


**Figure 6.** Soil organic matter (OM), clustered by the Scott-Knott test at 1 %, in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Vegetation type: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Impact level: Ni (not impacted), Pi (partially impacted), Di (directly impacted). Evaluated layers: 1 (surface layer – 0.00-0.03 m), 2 (subsurface layer – 0.10-0.13 m).

In the same way, the OM content in the soils is correlated with the clay values (Figure 7d), which explains why in the Ni soils the organic matter contents were significantly greater than in the Technosols, in agreement with the results of Batista et al. (2020), Silva et al. (2021a) and Couto et al. (2021). This result is due to organic matter variability matter carried by the dam rupture, which produced its accumulation at random in the Technosols. The reduction of OM in the Technosols is also closely related to the reduction in microbial activity in these soils (Silva et al., 2021a). In this respect, Batista et al. (2020) showed that the physical-chemical properties and the presence of low bioavailable heavy metals contents in the dam tailings led to changes in the microbial communities through reductions in C storage and in biogeochemical cycling of nutrients in comparison with those in undisturbed reference soils in the surroundings. This, therefore, has negative implications for ecosystem operations.

Total clay content has been indicated as the main characteristic that determines soil properties, due to its effect on soil structure, density, porosity, organic matter, and other properties (Dexter, 2004; Mazurana et al., 2017; Martín et al., 2018). In this study, this response can be seen in figure 7 by the high correlation between clay and the other properties evaluated. There is thus a high negative correlation with PD (r = -0.88) and BD (r = -0.92), and high positive correlation with TP (r = 0.87) and OM (r = 0.91). In the same way, this figure shows the similarity of the Technosols regarding the properties evaluated, regardless of their position in the landscape, as a consequence of their formation from the tailings that were deposited at random over the original soils, which exhibited greater variability resulting from the differentiated pedogenesis in the natural environment.

On the other hand, it has already been demonstrated that high silt contents in these soils, can result in surface crusting and consequent erosion problems (Rabot et al., 2018; Cruz et al., 2020; Silva et al., 2021a). In addition, together with the very fine sand, silt is associated with the predominance of smaller size pores, with consequent problems of permeability, imposing restrictions on water movement (Silva et al., 2018, 2021b). This occurs because the predominance of these particles generates a structure of greater density in which the grains of fine sand and silt occupy the spaces (plug) of the pores formed by the coarser sand, leading to the predominance of small pores in the soil, as reported by Ribeiro et al. (2007). Therefore, regarding their physical properties, the Technosols represent a challenge for management, whether for reforestation for biodiversity recovery or for agricultural use, considering that the tailings also reached areas under cultivation.

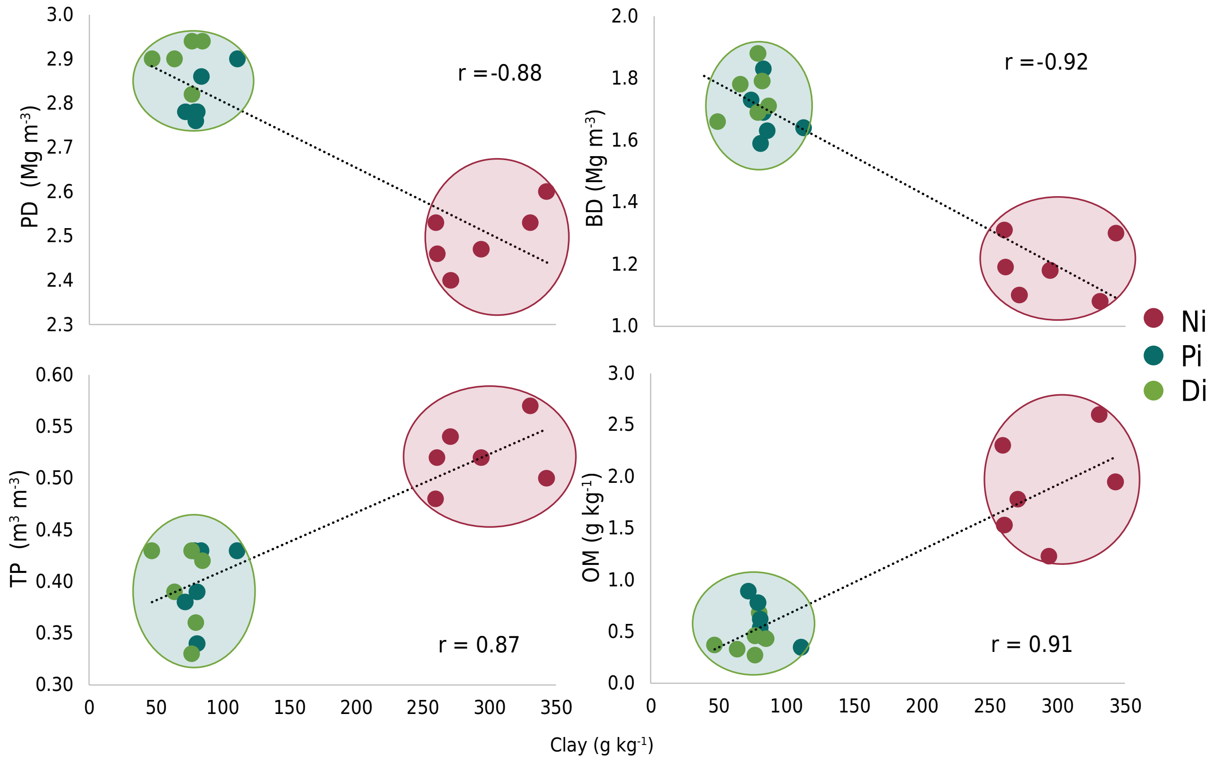


**Figure 7.** Relationship between clay content and particle density (PD) (a), soil bulk density (BD) (b), total porosity (TP) (c), and organic matter (OM) (d) in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Impact level: Ni (not impacted), Pi (partially impacted), Di (directly impacted).

In contrast, the properties and characteristics of the original soils classified as sandy clay loam generally fit within what is expected for soils of this textural classification in comparison with diverse studies regarding this type of soil (Ottoni et al., 2014; Obour et al., 2019; Arruda et al., 2021). Nevertheless, this comparison does not allow differences to be seen regarding their degradation or loss of quality, which is expected in highly human-impacted soils.

**Table 1.** Comparison of the load-bearing capacity models [$\sigma p = 10(a + b\Theta)$] for the 0.00-0.03 m layer in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil, according to the procedure described in Snedecor and Cochran (1989)

| Model | Homogeneity | F | | Decision | |
|---|---|---|---|---|---|
| | | Linear coef. (log a) | Angular coef. (b) | | |
| EucDi*NFDi | H | NS | NS | Cluster | |
| EucDi+NFDi*RFDi | H | NS | NS | Cluster | |
| EucPi*NFPi | H | NS | NS | Cluster | |
| EucPi+NFPi*RFPi | H | NS | NS | Cluster | |
| EucNi*NFNi | H | NS | NS | Cluster | |
| EucNi+NFNi*RFNi | H | NS | NS | Cluster | A1 |
| EucDi+NFDi+RFDi* EucPi+NFPi+RFPi | H | NS | NS | Cluster | A2 |
| EucDi+NFDi+RFDi+ EucPi+NFPi+RFPi *EucNi+NFNi+RFNi | H | NS | *, ** | Don't cluster | |

Vegetation type: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). F test of homogeneity of variance for the regression parameters fitted; H: homogeneous; *: significant at 5 %; **: significant at 1 %; NS: not significant.

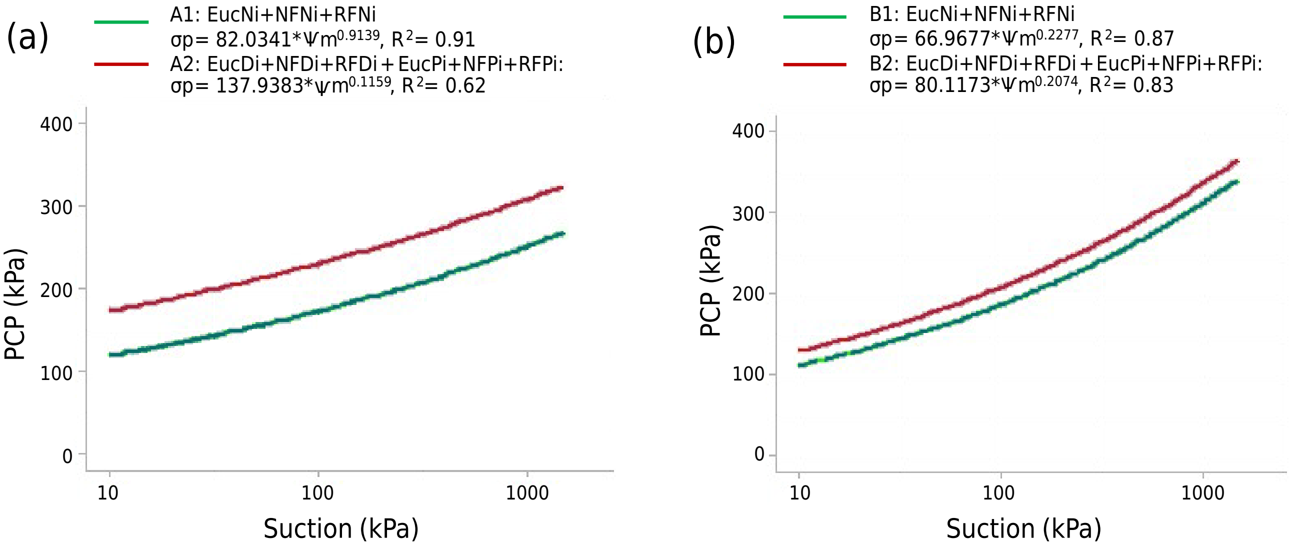


**Figure 8.** Load-bearing capacity models of the surface layer (0.00-0.03 m) (a) and subsurface layer (0.10-0.13 m) (b) in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Vegetation type: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Impact level : Ni (not impacted), Pi (partially impacted), and Di (directly impacted).

### Soil load-bearing capacity

For all evaluated soils, the $\sigma_p$ increased as suction decreased (Figure 9). Similar results were observed by several authors (Martins et al., 2013; Severiano et al., 2013; Andrade et al., 2017; Tassinari et al., 2019). Both in studies to evaluate load-bearing capacity (LBC) and in the compaction evaluation. Reduction in soil resistance in accordance with greater moisture content is because as soil moisture content increases, the activity of the cohesive forces of the soil and the internal friction decrease, thus leading to a reduction in soil mechanical resistance (Assis et al., 2009; Lima et al., 2013).

Technosols had higher $\sigma_p$, and this condition is closely associated with soil granulometry, as reported by Severiano et al. (2013), whose research showed that soil resistance decreases as clay content increases. In addition, Technosols have high silt contents, and,

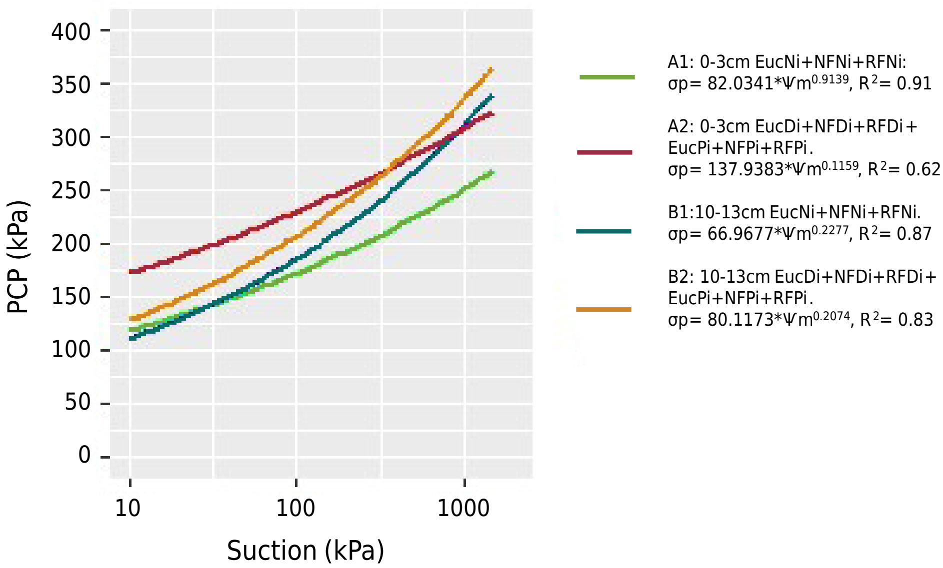


**Figure 9.** Final soil load-bearing capacity models in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil.

**Table 2.** Comparison of the load-bearing capacity models [σ = 10(a+bθ] for the 0.10-0.13 m soil layer in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil, and according to the procedure described in Snedecor and Cochran (1989)

| Model | Homogeneity | F | | Decision | Model |
|---|---|---|---|---|---|
| | | Linear coef. (log a) | Angular coef. (b) | | |
| EucDi*NFDi | H | NS | NS | Cluster | |
| EucDi+NFDi*RFDi | H | NS | NS | Cluster | |
| EucPi*NFPi | H | * | NS | Don't Cluster | |
| EucPi*RFPi | H | NS | NS | Cluster | |
| EucNi*NFNi | H | NS | NS | Cluster | |
| EucNi+NFNi*RFNi | H | NS | NS | Cluster | B1 |
| EucDi+NFDi+RFDi* EucPi+ RFPi | H | NS | NS | Cluster | |
| EucDi+NFDi+RFDi+ EucPi+ RFPi*NFPi | H | NS | NS | Cluster | B2 |
| EucDi+NFDi+RFDi+ EucPi+RFPi+NFPi * EucNi+NFNi+RFNi | H | * | NS | Don't Cluster | |

Vegetation type: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Impact level: Ni (not impacted), Pi (partially impacted), Di (directly impacted). F test of homogeneity of variance for the regression parameters fitted; H: homogeneous; *: significant at 5 %; **: significant at 1 %; NS: not significant.

under these conditions, the internal contact friction becomes significant, increasing soil resistance (Carrera et al., 2011).

These results coincide with those obtained by Islam (2023), who evaluated three different types of mining tailings, demonstrating that tailings with higher clay content presented lower consolidation values. In this sense, Radhika et al. (2020) affirm that tailings deposits suffer significant deformations and alterations in the proportion of voids, which, together with the effect of the weight of the material itself, produces the consolidation of these residues.

Greater resistance of the subsurface layers shown in figure 8 is consistent with different studies that show that the soil subsurface layers tend to have greater resistance than the surface layers (Oliveira et al., 2003; Araujo-Junior et al., 2011; Iori et al., 2012), which is closely related to the greater biological activity and, consequently, to the significantly greater OM of the surface layers. Technosols, however, had lower OM, as well as high variability in the different uses and layers evaluated, as a consequence of microbial activity reduction. This generated the selection of microbial groups more adapted to the conditions of the tailings with low OM content and greater silt content, as found by Silva et al. (2021a), which makes these newly-formed soils have greater LBC, even greater in the surface layer, compared to the non-impacted soils under pressures lower than 500 kPa.

In addition to the emergency measures adopted after the collapse of the Fundão Dam, programs were later developed and monitored related to coverage and production of plant biomass, monitoring of soils (including evaluation of physical, chemical, and microbiological properties), and forest restoration activities. At the beginning of 2019, increases were already seen in the organic matter contents through the evolution of this planting (Fundação Renova, 2019; Ramboll, 2019).

Among the activities developed for tailings management, using a mixture of herbaceous seeds (legumes and grasses) stands out to create a root network that can reduce

**Table 3.** Comparison of the load-bearing capacity models [p = a*Ψm b] for the 0.00-0.03 and 0.10-0.13 m layers in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil, and according to the procedure described in Snedecor and Cochran (1989)

| Model | Homogeneity | Linear coef. (log a) | Angular coef. (b) | Decision |
|---|---|---|---|---|
| A1 0.00-0.03 m: EucNi+NFNi+RFNi * B1 10-13: EucNi+NFNi+RFNi' | H | NS | *, ** | Don't Cluster |
| A20-3cm: EucDi+NFDi+RFDi+ EucPi+NFPi+RFPi * B2 0.10-0.13m: EucDi+NFDi+RFDi+EucPi+ RFPi+NFPi | H | NS | *,** | Don't Cluster |
| A1 0.00-0.03 m: EucNi+NFNi+RFNi * B2 0.10-0.13 m: EucDi+NFDi+RFDi+ EucPi+ RFPi+NFPi | H | *,** | NS | Don't Cluster |
| B1 0.10-0.13 m: EucNi+NFNi+RFNi * A2 0.00-0.03 m: EucDi+NFDi+RFDi+ EucPi+NFPi+RFPi | H | * | NS | Don't Cluster |

Vegetation type: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Impact level: Ni (not impacted), Pi (partially impacted), Di (directly impacted). F test of homogeneity of variance for the regression parameters fitted; H: homogeneous; *: significant at 5 %; **: significant at 1 %; NS: not significant.

instability and sliding of the accumulated tailings (Fundação Renova, 2019). Therefore, it is quite probable that these actions, together with the pedogenesis that occurred, favored differentiation of the layers of the Technosols, generating significant differences in the LBCM.

Furthermore, the A2 and B2 models generally have greater pre-consolidation pressures compared to the A1 and B1 models (Figure 9). In these models, greater load-bearing capacity is observed nearly throughout the entire suction range evaluated. However, for 1000 kPa, the B1 model, corresponding to the subsurface layer of the original soils, has an important increase, exceeding that of the A2 model. Nevertheless, the high pre-consolidation pressure at low moisture levels shown by the A2 and B2 models indicate that these soils may offer greater resistance to root development of the plants, as reported by (Dias Junior et al., 2019).

Preconsolidation pressure depends on intrinsic and extrinsic soil factors – texture and mineralogy, soil structure and bulk density, management and use, organic matter content and characteristics, among others (Richart et al., 2005; Severiano et al., 2013; Dias Junior et al., 2019). Thus, it is possible to understand how tailing deposition from mining and the Technosols formed from the pedogenesis that occurred on this material have greater resistance, even comparable to the soils affected by agricultural activity (Severiano et al., 2013; Andrade et al., 2017; Martins et al., 2018; Tassinari et al., 2019), even though the Technosols are quite different from the weathered soils of Brazil regarding particle-size composition.

Considering the physical limitations described for the Technosols studied and based on the functionality of these soils, Leguédois et al. (2015) highlight the importance of a holistic approach in focus on the multifunctionality of Technosols for providing local ecosystem services. Said proposals, commonly aim at recovering agricultural areas degraded by agriculture, based on the development of sustainable systems that can promote high resilience and conserve natural resources (Mosier et al., 2021; Shahmohamadloo et al., 2021; Spratt et al., 2021). However, it can be applied to manage the areas under study here and the agricultural areas that were impacted by the dam rupture. We understand that from the homogeneity of the tailings, which, in turn, generated quite homogeneous Technosols, it is possible to predict the current physical condition of all the impacted soils.

To this end, several authors propose the combination of strategies commonly used in environmental restoration and soil recovery plans, including the combination of various practices, such as cover plants, conservationist growing systems, use of organic compost, phytoremediation, reforestation and short-term rotational (LaCanne and Lundgren, 2018; Schreefel et al., 2020; Fenster et al., 2021; Kaczmarek et al., 2021; Kozłowski et al., 2023; Oliveira Filho and Pereira, 2023). Therefore, it is recommended to continue investigating the formed Technosols to determine which management practices are the most appropriate to improve their properties.

## CONCLUSIONS

Higher silt and very fine sand contents in the Technosols generated an increase in soil bulk density and a decrease in total porosity. Technosols generally have the highest pre-consolidation pressure values and the lowest organic matter values, resulting in greater load-bearing capacity for these soils. The high resistance of the Technosols is their main physical limitation, and it is necessary to combine various management practices to improve their physical properties and full multifunctionality.

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**Writing – review & editing:** Eduardo da Costa Severiano (lead).

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