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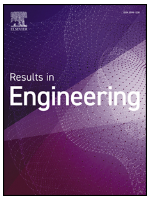

Research paper

Full-scale filtered tailings compaction field test in tropical environment

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ABSTRACT

The compaction of filtered tailings has become an increasingly important topic in mining engineering, particularly as the industry shifts away from traditional tailings dams to disposal in piles. This study examines the compaction behavior of iron ore tailings, focusing on the influence of critical parameters such as water content, layer thickness, the number of compactor passes, and vibration technique. The results show that water content is the most crucial factor in preventing under-compaction, while the combination of optimal layer thickness and passes can significantly reduce compaction time without compromising quality. Furthermore, vibration improves compaction efficiency by reducing the required passes and increasing energy penetration depth. These findings provide practical guidance for enhancing the compaction process in tailings disposal, contributing to safer and more stable tailings storage facilities.

1. Introduction

Compaction significantly influences the dry density of geomaterials, making it one of the most critical factors in regulating the mechanical behavior of earthworks. As one of the oldest and simplest ground improvement methods, compaction increases bulk density, reduces porosity, and enhances soil strength and bearing capacity while minimizing permeability and compressibility [1]. In landfills, hydraulic conductivity is also a key property, typically regulated by established standards [2].

Compaction is widely applied in civil engineering projects such as foundations, highways, railways, clay liners [3–5], landfills [2], dams [6], and piles. The key parameters controlling compaction are optimum water content and maximum dry density achievable for a given compaction effort [1,7,8]. An alternative approach is using the line-of-optimum concept for compaction control [3,9,10].

According to [7], the first appearance of the idea of changing the water content during earthwork compaction comes from California Division of Highways in 1929, where a series of tests were done to study water content for compaction of specimens. Proctor [11] published four years later his finds about the influence of compaction on strength and hydraulic parameters on earth dam construction and stated the principles of "modern" compaction. Johnson and Sallberg [12] summarized several papers, such as such as [13–16], and present the effects essential to be evaluated in each compaction technique. A broader review of the history of compaction was performed by [17]. In recent years, soil compaction technique has been applied largely for mining tailings, motivated by the progress of filtering technologies, currently able to reach 50.000 tons of filtered material per day (tpd) [18,19] and appearances of recent failures such as those that occurred in the Mariana and Brumadinho dams in Brazil. Those accidents also led to the investigation and wider application of safer and newer methods, such as filtered tailings stockpiles, and to improvements in Brazilian regulations related to tailings storage structures.

Regarding field tests for setting compaction parameters, those are essential due to the limitations of laboratory simulations, a fact well-documented in the literature [20–23]. Consequently, full-scale field tests are necessary despite their higher costs, longer durations, and greater effort. Johnson and Sallberg [7] extensively documented full-scale compaction experiments conducted between 1940 and 1960, highlighting the effectiveness of smooth-wheel rollers in construction projects. They explored the impact of different roller types and weights, ranging from 3 to 13 tons.

Compaction equipment selection is crucial for achieving desired compaction levels. Traditional compacting devices, such as three-wheel rollers, sheepsfoot rollers, pneumatic-tired rollers, and vibratory

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compactors, are commonly used. Effective field compaction primarily depends on regulating the number of passes and the thickness of each compacted layer. Johnson and Sallberg [7] and Cambi et al. [24] indicates that bulk density increases significantly after the initial passes, with diminishing returns in subsequent passes. Moreover, Johnson and Sallberg [7] noted a substantial reduction in compaction effectiveness with increasing depth.

Soil testing techniques, including cone penetrometer tests, are vital for evaluating parameters such as dry density, water content, porosity, and soil strength [25–28]. Compaction typically results in soil structures characterized by macropores, as compaction efforts have minimal impact on micropores [29–33]. This complex interaction between equipment selection and soil structure highlights the challenges in achieving optimal compaction in construction projects.

Vibratory compactors are another method to increase maximum dry density. Ghorbani et al. [34] reported that dynamic compaction is one of the most cost-effective technologies, reducing the overall time required for soil compaction. Vibration rollers can operate at high amplitude and low frequency or low amplitude and high frequency, depending on the soil type. High amplitude, low-frequency vibrations are used to penetrate deeper zones and compact soft soils, while low amplitude, high-frequency vibrations are suited for shallow depths and stiff soils [35]. Additionally, Anderegg and Kaufmann [36] introduced intelligent compaction rollers capable of detecting compaction zones to prevent over-compaction. A mathematical model developed by [37] aids in understanding compaction by impact. Ping [38] demonstrated that vibratory rollers operating at a high amplitude and a velocity of 6.5 km/h achieve better compaction behavior compared to static rollers operating at 4.4 km/h, indicating higher field productivity.

Compaction of soil is a complex process influenced by various factors, primarily dictated by soil properties. Among these factors, water content emerges as the principal parameter manipulated by technical engineering to achieve optimal dry density values. Achieving the desired density relies heavily on controlling moisture content, alongside the compaction effort applied, since they are both considered pivotal soil properties in the science of compaction. The relationship between these properties and the resulting density is well established. However, the effect of soil type cannot be overlooked. Johnson and Sallberg [7] highlighted that soil types vary in their response to moisture content alterations. For instance, uniformly graded sand and heavy clay soils exhibit less sensitivity to changes in moisture content compared to sandy soils with small proportions of silt and clay, which are highly responsive to such variations. Tunnell and Dippenaar [39] claim that the soil type influence on compaction is mainly controlled by mineralogy, which dictates physical and chemical properties, and grain size distribution.

While soil type and moisture content are primary considerations, other factors also play a role in soil compaction. These factors encompass a wide range of variables, including soil structure, organic content, and temperature variations. However, not all factors are economically viable for improving soil compaction. Cambi et al. [24] shed light on the economic viability of different factors influencing soil compaction. Their research underscores the importance of prioritizing economically feasible methods for achieving optimal compaction. By focusing on factors that offer the greatest return on investment, engineers and practitioners can effectively enhance soil compaction while minimizing costs. This approach ensures that soil compaction efforts are not only technically sound but also economically sustainable.

In the context of tailings, the degree of saturation is dependent on the filtering technology used in the mine [40]. Ideally, the water content should reach the desired value for field compaction without the need for further adjustment. Morrison et al. [40] suggests that in dry climates, starting with 1% above the optimal water content (w_{op}) is beneficial for the filtration process. Table 1 presents a summary of studies analyzing factors that affect the compaction and their respective authors.

Apart from directly controlled mechanical and operational factors, the mixture of materials is another critical variable influencing the compaction effort, especially when it comes to tailings. Mixing aims to enhance chemical, hydraulic, strength, and deformation properties of the soil. Mixtures may include additional materials such as fibers [50] or binders. Wang and Huang (1985) developed equations to predict maximum dry density, optimal water content (OWC), and permeability for 57 different mixtures of clay, silt, sand, and gravel-sized materials.

In the mining industry, material mixtures address challenges related to mechanical stability, environmental contamination, water management, and design constraints [51–56]. Bastos et al. [57] proposed a procedure to evaluate the feasibility of tailings mixtures with varying contents of cement, slag, and lime. Co-disposal of water, rock, and tailings is another prevalent method in mining projects [19,52,53,56,58–60]. Borja and Bareither [56] presented studies on the proportions and handling methods for co-disposal techniques.

For tailings, material separation using hydrocyclones is common, dividing the feed into a sand-rich underflow stream and a fine-material-rich overflow stream [40]. Additionally, Morrison et al. [40] noted that classifying tailings can help mitigate acid mine drainage (AMD). However, studies focusing on the strength of such mixtures are scarce.

Therefore, this paper aims at presenting a series of full-scale test pits developed to understand the behavior of filtered tailings and the influence of overflow material on their compaction. Initially, laboratory tests were conducted to characterize the behavior of filtered tailings. These tests included evaluating the coefficient of variation for maximum dry density and OWC to assess the influence of material mixtures. It is essential to highlight that spatial variability can occur during the stacking of filtered tailings [61]. Subsequently, field tests were performed using multiple layers to evaluate the effects of the number of compactors passes, layer thickness, deviations in water content from target values, and the application of vibration. Both laboratory and field tests measured dry density and water content to support these analyses. Finally, data comparisons were made to evaluate the behavior of filtered tailings against various soil types as documented by [7].

2. Materials and methods

2.1. Materials

The filtered iron ore tailings (IOTs) used in this study were classified into three types based on the hydrocyclone separation process, and they are sourced from the Quadrilátero Ferrífero, state of Minas Gerais, Brazil. The three types include:

- Mixture 1 (M-1): Composed of 80% underflow and 20% overflow;
- Mixture 2 (M-2): Composed of 90% underflow and 10% overflow;
- Sandy tailings (ST): Consisting entirely of underflow (100%).

These proportions are selected based on improved strength and deformation characteristics with increasing sandy tailings content, as [62] noted. Furthermore, in practical mining operations, optimum water content (w_{op}) is advantageous to be close to the initial water content of the filtered material (Table 2), minimizing the need for pre-compaction adjustments. From this perspective, ST offers the most efficient option for compaction.

The laboratory values were obtained from Standard Proctor tests, providing both average and range for maximum dry density and w_{op}. Field values for w_{op} were determined based on laboratory results and practical workability for field compaction. The initial water content represents measurements collected over one year from the IOTs.

The selected mixtures align with findings from previous studies, including [43–45,47,62,63]. This procedure aims to assess the compaction behavior of tailings with varying fine content. Fig. 1 shows the upper and lower limit for all the 103 particle size distribution tests for three materials.

Table 3 presents the average grain size distribution and specific gravity (G_s) of each type of material. The higher G_s mainly affects the dry density scale, not the fundamental shape of the compaction curve. This

Table 1
Summary of factors affecting soil compaction, grouped by category and referenced by key literature.

Group	Factor	Authors
Soil properties	Optimum water content (w_{op})	[8,12,41,42]
	Soil type (Grain-size, Atterberg limits, organic content)	[12,16]
	Mixture of material/binder	[16,43–45]
	Breakage	[46–48]
	Distribution of water content	Not found
Geotechnical work	Number of passes	[12,41,49]
	Speed of travel	[12,38]
	Thickness of the compacted layer (depth)	[12,41]
	Contact pressure (tire pressure, track type, roller type)	[12,24]
	Equipment weight	[12]
	Type of compactors (vibration)	[12,38]
	Slope	[24]
Other	Temperature	[12]

Table 2
Water contents and related quantities for each material type.

Material type	Maximum dry density (g/cm^3)	Laboratory w_{op} (%)	Proposed field w_{op} (%)	Initial water content (%)
M-1	1.942 (1.872-2.012)	12.3 (10.5–13.8)	10.5–13.0	14.4–15.2
M-2	1.955 (1.867-1.955)	11.9 (9.8–13.6)	10.5–12.5	14.6–14.9
ST	1.783 (1.691-1.913)	15.4 (13.0–16.5)	13.0–16.5	16.4

Table 3
Characteristics of the tailing types analysed in this study.

Material type	Clay (%)	Silt (%)	Fine sand (%)	Medium sand (%)	10μ (%)	Gs	Number of tests
M-1	5	39	47	9	13	3.055	40
M-2	4	33	54	9	8	3.074	35
ST	3	26	61	10	5	3.027	28

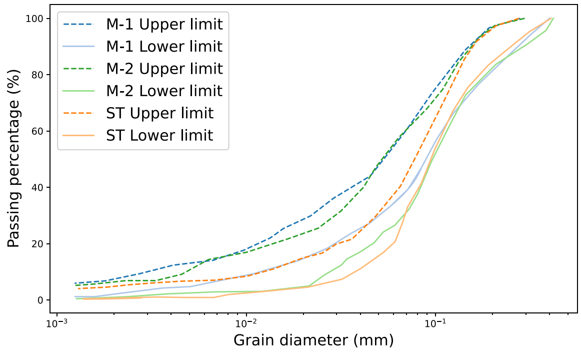

Fig. 1. Upper and lower limit on grain size tests for each type of material.

occurs because tailings have a weaker capillary structure than natural soils.

There, the column labelled 10μ indicates the percentage of particles with sizes $\leq$ 0.01 mm. The number of tests performed on each material is also provided in Table 3. Notably, the coefficient of variation (COV) for the specific gravity values ranges from 2.29 to 2.57%. These values are compatible to the ones in the literature for tailings. For comparison, ElGhoraiby et al. [64] reported a COV of 0.78% for specific gravity tests on Ottawa sand, which is a more controlled and less diverse material than tailings in general. All materials in this study are classified as non-plastic, with a Unified Soil Classification System (USCS) classification of SM (silty sand).

2.2. Methods

Compaction laboratory tests were performed to ensure the degree of compaction (DoC) of materials. The degree of compaction (DoC) is a dimensionless parameter used to quantify how dense a compacted soil, granular material or filtered iron ore tailings (IOTs) is relative to a reference maximum density obtained under controlled laboratory conditions. It is commonly defined as the ratio between the field dry density and the maximum dry density obtained in a laboratory compaction test, such as the Proctor test [65].

Field tests were executed to evaluate these properties, including the collection of field cores from each layer and laboratory tests to determine the optimum water content and dry density. The scope of this study is restricted to surface compaction, and therefore neither liquefaction nor long-term consolidation is investigated.

2.2.1. Experimental embankments: ranges of compaction parameters

Experimental tailing embankments with different sections were designed to accommodate the different combinations of number of passes of the compaction equipment and its vibration frequency. The equipment's low (LF) and vibration high frequency (HF) settings were evaluated. Also, different layers of the embankment have different thicknesses. Fig. 2 presents the configuration of the mentioned structure. The region of interest is concentrated inside Detail 1 of that figure, because the lateral confinement is smaller closer to the slopes of the embankment and that can influence the observed results.

The compaction equipment used to obtain the data presented in this paper is a single-drum smooth vibration roller weighing 20 tons with low and high frequency modes, each having, respectively, a 27 or 30 Hz frequency, a vibration amplitude of 2.05 or 1.22 mm, and a centrifugal force of 331 or 242 kN. The static linear load of the machine is 61.7 kg/cm. The prescribed velocity was 3 km/h.

Tailings were deposited on the structure by a tipper truck. After that, the material was spread by a D8 type crawler tractor inside the region indicated by the pre-positioned stakes indicating the planned thickness of the layer. The leveling of the material before starting the compaction was done by a motor grader.

Two separate embankments were built, both according to the plant presented in Fig. 2. The first embankment, hereinafter referred to as ex-

Table 4
Thickness and water contents from layers in the experimental piles.

Pile	Material type	Layer	Thickness (cm)	Water content from filtering plant (%)	Water content at compaction (%)
1	M-1	7	70	14.2	12.1
		8	50	12.7	10.8
		9	50	13.8	13.5 (wetting)
		10	50	16.3	10.6 (drying)
		11	50	12.2	8.9 (drying)
		12	50	12.0	10.9 (drying)
1	M-2	1	50	15.0	10.2
		2	50	16.0	10.7
		3	50	13.7	12.9 (wetting)
		4	30	13.7	12.6 (wetting)
		5	70	13.7	10.3
		6	30	14.2	13.3
2	ST	1	50	15.5	11.3
		2	50	16.0	14.0
		3	70	14.7	14.0 (wetting)
		4	100	18.0	12.1
		5	70	13.2	12.6
		6	50	10.0	10.3

Table 5
Material properties and statistical analysis results.

Material type	$\gamma_{d,max}$ (g/cm^3)		w_{op} **(%)**		Number of tests	Kolmogorov-Smirnov
	Average ($\bar{X}$)	COV (%)	Average ($\bar{X}$)	COV (%)	(N)	(p-value)
M-1	1.943	1.56	12.3	6.23	32	0.481
M-2	1.955	2.90	11.9	5.80	40	0.946
ST	1.783	2.98	15.4	7.36	28	0.788

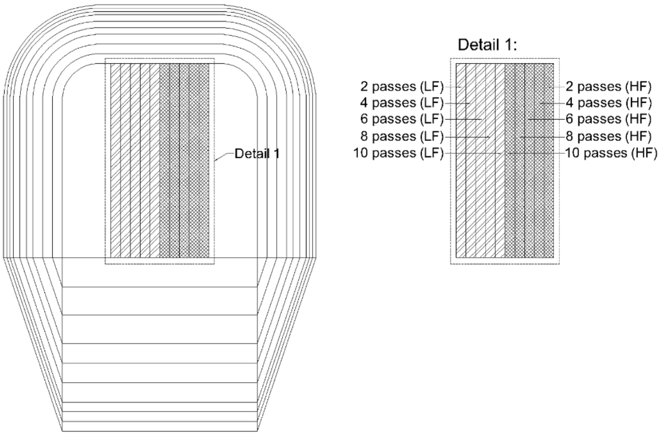

Fig. 2. Top view and detail of the experimental dry stack and compaction scheme.

perimental embankment 1, consists of 12 layers, lateral slope steepness of 2.5H:1.0V and a final height of 6 m. The second embankment, hereinafter referred to as experimental embankment 2, consists of 6 layers of a single material, which is sandy tailings (ST). Its final height is 3.9 m, and the slope steepness is 2.0H:1.0V. Table 4 presents the thickness and composition of each layer.

Regarding compaction humidity, the remaining water content from the filtering plant exceeded in most cases the optimal one determined by the Standard Proctor test, described in Table 2. After the tipping and levelling, however, this water content was usually smaller than the optimum, and thus the material required the addition of water and harrowing for homogenization. To achieve the optimal water content, some layers underwent wetting, other drying and other were compacted as they were. Table 4 presents the water contents from the filtration plant and later at compaction. Some layers were intentionally compacted outside the optimal water content range to evaluate its influence.

3. Results and discussion

Results are discussed in terms of laboratory test values in Section 3.1 and in terms of field compaction parameters in Section 3.2. After that, literature comparisons will be drawn in Section 3.3.

3.1. Maximum dry density and optimum water content analysis

In Table 5 it is observed that the maximum dry density ($\gamma_{d,max}$) shows similar values for both mixtures (M-1 and M-2), while the values for sandy tailings (ST) are comparatively lower. The coefficients of variation (COV) for $\gamma_{d,max}$ fall below the average reported in the literature (7%) and are within the lower range (2-13%) documented by [66–68].

Regarding the optimum water content (w_{op}), the average values for M-1 and M-2 are similar, while the average for ST is notably higher. The COVs for w_{op}, while higher than those for maximum dry density, fall within the range of 5.80 to 7.36%, which is reasonable given the variability expected in such materials.

To assess whether the data for w_{op} followed a normal distribution, a Kolmogorov-Smirnov (K-S) test was conducted. The results showed that the p-values for M-1, M-2, and ST were all greater than the significance level of 0.05, indicating that the null hypothesis of normality could not be rejected. Therefore, it can be concluded that the optimum water content for all three materials follows a normal distribution, as the p-values exceeded 0.05, which is the commonly accepted threshold for determining statistical significance in normality tests.

Table 6 presents the range of optimum water content required to achieve a DoC higher than 95%, based on compaction curves. Materials falling outside this range are considered out of specification materials. For the sandy tailings, the range of w_{op} is substantially larger than for the other two materials. Because of that, its w_{op} when leaving the filtration station is usually adequate for compaction without further additions of water or drying. For this material, it was also observed during the experimental work that its w_{op} reduces rather fast when manipulating it, suggesting compacting the material without it being first exposed or stored

Table 6
Range of OWC required to achieve a degree of compaction DoC higher than 95%, based on compaction curves.

Material type	Range of w_{op} (DoC ≥ 95%)	68% values $[\bar{X}-\sigma; \bar{X}+\sigma]$	95% values $[\bar{X}-2\sigma; \bar{X}+2\sigma]$
M-1	[10.5–13.5]	[11.6; 13.1]	[10.8; 13.9]
M-2	[10.5–12.5]	[11.2; 12.6]	[10.5; 13.3]
ST	[13.0–16.5]	[14.2; 16.5]	[13.1; 17.6]

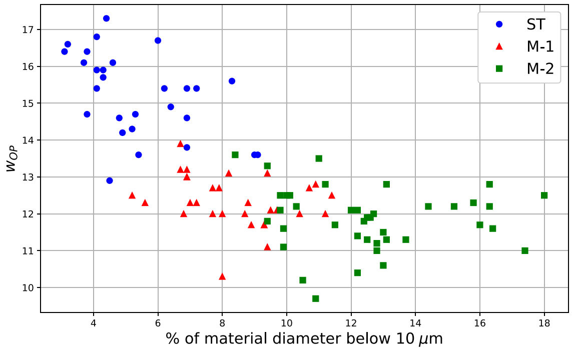

Fig. 3. Post compaction OWC versus diameter below 10μ.

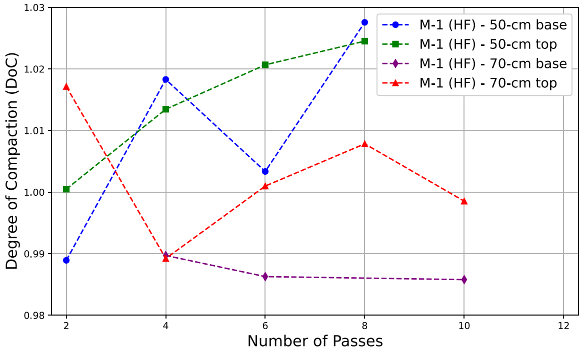

Fig. 4. M-1 ° of compaction values for high-frequency roller.

exposed to atmospheric humidity levels and, by doing so, avoiding the need to moisten it again.

The acceptable range of OWC (w_{op}) used in this project for M-1, M-2, and ST are 3, 2, and 3.5%, respectively, according to the second column of Table 6. Compared to M-1 and M-2, ST is less sensitive to water content variations. It is important to note that for all 28 compaction tests, when the water content is less than or equal to 20%, the DoC remains equal to or greater than 95% for this material. However, other factors, such as workability, must be considered when dealing with material that has high water content and is far from the OWC.

Further analysis reveals that the range of optimum values lies within 81.8% of the water content values, specifically between $[\bar{X}-2\sigma; \bar{X}+2\sigma]$. This suggests that the variation in standard deviation on the dry side is less sensitive to changes in DoC than on the wet side. This simplification should be verified with laboratory results and can serve as a preliminary estimate for the compaction range 68% and 95% of w_{op}.

Fig. 3 shows the results of grain size analysis post compacting test, indicating that adding overflow material reduces the OWC values. It is essential to point out that this addition also increases the dry density (1.88 to 2.84 g/cm^3) [48,69], as the characteristic of this overflow material is iron oxide, which has a solid density between 3.59 to 3.97 g/cm^3 [70].

3.2. Field compaction

Compaction behavior of filtered iron ore tailings differs in several fundamental ways from the classical framework developed for natural soils (sands, silts, and clays). The classical compaction theory (largely based on the work of Ralph Roscoe Proctor and the Proctor compaction test) assumes soils with typical mineralogy (mainly quartz), moderate particle density, and relatively stable grain shapes. When applied to filtered iron ore tailings, however, several mechanical aspects differ from those typically observed in natural sands or silts due to mineralogical composition, particle density, grain morphology, and the presence of very fine fractions originating from the overflow of beneficiation processes [71–73].

Field compaction results will be presented in the following subsections as a function of number of passes, layer thickness, water content, and vibration during compaction. Because field compaction tests are subject to variability arising from mineralogical heterogeneity and operational factors, the results carry an inherent degree of uncertainty that lies within standard reproducibility limits.

With respect to DoC values above 100%, they indicate a field value higher than the maximum dry density established in the laboratory. That occurs mainly for two reasons, namely, different soil composition in the field and greater compaction effort applied in the field than was planed beforehand. Values between 100 and 105% are generally acceptable, but above this range grains can start to fracture and also permeability can be affected, which can lead to issues with shear strength and drainage [74–78]. In this study, all DoC values obtained are within the acceptance range. In case they were in the dry side, and in the hypothesis that the operation realizes that in the beginning of the dry stacking process, the designer can be consulted and can evaluate the static performance of the material, check if the strain behaviour is still dilating, and either change the acceptance criteria for the compacted material or reject the operation completely.

3.2.1. Influence of passes and of layer thickness

The number of passes is a critical factor compaction. Increasing the number of passes generally increases the dry density [7,8,49]. As illustrated in Fig. 4, it was observed that two passes were sufficient to achieve a degree of compaction of at least 95% for M-1 material with high-frequency compaction. Notably, the effect of additional passes is more pronounced in a 50-cm layer compared to a 70-cm layer, where there is even a decrease in the degree of compaction. Physical properties and depth determine the differences in compaction progression [24,79]. Regarding the effect on the top and base, the 50-cm layer appears more uniform than the 70-cm layer, which shows a higher non-uniformity with a gap around DoC = 1%. According to the technical literature, the most significant impact of compaction occurs during the initial passes [80–82].

For M-2, two passes were sufficient to achieve a degree of compaction of at least 95%. This was consistent regardless of whether the water content in the material was below the lower limit or above the upper limit, as 95% compaction was achieved with four passes. As shown in Fig. 5, the effect of the number of passes on M-2 increases for the 50-cm top layer and the 30-cm first and second layers. The 50-cm base layer remains relatively unchanged between 2 and 10 passes, but it still closely aligns with the values observed for the 50-cm top layer.

Fig. 6 presents the ST DoC values for different layer thicknesses: 50 and 100 cm. It can be observed that the ST values for the base layer

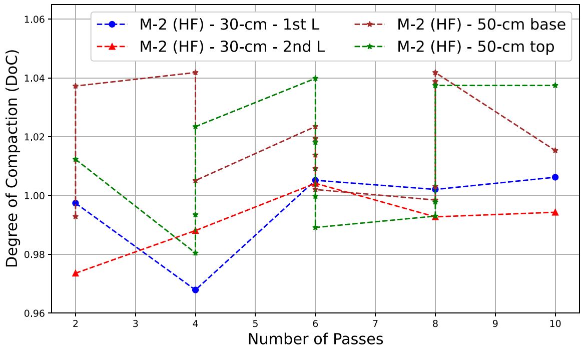

Fig. 5. M-2 ° of compaction values for high-frequency roller, considering first layer (1*st* L), and second layer (2*nd* L).

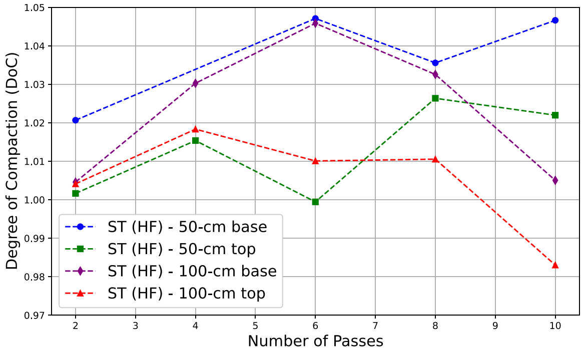

Fig. 6. ST degree of compaction values for high-frequency roller.

are higher than those for the top layer. This trend is also evident for the 100-cm layer, where the base values are higher than the top values. For this layer, it observed shows no significant change with additional passes. Analysis of the raw data suggests that the highest value is observed around six passes. Acceptable results could be shown for 100-cm layer if a high-frequency roller was used.

Notably, in natural soils, particularly sands and silts, compaction is predominantly governed by particle rearrangement, where grains slide, rotate, and reposition into a denser configuration under applied energy. Because most natural granular soils are composed mainly of quartz particles with relatively high mechanical strength, grain breakage during typical compaction efforts is limited. In contrast, mining tailings, especially those generated by grinding processes, commonly contain angular particles with internal microfractures and weaker mineral structures. As a result, compaction in tailings often involves a combination of particle rearrangement and particle crushing, where part of the applied energy is consumed in grain breakage, progressively modifying the particle size distribution and soil fabric [83,84].

When degrees of compaction exceeding 100% (DoC > 1.00) are achieved, the structural implications also differ. In natural soils, such values usually reflect differences between field and laboratory compaction energies and remain largely associated with enhanced particle packing. In mining tailings, however, high compaction levels frequently indicate significant particle breakage and fabric alteration, resulting in denser but mechanically different structures. This process may increase stiffness and reduce permeability but can also generate higher fines content and potentially more brittle behavior, meaning that the apparent densification may not necessarily correspond to improved long-term mechanical stability. Lower permeability, when associated with contractive materials, might also indicate liquefaction risk [85].

3.2.2. Influence of water content

As is well known, the influence of water content changes the behavior of all types of soil-like materials. Fig. 7 illustrates the behavior of mixtures M-1 and M-2 compared to out-of-spec materials, which fall outside the proposed water content range presented in Table 6. It is observed that out-of-specs materials, such as this instance of M-1, could not achieve the desired degree of compaction even after ten passes. It is crucial to note that completing the desired degree of compaction is not the only factor; ease of field compaction is also essential.

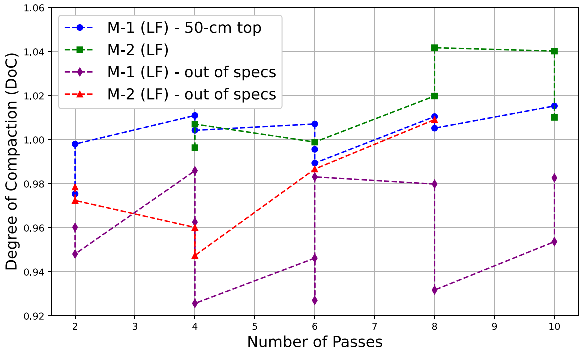

Fig. 7. Number of passes x DoC for out-of-specs and according to specifications materials.

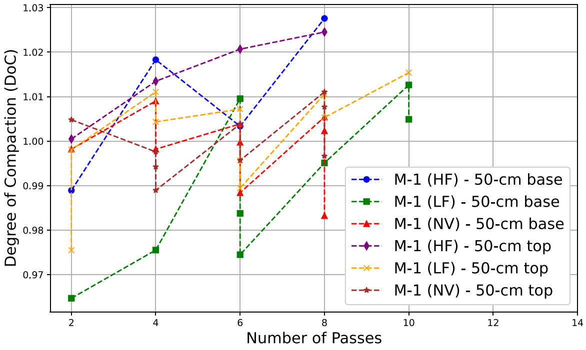

Fig. 8. Number of passes x DoC for 50 cm top and base layers of M-1 compacted with HF and LF.

Water plays a somewhat different role in tailings compaction due to the larger specific surface area and physicochemical characteristics of iron oxide minerals. At lower moisture contents, stronger capillary forces can develop between particles, creating an apparent cohesion that resists rearrangement during compaction. As moisture increases, thin films of water around the particles can facilitate sliding and rotation, promoting particle reorganization and densification. This lubricating effect can sometimes lead to slightly flatter or less defined compaction curves than those observed in classic soil compaction behavior [86]. Based on the data and records from the compaction process, out-of-spec materials fail to exhibit the desired compaction behavior.

3.2.3. Influence of vibration during compaction

Fig. 8 shows the behavior of the 50-cm top and base with high frequency (HF), low frequency (LF) and no vibration roller (NV). It is possible to notice that the higher values of DoC and higher inclination were with HF. LF has a similar inclination of HF, with initial and final values lower than HF. No vibration roller (NV) proposes a close to unchanged for the effect in passes.

Fig. 9 presents the effect of vibration on M-2 material. It is noted that for the 50-cm layer, the initial value of DoC for high frequency (HF) was higher than that for low frequency (LF), but this difference decreases with subsequent passes. This difference is less pronounced for the two 30-cm layers but is still observed.

Fig. 10 shows the ST DoC values with high frequency (HF) and low frequency (LF) for 50-cm and 70-cm layers. It can be observed that there is a 2% difference in the DoC at the bottom of the 50-cm layer, but the

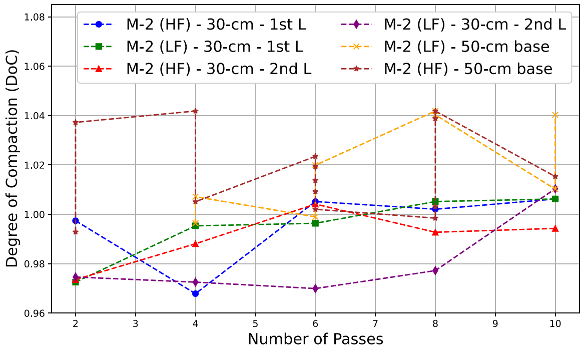

Fig. 9. Number of passes x DoC for 50 and 30 cm layers of M-2 compacted with HF and LF, considering first layer (1^{st} L), and second layer (2^{nd} L).

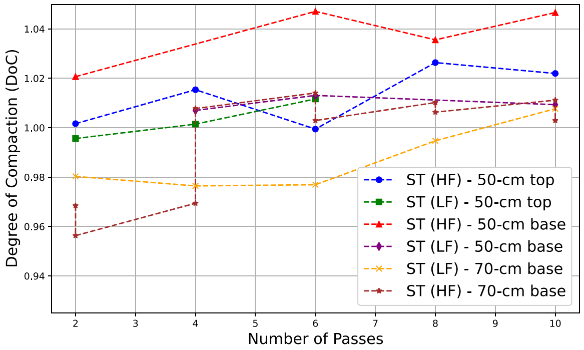

Fig. 10. Number of passes x DoC for 50 and 70 cm layers of ST compacted with HF and LF.

difference is less pronounced at the top. For the 70-cm layer, the initial values are similar for both HF and LF, however, the HF shows a higher degree of compaction by the end.

It is known that the propagation of vibrational energy also differs between these materials and natural soils due to their distinct mechanical and textural characteristics. In natural granular soils, lower damping and relatively uniform grain contacts allow vibratory stresses to propagate efficiently, facilitating particle mobility and rearrangement, particularly under low-frequency and high-amplitude vibrations [87]. Mining tailings typically present higher fines content, broader gradation, and greater internal friction, which increase material damping and reduce the efficiency of energy transmission. Consequently, vibratory energy attenuates more rapidly with depth in tailings, often following exponential decay relationships, leading to shallower effective compaction zones compared to those observed in natural sands under similar compaction energy (Fig. 8 to Fig. 10).

Additionally, particle breakage may occur more frequently in iron ore tailings than in natural quartz sands. Some tailings particles are composed of laminated or fragile mineral fragments that can fracture under compaction energy, particularly under vibratory or heavy compaction conditions. Grain breakage produces new fine particles and can allow further reduction of void spaces, sometimes resulting in continued densification even beyond what would normally correspond to the conventional optimum moisture condition.

3.3. *Comparison with literature*

Fig. 11 shows the upper and lower limits of the tests for M-1, M-2, and ST, comparing with the data from [7]. It is noted that the initial behavior, up to 4 passes, is similar to that of well-graded sand and gravel sand. However, the behavior differs for sandy clay and silty clay materials. Johnson and Sallberg [7] indicated that two passes are sufficient to achieve a degree of compaction of 95% for sandy materials.

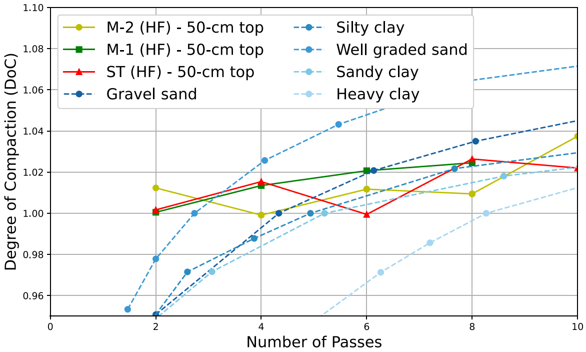

Fig. 11. Comparisons between the presented compacted materials and the ones presented in [7].

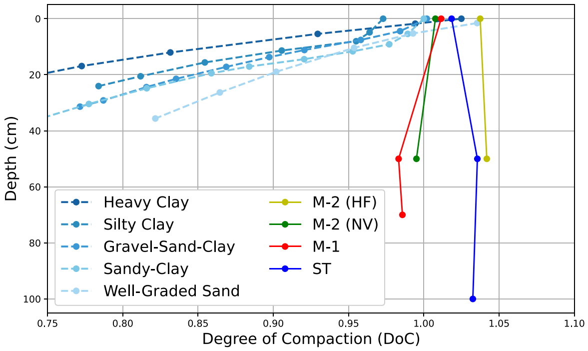

Fig. 12. Comparison between [41] and IOTs.

For silts, Thaddeus et al. (1979) highlighted that silts typically reach a DoC of around 90%. These observations emphasize that the behavior of the filtered tailings in this study aligns with the expected behavior for well-compacted geomaterials.

Another comparison can be made regarding the degree of compaction and depth. Fig. 12 shows that most of the data from [41] indicate a significant reduction in the degree of compaction, even for well-graded sand at a relatively low depth (40 cm). The degree of compaction in this data remains around 1 to 1.05. This is another positive aspect of the compaction process in this study. Notably, the trend of increasing degree of compaction with depth is consistent with the literature. Several authors have reported that the impact of compaction declines with depth, but the degree of compaction trend depends on factors such as equipment type, topographic conditions, and soil properties [7,24,79,88–91].

4. Conclusion

Nowadays, field compaction of filtered tailings is a relevant topic in the mining sector due to the limited number of studies available on the subject and also due to the transitioning tendencies from dams to dry stacking. As a result, a better understanding of key properties, such as water content, vibration technique, layer thickness, and compaction depth could significantly improve the handling of these materials in the field.

The results indicate that water content is the most critical parameter for preventing under-compaction, whereas the appropriate combination of layer thickness and number of passes can substantially reduce compaction time without compromising the quality of compaction achieved in the field. In addition, the use of vibratory compaction enhances the efficiency of the process by reducing the number of required passes and increasing the depth of energy transmission within the material.

Overall, these findings contribute to a better understanding of the compaction behavior of mine tailings and provide practical guidance for optimizing operational parameters during field compaction. Such improvements can enhance construction efficiency and support the development of safer and more stable tailings storage facilities.

CRediT authorship contribution statement

Clara M. Toffoli: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis; **Weber Anselmo dos Ramos Souza:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization; **Ana Luisa Cezar Rissoli:** Methodology, Data curation; **Anselmo José Coelho Mendes:** Methodology, Data curation; **Thiago Augusto Mendes:** Writing – review & editing, Supervision.

Data availability

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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