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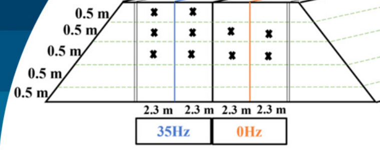

Assessment of strength and stiffness properties of compacted filtered iron ore tailings-Portland cement blends field stack

Evaluación de las propiedades de resistencia y rigidez de mezclas compactadas de relaves de hierro filtrados con cemento Portland apiladas in situ

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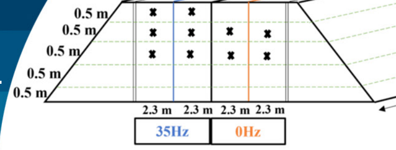
Dry stacking of iron ore tailings (IOTs) with cementitious materials is a viable disposal option, but its large-scale implementation faces challenges. Therefore, this study investigates the key factors influencing compaction in real field conditions, including moisture content (optimum moisture content and less than optimum moisture content), vibration frequency (0 Hz and 35 Hz), and number of roller passes (4P and 6P). To achieve this objective, an experimental IOT stack was constructed in five different layers using a specific amount of Portland cement as a cementing agent (2.5% by dry solid weight). Then, laboratory tests, such as unconfined compression, splitting tensile, and ultrasonic pulse velocity (UPV), were conducted on undisturbed samples to evaluate the unconfined compressive strength (q_u), splitting tensile strength (q_t), and initial shear modulus (G_0). Based on the laboratory tests conducted on the field-collected specimens, it was concluded that samples with moisture contents closer to the optimum moisture content (OMC), exposed to vibration, and subjected to six-roller passes exhibited superior mechanical performance. This study provides insights into optimizing the compaction process for large-scale IOT stack structures.

Keywords: iron ore tailings (IOTs), experimental stack, undisturbed samples, compressive strength, tensile strength, shear modulus

El apilamiento en seco de relaves de hierro (RH) con materiales cementantes es una opción viable de depósito, pero su implementación a gran escala enfrenta desafíos. Por lo tanto, este estudio investiga los factores clave que influyen en la compactación en condiciones de terreno reales, incluido el contenido de humedad (contenido de humedad óptimo y contenido de humedad inferior al óptimo), frecuencia de vibración (0 Hz y 35 Hz) y el número de pasadas de rodillo (4P y 6P). Para lograr este objetivo, se construyó una pila experimental de RH en cinco capas diferentes utilizando una cantidad específica de cemento Portland como agente cementante (2.5% en peso sólido seco). Luego, se realizaron ensayos de laboratorio, como compresión no confinada, tracción y velocidad de pulso ultrasónico (UPV), en muestras no perturbadas para evaluar la resistencia a la compresión no confinada (q_u), la resistencia a la tracción (q_t) y el módulo de corte inicial (G_0). Con base en los ensayos de laboratorio realizados en las muestras recolectadas en terreno, se concluyó que las muestras con contenidos de humedad más cercanos al contenido de humedad óptimo (CHO), expuestas a vibración y sujetas a seis pasadas de rodillo exhibieron un rendimiento mecánico superior. Este estudio proporciona información para optimizar el proceso de compactación para estructuras de pilas de RH a gran escala.

Palabras clave: relaves de hierro RH, pilas de ensayo, muestras no perturbadas, resistencia a la compresión, resistencia a la tracción, módulo de corte



Introduction

Large quantities of mine tailings, predominantly composed of crushed rock and processing fluids from mills, washeries, or concentrators, are generated annually (Kossoff *et al.*, 2014). Concerns have arisen regarding the potential risks associated with the production of tailings, such as contamination caused by the dispersion of dust, seepage, or the failure of tailings dam walls, as well as the direct disposal of tailings into waterways (Edraki *et al.*, 2014).

The available methods for storing these tailings, such as embankments, dams, and surface land for dry stacking, are predominantly utilized in tailings storage facilities (Amoah *et al.*, 2018; Wei *et al.*, 2013; Xu *et al.*, 2020). Dry stacking is considered one of the most advanced techniques for storing tailings and offers numerous advantages (Cox *et al.*, 2023; Li *et al.*, 2022; Wagner *et al.*, 2023). This method enhances the stability of tailings deposits while minimizing the contamination of surface and underground water. By providing an alternative to conventional slurry disposal in tailings dams, dry stacking significantly reduces the risks associated with tailings runoff and potential dam failures (Consoli *et al.*, 2022).

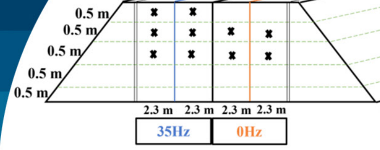
While unexpected weather conditions such as heavy rainfall can lead to the failure of traditional tailings dams, dry stacking provides increased security due to the utilization of filtered and compacted materials (Davies, 2011). Studies have shown that the dry stacking of tailings, such as implementing a dewatering plant for iron ore tailings in Brazil, can be more cost-effective and sustainable than maintaining tailings dams (Gomes *et al.*, 2016). Furthermore, the dewatering of coal tailings slurries through filtration or centrifugation techniques can transform them into a semi-solid state known as cake, which can be disposed of safely (Doi *et al.*, 2023).

To ensure the stability of the tailings, the addition of cementitious materials can further enhance the mechanical properties of the tailings (Carvalho *et al.*, 2023; dos Santos *et al.*, 2022; Mafessoli *et al.*, 2023; Servi *et al.*, 2022). Moreover, the chosen design parameters should accurately reflect the performance of the structure in real conditions (Bittar Marin *et al.*, 2023).

Various studies have investigated the impact of moisture content on different types of tailings, as it is a crucial factor in diverse geotechnical applications, including dry stacking (Osinubi *et al.*, 2015; Rima and Beier, 2022). Bastos *et al.* (2016) reported the changes in moisture content and dry density of iron ore tailings (IOTs) when different stabilizers, such as lime, Portland cement, and slag, were incorporated. They found that the chemically stabilized mixtures exhibited a decrease in maximum dry density (MDD) and an increase in the optimum moisture content (OMC) compared to the natural tailings sample. The increased fineness of the mixtures led to higher water dosages, resulting in higher OMC. Regardless of the binder type (Portland cement/lime/slag), an increase in binder content caused a reduction in the MDD of the mixtures and an increase in OMC.

Furthermore, numerous studies have evaluated the behavior of IOTs in various applications, including pavement engineering, road infrastructure, cementitious composites, and dry stacking (Djellali *et al.*, 2019; Huang *et al.*, 2013; Schatzmayr Welp Sá *et al.*, 2022). In a laboratory-scale study, Consoli *et al.* (2022) proposed stacking compacted filtered IOT–Portland cement blends for tailings disposal, considering the effects of different cement contents and compaction degrees. The presence of the binder in the mixture improved the compaction properties and reduced the liquefaction potential.

The current study aims to address the gaps in the literature regarding dry stacking applications by examining the key factors affecting the type of compaction on the mechanical behavior of cemented IOTs under real field conditions. To achieve this, an experimental stack was constructed on-site, considering variables such as compaction moisture content, exposure to vibration frequency (or not) during compaction, and the number of roller passes. The study focuses on assessing various properties, including compressive strength (q_u), splitting tensile strength (q_t), and initial shear modulus (G_0). A series of laboratory tests, namely, unconfined compression, splitting tensile, and ultrasonic pulse velocity (UPV), were conducted to determine these properties. By examining the mechanical behavior of cemented IOTs under real field conditions and comprehensively evaluating a range of geotechnical parameters, this study provides valuable insights for the design and implementation of dry stacks.



Materials and methods

The iron ore tailings used in this research to construct the piles were obtained from a dewatering plant located in Minas Gerais, southeast Brazil. These tailings are a byproduct of iron ore processing production. The grain size distribution curve of the IOTs is presented in Figure 1, and its physical characteristics are listed in Table 1. The studied tailings are classified as Inorganic silt (ML) according to the Unified Soil Classification System (USCS), with a high percentage of fine sand and silt.

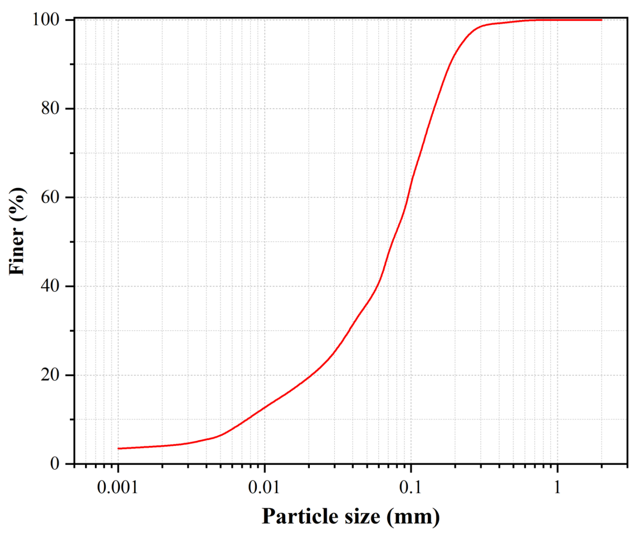


Figure 1: Particle size distribution of the studied iron ore tailings (IOTs)

Table 1: Physical properties of the studied IOTs

Physical property	Content/ Description	Standard designation
Specific gravity of solid particles, G_s	3.08	ASTM D854 (2014)
Plasticity index, %	Nonplastic	ASTM D4318 (2010)
Coarse sand (0.425 mm < diameter < 2.0 mm), %	0.00	ASTM D7928 (2017)
Medium sand (0.425 mm < diameter < 0.2 mm), %	0.00	
Fine sand (0.075 mm < diameter < 0.425 mm), %	48.00	
Silt (0.002 mm < diameter < 0.075 mm), %	48.27	
Clay (diameter < 0.002 mm), %	3.73	
Mean particle diameter, mm	0.09	
Uniformity coefficient C_u	10.47	
USCS Classification	Inorganic silt (ML)	ASTM D2487 (2011)

The Proctor compaction tests were carried out and the maximum dry densities (MDD) corresponding to standard, intermediate, and modified compaction energy were measured at 19.6, 20.07, and 20.96 kN/m^3, respectively, following the standard NBR 7182 (2020), these results are presented in Figure 2. The respective Optimum Moisture Contents (OMC) were: 11.4%, 10.05%, and 8.86%. In this study, an intermediate energy level is employed for the compaction process in the field.

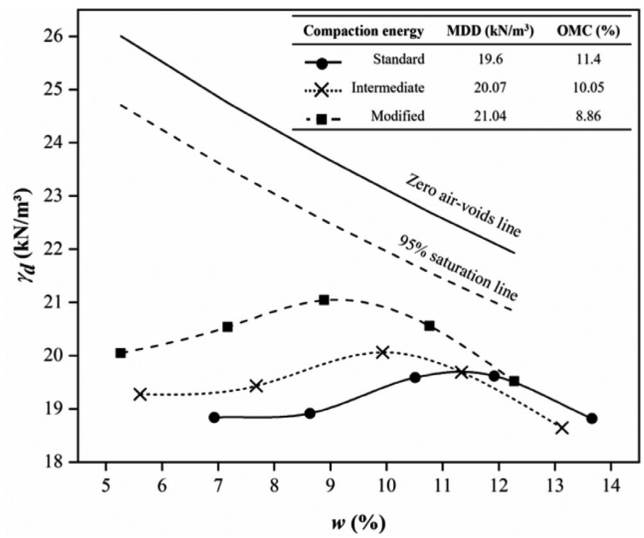
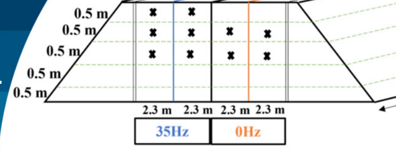


Figure 2: Compaction curves of the studied iron ore tailings at standard, intermediate, and modified energies.

As the binding material, the study employed a widely used commercial version of cement, namely high early-strength Portland cement (PC III) (ASTM C150, 2022). The cement's specific gravity was determined per the ASTM D854 (2014) and was found to be 3.05. Some preliminary laboratory tests were conducted to determine the appropriate cement content for constructing the experimental stack. A single representative cement content (PC III = 2.5%) was then selected for the construction of the experimental stack.

An experimental stack was constructed using a blend of IOTs and 2.5% Portland cement. One side of the stack was initially compacted using a vibratory roller compactor at a frequency of 35 Hz, while the other side was compacted afterward without vibration. The stack was then divided into two pieces, each compacted with a different number of roller passes (4P and 6P). The stack underwent compaction in five distinct layers to a thickness of 50 cm.



The optimum moisture content of 10%, obtained from the Proctor intermediate energy level compaction, was used as a reference. However, only layer 03 was compacted with a moisture content below the optimum level, to investigate potential variations resulting from lower moisture content acquisition due to field conditions.

The construction process began with mixing cement and filtered IOTs in a soil-cement mixing plant near the experimental field. The water was carefully measured and thoroughly mixed with the dried materials until a homogeneous consistency was achieved. It should be noted that only layers 03, 04, and 05 are the focus of this paper, as layers 01 and 02 were constructed to ensure the homogeneity of the stack foundation soil and avoid the influence of possible effects of the heterogeneity of the natural soil. The moisture content was measured both before and after compaction to monitor the underlying layers.

The mixture was then transported to the field and compacted using different numbers of roller passes with or without vibration frequency to the specified dry unit weight. It is important to note that the tailings and tailings-cement mix were tested for moisture levels using both oven drying and microwave heating methods before mixing, before compaction, and after compaction, as per ASTM D2216 (2019) and ASTM D4643 (2017), respectively.

The unconfined compression and splitting tensile tests were conducted following the ASTM D2166 (2006) and ASTM C496/C496M (2017), respectively. Both tests were performed at a constant displacement rate of 1.14 mm/min using a load cell with a maximum capacity of 10 kN. It is noteworthy that the specimens were submerged in water for 24 hours before testing to minimize suction effects, as suggested by Consoli *et al.* (2007). Ultrasonic Pulse Velocity (UPV) tests were conducted to assess the stiffness of the IOTs-PC III specimens at very small strains. The PunditLab portable device, equipped with 150 kHz transducers capable of emitting and receiving shear waves, was utilized for this purpose. These transducers were attached to the top and bottom of the samples using a coupler gel. Before the unconfined compression test specimens were immersed in water, they underwent non-destructive testing to measure their initial shear modulus.

The geometric characteristics of the stack and the configuration of each layer are presented in Figure 2. Cubic blocks with 0.3 m edge size were retrieved. They were collected from both vibrated and non-vibrated sections of the stack. Each side of the stack was divided in 4 and 6 passes of the compacting roller (4P and 6P). The points where undisturbed samples were retrieved are also depicted in Figure 3. These blocks were handled with care, wrapped in plastic film, and placed in a wooden container filled with sawdust. They were then transported to the laboratory and kept in a controlled environment room with a temperature of 23±2°C and relative humidity of 95% until they were tested.

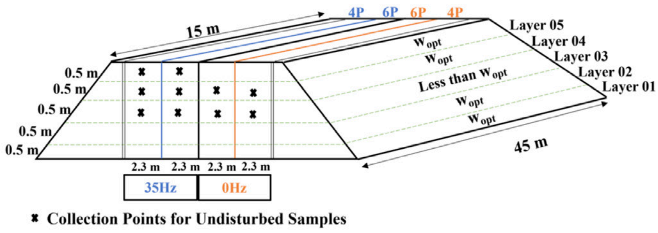


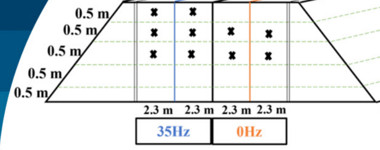
Figure 3: The geometric characteristics of the stack and the configuration of the layers.

Results and discussion

Compaction properties

Tailings stacks can have quite a bit of variation in their moisture content across different locations, depths, and even within the same pile. This makes it tough to maintain the exact OMC throughout the entire stack. Moreover, the real-world field conditions are different from the controlled lab conditions. Factors like weather, temperature, and sunlight can affect the moisture content of the tailings. It is crucial to closely monitor and adjust the moisture to ensure stability and prevent issues like excessive drying or saturation. Compaction is a key factor in constructing stable IOT stacks.

The data in Tables 2 and 3 show the compaction properties of the tested samples from layers compacted with moisture below OMC and at OMC, respectively. As can be seen, the data aligns well with the compaction curve of the tailings, indicating consistency. The OMC of the intermediate energy level (10.05%) was used as the reference for on-site stack compaction. The average moisture in the layer with less



than OMC was 6.87%, while the layer compacted at OMC had 9.73% moisture, which is very close to the laboratory measurement. Achieving the same level of compaction in the field as in the laboratory can be challenging due to the larger scale and other practical limitations.

Table 2: Details of the moisture content and dry density of the tested data points in the layer compacted with less than optimum moisture content

Unconfined compression test				Splitting tensile test			
No.	Designation	w, %	γ_d, kN/m^3	No.	Designation	w, %	γ_d, kN/m^3
1	4P-0Hz	8.61	19.50	1	4P-0Hz	8.62	19.45
2	4P-0Hz	8.41	19.38	2	4P-0Hz	7.27	19.52
3	4P-35Hz	7.35	19.87	3	4P-35Hz	7.00	19.64
4	4P-35Hz	6.83	19.57	4	4P-35Hz	7.13	19.67
5	4P-35Hz	7.47	19.74	5	4P-35Hz	7.05	19.49
6	4P-35Hz	6.96	19.17	6	6P-0Hz	6.71	18.97
7	4P-35Hz	7.04	19.39	7	6P-0Hz	6.25	18.67
8	6P-0Hz	6.31	18.50	8	6P-0Hz	6.22	18.98
9	6P-0Hz	6.40	18.67	9	6P-0Hz	5.46	18.54
10	6P-0Hz	7.23	19.21	10	6P-35Hz	6.56	19.56
11	6P-0Hz	7.10	19.00	11	6P-35Hz	6.00	19.75
12	6P-35Hz	6.22	20.07				
13	6P-35Hz	6.94	19.85				
14	6P-35Hz	4.52	19.38				

Table 3: Details of the moisture content and dry density of the tested data points in the layer compacted with optimum moisture content

Unconfined compression test				Splitting tensile test			
No.	Designation	w, %	γ_d, kN/m^3	No.	Designation	w, %	γ_d, kN/m^3
1	4P-0Hz	10.07	19.74	1	4P-0Hz	10.29	20.00
2	4P-0Hz	9.83	20.00	2	4P-0Hz	11.12	19.62
3	4P-0Hz	10.08	19.57	3	4P-35Hz	8.76	20.25
4	4P-0Hz	10.55	19.61	4	4P-35Hz	9.63	20.31
5	4P-35Hz	8.91	20.41	5	4P-35Hz	8.93	19.55
6	4P-35Hz	9.21	20.51	6	4P-35Hz	9.16	19.78
7	4P-35Hz	10.17	19.74	7	6P-0Hz	11.65	19.71
8	4P-35Hz	9.79	19.61	8	6P-0Hz	9.14	20.07
9	6P-0Hz	11.16	19.73	9	6P-0Hz	9.76	19.83
10	6P-0Hz	8.62	20.17	10	6P-35Hz	8.92	19.92
11	6P-0Hz	10.11	19.71	11	6P-35Hz	10.04	19.46
12	6P-35Hz	8.60	20.17	12	6P-35Hz	9.01	19.88
13	6P-35Hz	9.25	19.96				
14	6P-35Hz	10.34	19.45				

Strength and stiffness properties

Figures 4, 5, and 6 illustrate the variations in the unconfined compressive strength q_u, splitting tensile strength q_t, and initial shear modulus G_0 of undisturbed samples retrieved from different constructed layers with varying moisture contents. The figures show that similar trends can be observed in the variations of strength and stiffness properties.

As can be seen from Figures 4 and 5, the range for q_u is between 505 and 882 kPa, and the range of q_t for the undisturbed samples falls between 70 and 140 kPa. Furthermore, based on Figure 6, the range of G_0 is found to be between 1349 and 1774 MPa.

From the results of these figures, it can be concluded that an increase in the number of roller passes improves the strength and stiffness properties of the compacted IOT stacks. Specifically, the sample taken from layer 04

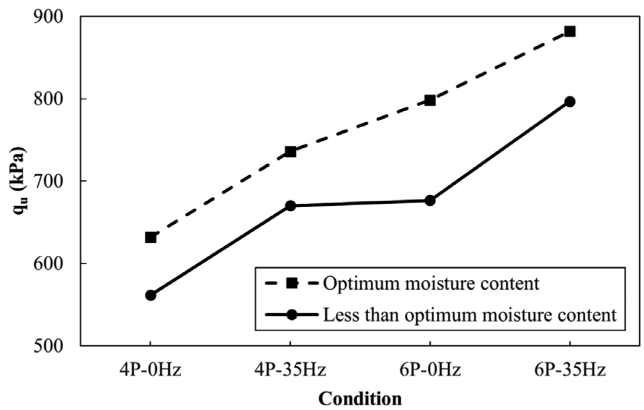


Figure 4: Variations of q_u versus different moisture contents, vibration frequencies, and the number of roller passes

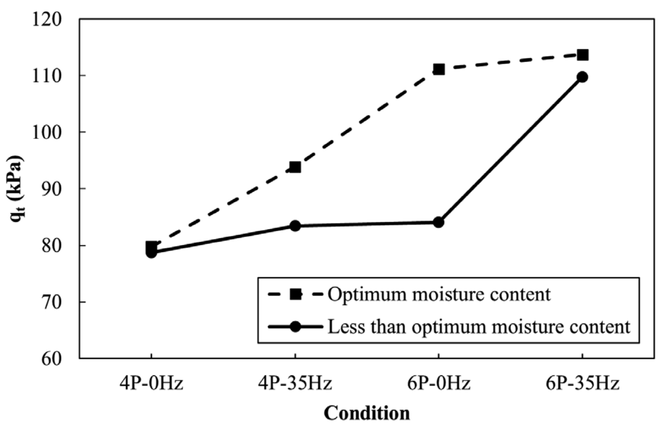
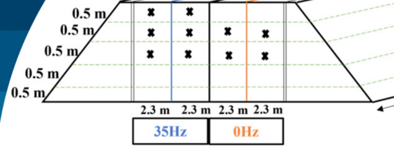


Figure 5: Variations of q_t versus different moisture contents, vibration frequencies, and the number of roller passes



(compacted at the optimum moisture content) reached a q_u value of 881.9 kPa, while the G_0 value reached 1774.8 MPa in the sample from layer 03 (compacted at a moisture content less than the optimum).

Furthermore, the samples subjected to vibration frequency exhibited higher strength and stiffness values compared to those without vibration frequency. It is worth noting that the strength ranges of all the samples meet the requirements for dry stacking applications.

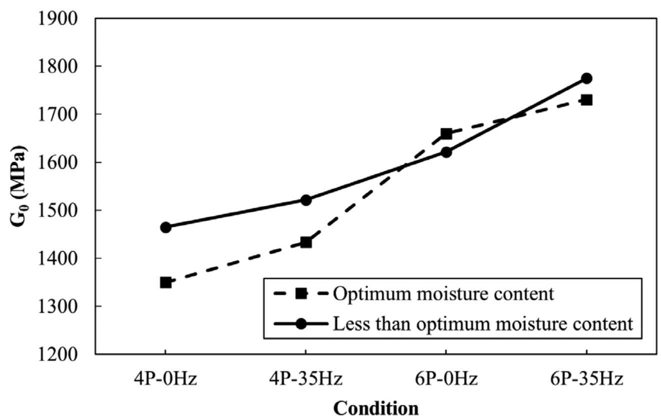


Figure 6: Variations of G_0 versus different moisture contents, vibration frequencies, and the number of roller passes

Conclusions

The purpose of this study was to investigate the mechanical performance of a constructed stack by applying the practical technique of dry stacking in real-world conditions. This was accomplished by blending iron ore tailings and Portland cement (IOTs-PC III blends) and considering various influential factors on-site, such as moisture content, vibration frequency, and the number of roller passes. The results showed similar trends in the variations of compressive strength, splitting tensile strength, and initial shear modulus properties. The study concluded that increasing the number of roller passes improved the strength and stiffness properties of the stack. Also, the samples subjected to vibration frequency exhibited slightly higher strength and stiffness values compared to those without vibration frequency.

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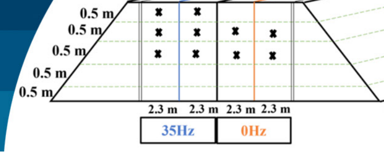

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