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Unlocking the benefits of using recycled wastes in geotechnical tailings treatment: A sustainable approach

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Abstract

Purpose. This paper aims to establish a robust soil treatment plan designed to enhance the geotechnical engineering properties of tailings. The study evaluates the efficacy of various soil additives, including both traditional and non-traditional types, in reinforcing tailings dam materials.

Methods. A comprehensive experimental program was conducted, where polymeric resin and a combination of recycled gypsum (B), cement kiln dust (CKD), and ordinary cement (OC) were added to tailings in a controlled laboratory setting. The assessment methodology included unconfined compressive strength (UCS) tests to determine the optimal treatment percentage, Oedometer tests to evaluate stiffness and consolidation properties, and direct shear strength tests to assess the material's response to shearing.

Findings. The study provides valuable insights into the performance of the CKD:B compound, revealing a critical OC percentage that must be maintained to prevent sample dissolution in water due to anhydrate presence. The tailings treated exhibit improved mechanical properties, contributing essential data that can support numerical modeling for assessing the stability of tailings dams.

Originality. This research offers novel data on tailings treatment, particularly regarding the combination of CKD and B with OC. The study's findings advance understanding in the field by identifying the optimal conditions for enhancing tailings dam stability, which has not been extensively explored in previous literature.

Practical implications. The results of this study contribute to improved tailings storage facility management and environmental best practices. By optimizing soil treatment strategies, the research supports more effective utilization of natural resources and enhances the safety and sustainability of tailings dam structures.

Keywords: *tailings storage facilities, geohazards, soil improvement, waste management, recycling*

1. Introduction

Mining activities generate tailings as a secondary product, resulting from the process of crushing and grinding rocks to extract the valuable "ore". Typically, the ore content within the raw material ranges from 40 to 0.4%, leading to the disposal of significant volumes of mined materials daily into tailings storage facilities (TSFs) [1]. A single mine may generate tailings ranging from 1 to 6 million cubic meters annually. TSFs come in various types, broadly categorized as manmade and natural. Manmade TSFs are further classified into three major sub-divisions: upstream, downstream, and centerline methods.

Significant strides have been made in researching and enhancing the performance of traditional earth dams, resulting in a mature understanding of established design practices and construction methods. This effort has yielded robust design principles, management guidelines, and construction methodologies. In contrast, tailings dams have historically received scant attention from researchers. However, this narrative has begun to shift, likely spurred by documented instances of tailings dam failures [2]-[4]. Despite the newfound focus, the incidence of tailings dam failures has surged notably over the past two decades, with an average of two to five major failures occurring annually [2], [5]. This alarming trend far surpasses the failure rate observed in conventional earth dams. Consequently, there is an urgent imperative for a thorough analysis and assessment to uncover prevalent failure modes and their root causes.

Comprehensive risk assessment studies are, therefore, crucial to evaluate the environmental and geohazard risks associated with TSFs and to aid decision-making in mitigating these risks to the surrounding environments and communities, promoting sustainable mining development [3], [6]-[8]. One significant risk is slope instability of TSFs, which, if occurs, can result in the catastrophic release of large volumes of stored tailings into nearby habitats and ecosystems. Such events can pose significant challenges, with consequences that may be long-lasting. An illustrative example is the Bent-Rodrigues mine tailings failure of 2015, where an upstream tailings dam for iron ore collapsed, result-

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ing in the loss of many lives and the discharge of millions of toxic materials into surrounding rivers, leading to one of the largest legal disputes in history.

Extensive investigations of tailings dam failures over a century have identified key risk factors affecting both active and abandoned dams [9]. These include Construction methods, compaction issues, elevated fine contents, heightened PP. weak foundation materials, inadequate consideration of excess pore water pressure during design, earthquake loading, static liquefaction.

To illustrate, the tailings dams failure can occur due to excessive deformation at the embankment's crest or toe, often caused by construction on weak foundation materials like soft clay. Furthermore, inadequate consideration of excess pore water pressure during the design phase can lead to elevated water tables in the dam body, exacerbating risks. Earthquake loading poses another significant risk, inducing cyclic shearing forces capable of liquefying parts of the dam body or its foundation soil, thus reducing shear strength. Static liquefaction may also occur if the time interval between successive layer placements is insufficient for the dissipation of generated pore water pressure. This phenomenon is believed to be a primary factor in reported failures of normally consolidated tailings dams, where stability relies on effective shear strength at the slip surface; a decrease in effective strength correlates with a reduction in the factor of safety [6], [10]. These findings underscore the critical importance of sound design and construction practices in the mining industry, necessitating tailings dam designs that meet safety standards and robust construction methodologies to ensure stability under various loading conditions.

Among the three primary construction methods, the upstream approach is most commonly used due to its efficiency in managing large volumes of tailings [11], [12]. This method involves building a dyke to contain early waste, gradually raising its height "upstream" toward the TSF center. However, a key drawback is its susceptibility to seismic activity, leading countries like Chile to abandon it for safety reasons [13], [14]. Consequently, mining companies must explore alternative methods, increasing costs and time for construction. In contrast, the downstream and centerline methods have a lower risk of failure [15], [16]. Environmental risks from TSFs include leaching of toxic materials, overtopping, and acid mine drainage (AMD). Despite these risks, the upstream method is favored for its cost-effectiveness and simplicity. TSF performance is typically evaluated through finite element modeling and field observations of crust movement, cracks, and pore pressure. Inclinometers and pore pressure transducers are used, along with geochemical sampling to control spills proactively.

This paper aims to enhance the tailings used for constructing upstream tailings impoundments, as literature indicates they are most likely to fail and have frequently experienced major incidents [3].

In this study, we introduce a novel treatment approach for slurred tailings sourced from a gold mine in Northern Ontario. Our objective is to enhance the performance of tailings management under wet disposal methods. A key focus of our research is the utilization of ecofriendly recycled materials to optimize the disposal process in an environmentally friendly and efficient manner. Through chemical analysis, sedimentation column tests, consolidation tests, and shear strength evaluations, we compare the properties of treated and untreated tailings. The insights gleaned from this investigation offer valuable perspectives on tailings management strategies and contribute to mitigating associated risks.

2. Methods

2.1. Scope of work

A detailed experimental program was conducted to study the impact of additives on tailings under compression and shearing. The process involved assessing the physical properties of tailings and additives, then mixing them to enhance stiffness and strength. The dual objectives were to use waste materials as additives and improve the geotechnical properties of tailings. Figure 1 illustrates the treatment methodology. Optimization techniques determined the optimal admixture percentage, followed by oedometer and direct shear tests. All tests adhered to ASTM standards.

Figure 1. Proposed treatment scheme

Traditional additives like lime, cement, fly ash, recycled gypsum, cement kiln dust, and slag furnace are common, while newer options include polymeric derivatives, fibers, and emulsified polymers. Traditional and non-traditional additives were tested in controlled lab studies to evaluate their effect on shear strength, addressing TSF failure issues linked to tailings' inherent weaknesses. As the non-traditional additives results were not promising, their results have been excluded from this study. Tailings samples from Golder Associates, Northern Ontario, were analyzed for physical, chemical, and mechanical properties. Notably, hazardous materials like Arsenic, Cadmium, Chromium, and Lead were found in concentrations exceeding Canadian Drinking Water Guidelines' Maximum Acceptable Limits (MAC) by significant margins.

ASTM procedures and the Unified Soil Classification System (USCS) (ASTM 2487) classified the soil as silt. Results, shown in Figure 2 and Table 1, detail the mean particle size, D_{50}%, effective particle size D_{10}%, coefficient of uniformity (C_u), and coefficient of curvature (C_c). The oven-dried tailings were sieved through a #40 U.S. sieve, crushed, and tested for liquid limit (LL), plastic limit (PL), and plasticity index (PI) using Casagrande's apparatus (ASTM D4318). The tailings were classified as low plasticity silt, ML.

2.2. Testing program

Traditional additives admixtures of recycled gypsum and cement kiln dust have been used to assess the strength and stiffness gain when added to tailings.

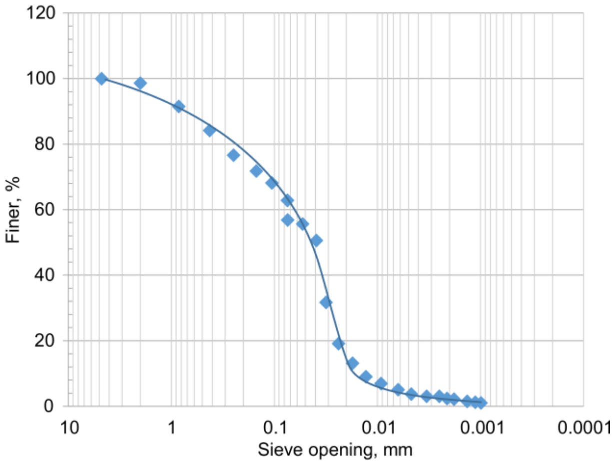

Figure 2. Sieve analysis test and hydrometer test's graph for tailings

Table 1. General physical properties of tailings

Index parameters	Value
USCS of the tailings	ML
Mean particle size, D_{50} (mm)	0.045
Effective particle size, D_{10} (mm)	0.0175
Coefficient of uniformity, C_u	3.4
Coefficient of curvature, C_c	0.8
Liquid limit, LL (%)	48
Plastic limit, PL (%)	NP
Liquidity index, LI	1.34
Specific gravity, G_s	2.69

These additives are commonly used in practice, which have been known for a very long time (sometimes dating back to prior B.C) such as lime, cement, fly ash, gypsum, cement kiln dust and slag furnace. The aim of using these two types of binders was to improve the strength and stiffness of the tailings. The testing program involved unconfined compressive strength testing for optimization purposed.

2.3. Optimization study

Initially, an optimization study was conducted to assess the effectiveness of traditional additives in enhancing the strength of tailings. Recycled gypsum (referred to as B) was blended with cement kiln dust (CKD) at various ratios, and these mixtures were combined with tailings at different percentages. The recycled gypsum was milled and sieved through #20 U.S sieve and heated for at least 2 hours in oven at temperature of 140°C. Figure 3 shows the recycled gypsum and the final product, bassanite.

Figure 3. Preparation of bassanite: (a) recycled gypsum (B) ready for grinding; (b) final product

Similarly, the CKD was milled and sieved through #40 US sieve. The recycled gypsum and CKD were then mixed together. The mixture was then proportioned according to Table 2 and dry mixed before slowly being added to the slurry while being stirred. The additives were incorporated at levels of 5, 10, and 20% of the total weight of the tailing's samples. Subsequently, batches were cast in plastic molds and subjected to unconfined compression strength (UCS) testing at 7 and 14 days. This investigation aimed to analyze the impact of increasing recycled gypsum percentages on the mix composition. Upon evaluating the effects of gypsum across different proportions, the optimal B:CKD ratios were identified and subsequently applied throughout the remainder of the study. The recycled gypsum and CKD were then mixed. The mixture was then proportioned according to Table 2 and dry mixed before slowly being added to the slurry while being stirred.

Table 2. Laboratory test matrix

Category	% of admi. / Ms	Compound	# of samples			Purpose / notes
			UCS	Oedometer	DST	
A. Optimization study	5	1CKD:1B:0.1OC	9	–	–	Define optimum treatment percentage
	10	10-1,10-2,10-3	27	–	–	
	20	20-1	9	–	–	
B. Stiffness and Strength evaluation	10	1CKD:1B	–	2	6	Little improvement when soaked in water
	7.5	0.45CKD:0.45B:0.1OC	–	2	6	Overcome solubility of anhydrite
		1CKD:1B:1OC	–	2	6	

2.3.1. Unconfined compressive shear strength

UCS tests were performed on treated tailings specimens with additives (CKD:B mixture) at 5, 10, and 20% by weight, following ASTM (D2166) standards. Additives were mixed into slurried tai-lings using a hand mixer for homogeneity. Typically, conventional admixtures reach most of their strength in 28 days, while gypsum-treated soil achieves peak strength in 14 days [15], [17], [18]. The slurry was mixed for 5 minutes, poured into greased cylindrical molds (50 mm diameter, 33.3 mm height), and layered with 10 taps using a 2 mm diameter rod.

Molds were placed on a shaking table for 2 minutes, then cured in air at room temperature for 24 hours before being capped for 7 and 14 days (Fig. 4).

UCS tests were conducted with a strain-controlled machine at 4.3 mm/min, with samples tested after 7 and 14 days. A total of thirty samples were cast, with half tested at each curing interval. Post-curing, samples underwent UCS testing. In many cases, the failure plane was unclear, and water content was measured to determine dry unit weight. Figure 5 illustrates the final sample setup before testing.

Figure 4. Sample placement on shaking table

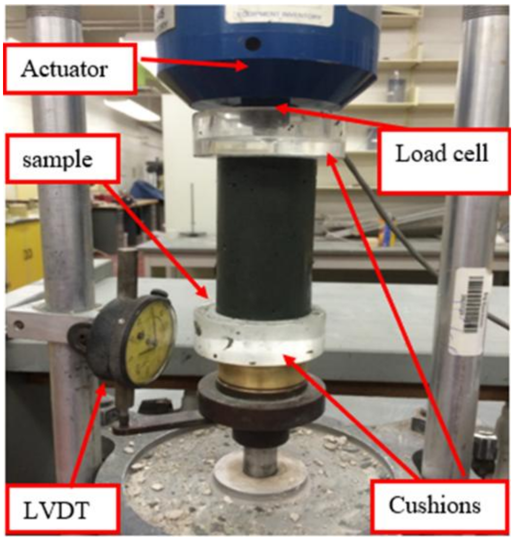

Figure 5. UCS Sample setup. The device is equipped with a dial gauge to measure the vertical displacement

2.4. Final tailings treatment scheme

To achieve enhanced strength, traditional additives were used. Paper [11] highlighted the effectiveness of a blend of recycled gypsum, bassanite (B), and CKD in improving tailings properties. Therefore, recycled gypsum and CKD were chosen for tailings treatment in this study. The strength of soil treated with the CKD:B mixture was evaluated through unconfined compression strength testing.

Based on the optimization study, two treatment approaches using CKD, basanite (B), and ordinary cement (OC) were applied to tailings 1. Treated tailings were prepared by blending the slurry with: 10% admixture (1CKD:1B), 7.5% admixture (1CKD:1B:1OC), and 7.5% admixture (0.45CKD:0.45B:0.1OC). Ordinary cement was included because DST samples without it dispersed almost immediately when soaked in water, attributed to calcium sulfate dehydrates water solubility [14].

The slurry was poured into a kneader bowl, with admixture added gradually while stirring. The kneader's speed was gradually increased, and mixing continued for 5 minutes to avoid bleeding or segregation. The mixture was then poured into square molds (62×62×20 mm) and allowed to set at room temperature.

2.4.1. Stiffness and strength tests

This section presents the scope of tests and the details of the followed procedures highlighting the constraints and overreaching goals.

2.4.2. Oedometer test

The tailings arrived in slurry form (LI = 1.34), prompting an initial sedimentation column test. The void ratio of the tailings was determined from the results of the Oedometer test. A bottom-perforated cylindrical mold was utilized to contain the soil slurry, allowing it to settle naturally for a period of 24 hours. To decrease water content and facilitate grain-to-grain contact between soil particles, the cylindrical sample was subjected to a pressure of 0.25 kPa for 24 hours, based on the observed behavior of the soil during sedimentation column testing. Following 24 hours of dewatering, the soil was carefully transferred to the Oedometer ring. A water content (w_c%) sample was extracted from the cylindrical sample to measure the initial water content, and the Oedometer test was conducted in accordance with ASTM (D2435) standards using conventional 50 mm samples with height of 19 mm utilizing conventional Oedometer (mechanical). The sample underwent 12 hours of consolidation in the oedometer, with an initial water content of 51.1%. Figure 6 illustrates the setup utilized for dewatering the slurry to achieve a zero-effective stress void ratio. The setup comprises a plastic cylinder, a porous stone, and a filter paper.

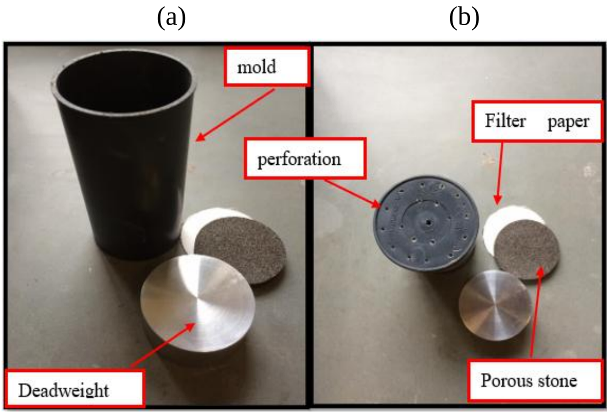

Figure 6. Setup utilized for dewatering the slurry: (a) the tools used for the dewatering setup; (b) perforation to allow collecting water from bottom

The testing apparatus featured a square box measuring 60×60 mm, complete with a fully computerized data logging system. It incorporated two LVDTs (accuracy of ±0.01 mm) for recording vertical and horizontal displacements, seamlessly integrated with the laboratory data logging program, Daisy. Additionally, the machine was outfitted with two normal loading cells – one positioned vertically to the box, and another shifted to enable mechanical loading through a lever arm. The maximum normal pressure applicable was 0.6 MPa.

Tests were conducted in adherence to ASTM (D3080) standards, employing strain-controlled loading at a rate of 0.03 mm/min. Each material underwent preparation of at least three samples, subjected to testing at three distinct normal stress values to establish the shear strength envelope of the material under examination. The ratio of the shear box's inner dimension to the largest particle size encountered was maintained at 30, surpassing the minimum established ratio of 10 as per laboratory standards. Furthermore, the thickness to maximum particle size ratio was set at 20, exceeding the minimum value of 6 [19] (ASTM D 3080).

3. Results and discussion

3.1. Unconfined compressive strength (UCS)

During all 45 UCS tests, the shear was accomplished over duration of 240 seconds. Figure 7 shows a typical sample after the completion of testing for both treated and untreated tailings samples.

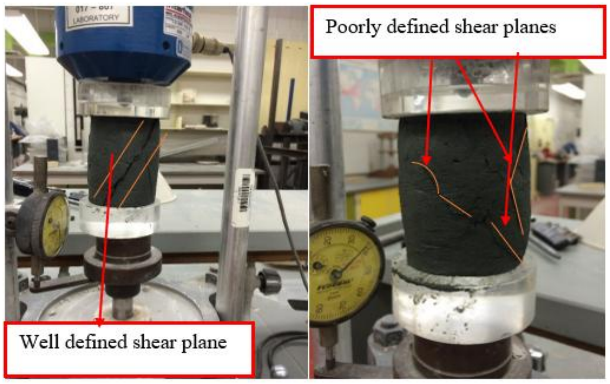

Figure 7. Shear planes of tailings samples: (a) untreated sample; (b) treated sample

As can be noted from Figure 7, the failure plane was not well-defined for sheared treated tailings samples, unlike those untreated samples. After shearing was completed, the water content was measured to establish the dry unit weight, which was found to be increasing with increasing additive concentration due to filler effects. Effects of internal forces one the treated soil.

Under undrained conditions for unconsolidated clay samples, the maximum undrained strength is theoretically independent of principal stresses, σ_1 and σ_3. Therefore, in theory, applying confinement without allowing consolidation does not impact the undrained strength. However, in scenarios where vertical stresses and associated settlement fluctuate over time, it is crucial to acknowledge the changes occurring within the treated material and how these variables influence its parameters.

Wetting and drying cycles can induce volumetric alterations to the treated soil, modifying its internal structure. Additionally, if the treated soil is situated within a freeze-thaw active region, its bonds will inevitably face internal freezing and thawing forces, potentially compromising their integrity. Hence, it is imperative to address these concerns early in the design phase to prevent unfavorable situations where field parameters deviate from the desired outcomes.

In this research, no freeze-thaw tests were conducted to evaluate their impact on the soil structure. Furthermore, it is noteworthy that the consolidation tests were performed up to a maximum stress of 800 kPa (the typical range for mine tailings embankments being between 0-2 MPa) to assess whether a certain stress or accumulation of stresses could induce bond breakage. This aspect will be discussed in the subsequent sections.

3.2. Effects of curing days

Figure 8 illustrates the evolution of unconfined compressive strength of the treated tailings over time using various treatment schemes. A noteworthy observation from Figure 8 is that reducing the proportion of CKD led to a decrease in the strength of the treated soil.

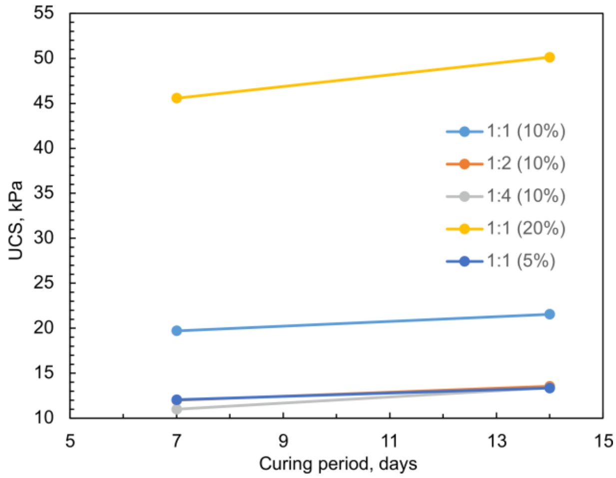

Figure 8. UCS of the five combinations for the period of testing

This reduction can be attributed to the increased proportion of gypsum, as CKD has a stronger strengthening effect compared to recycled gypsum. Conversely, augmenting the percentage of admixture in the tailings resulted in enhanced strength.

It is important to highlight that the recycled gypsum underwent sieving through a #20 U.S sieve, indicating the presence of coarse particles resembling fine sand. In contrast, CKD was sieved through a #40 U.S sieve, indicating finer particles. Consequently, the surface area of gypsum particles is smaller compared to CKD, leading to reduced water affinity. consequently, the outer surfaces of gypsum particles absorb water and set without significant absorption by their inner parts. This characteristic allows soil treated with gypsum to exhibit higher water content (w_c%) compared to soil treated with CKD or finer gypsum particles.

Furthermore, Figure 8 demonstrates that the strength of the treated soil increased with longer curing times, progressing from 7 to 14 days. However, the percentage increase in strength was approximately 10%, suggesting that most of the improvement occurs within the initial 7 days. This aspect is advantageous for application in tailings dams as it facilitates early strength gain.

3.3. Effect of commercial gypsum's proportion of UCS

To assess the effects of gypsum source on the realized results, two types of gypsum samples were used. The results indicated a decrease in unconfined compressive strength with an increase in the proportion of recycled gypsum in the mixture, attributed to the comparatively higher effectiveness of CKD. However, it was essential to investigate whether recycled gypsum had a detrimental effect on the strength of the treated tailings. Thus, powdered gypsum, commonly known as plaster, was utilized for tailings treatment instead of recycled gypsum. Employing the same procedure for sample preparation and curing as previously described for the sample treated with a combination of 10% admixture, nine samples were casted and left to cure for 7 days before testing.

The results obtained from tests on specimens containing plaster (designated with the letter P) are compared in Figure 9 with the results obtained for the same combination but with recycled gypsum. It is observed from Figure 9 that samples treated with admixtures including plaster exhibited higher UCS as the plaster proportion increased. For instance, the UCS of treated tailings increased by over 100% when the CKD: plaster ratio varied from 1:1 to 1:4.

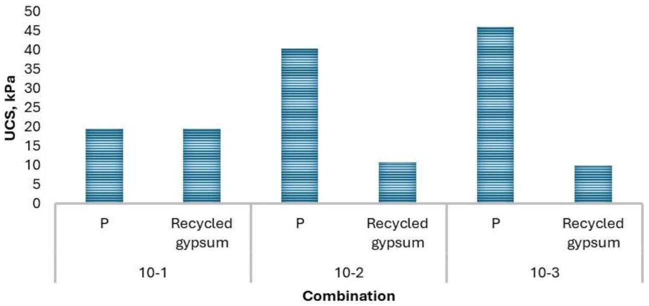

Figure 9. UCS of tailings treated with 10% admixture with different CKD: gypsum (recycled and commercial) proportions

These findings clearly demonstrate the effectiveness of gypsum in tailings treatment. The subpar performance of recycled gypsum in tailings treatment can be attributed to two primary reasons: the limited surface area of recycled gypsum, which consequently impacted the hydrophilicity of gypsum particles, and the lower calcium oxide (CaO) content of recycled gypsum (compared to plaster), as evidenced by the XRF analyses results presented in Table 2.

Understanding the stress-strain behavior of treated tailings is crucial for accurately modeling their performance as a construction material for tailings dams. Figure 10 illustrates the stress-strain curve of a specimen treated with 10% admixture (10-2). Similar stress-strain behavior was observed in all other specimens. While all specimens exhibited some degree of strain softening during shearing, no distinct peak-post-peak behavior was observed.

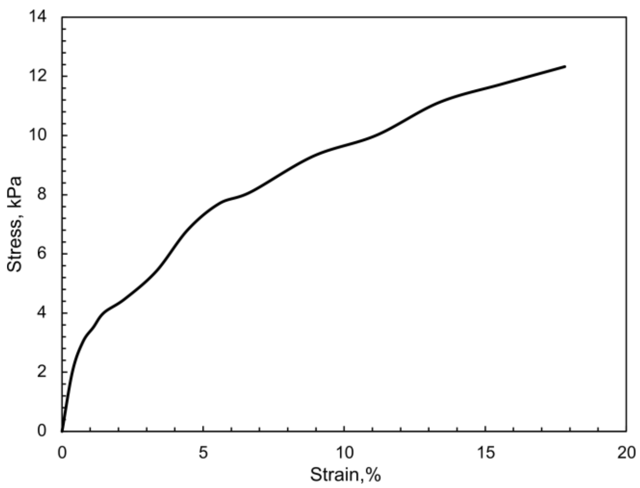

Figure 10. Stress-strain relationship of tailings 2 treated with (1CKD:2B) at 10% obtained from the UCS tests

It was observed that the proportion of gypsum did not have a clear effect on the cracking strain, as all samples developed cracks at approximately the same strain level. However, the inclusion of cementitious material altered the typical 45-degree cracking plane to multiple planes of cracking.

Based on its good performance in treatment of the clayey tailings, the admixture of CKD:B with 1:1 ratio was selected for consideration of treatment of silty tailings (tailings 1). Two different percentages were considered for treatment of tailings 1, and the treated tailings were tested to evaluate their consolidation behavior employing oedometer tests, and to determine their strength parameters using direct shear tests.

3.4. Oedometer testing

The coefficient of compressibility C_c indicates the potential consolidation settlement upon loading cohesive soils and is given by:

$$Cc = \frac{e_1 - e_2}{\log\left(\frac{\sigma_2'}{\sigma_1'}\right)}. \quad (1)$$

Here e is void's ratio and σ' is effective stress, subscripts 1&2 are arbitrary points on the virgin consolidation line.

The coefficient of compressibility (C_c) typically ranges from 0.1 to 0.2 for silty soils and 0.2 to 0.3 for clayey soils [20], [21]. No rebound measurements were taken for the untreated materials, hence only the C_s values were compared to those of treated tailings. The measured C_c value was found to be 0.1548. Figure 11 illustrates the volumetric strain of untreated tailings against log σ', indicating the extent of consolidation settlement. It's important to note that one of the objectives of treating the tailings was to reduce their coefficient of compressibility, thereby minimizing consolidation settlement. A significant volumetric strain, up to 20% additional to the 25% initial settlement due to particles settlement, is realized when subjecting the tailings sample to a 800 kPa.

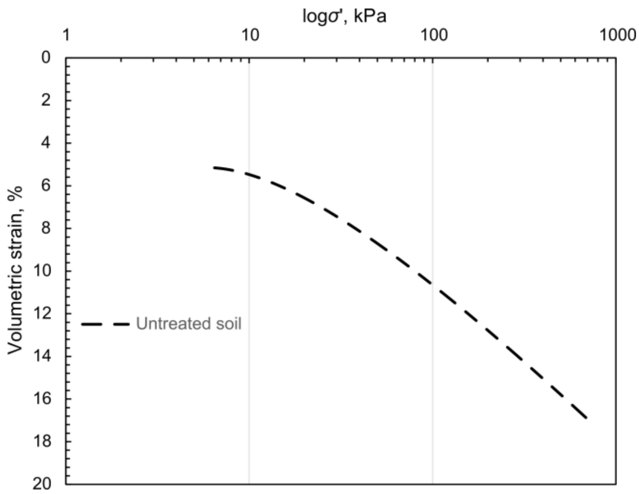

Figure 11. Volumetric strain against effective stress of untreated tailings

Measurements of the coefficient of consolidation (c_v) were conducted for the untreated tailings at various loading stages to establish both lower and upper bounds. Plotting the c_v values against e-log σ' revealed a general increase in their magnitude as effective stresses increased. The coefficient of consolidation ranged from 0.1 to 0.5 cm^2/minute, as depicted in Figure 12. Taylor's method [22] was employed for c_v measurements. Notably, Figure 12 illustrates that c_v obtained from the sedimentation column notably exceeds the average c_v value of 0.38 cm^2/minute. It's worth mentioning that the tailings experienced a volumetric reduction of 17.05% of their original volume when consolidated to 765 kPa.

Figure 13 depicts the e-log σ' curve comparing untreated soils with treated soils, providing a visual comparison of consolidation behavior across various treatment schemes and untreated tailings. When employing a 7.5% admixture ratio of (0.45CKD:0.45B:0.1OC), the tailings stiffness did not exhibit a significant increase.

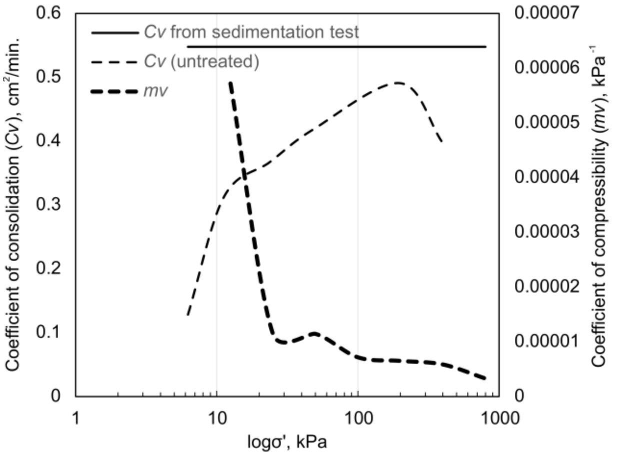

Figure 12. C_v values at different effective stresses of untreated tailings

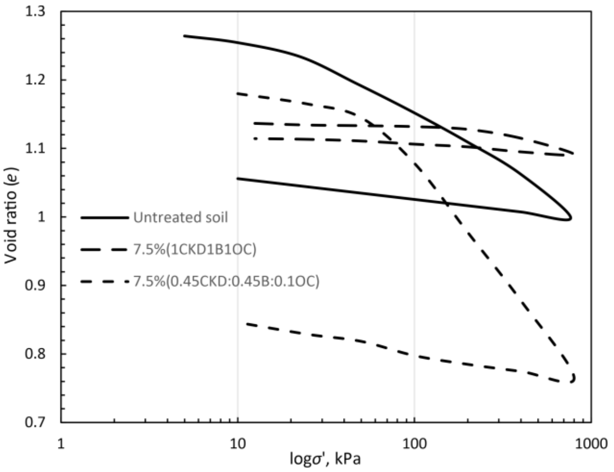

Figure 13. log σ′ curves of treated and untreated tailings

This could be attributed to either weak or insufficiently formed bonds, leading to bond collapse when effective stress exceeded 50 kPa. Conversely, a notable enhancement was observed in tailings treated with a 7.5% admixture of (1CD:1B:1OC). Volumetric strains notably decreased from 17% to 2%, as depicted in Figure 13. This substantial reduction is credited to the higher cement content, which promoted particle bonding and reduced voids within the slurry volume, consequently lowering water content and void ratio while increasing dry unit weight. As a result, hydraulic conductivity was also reduced. Figures 13 and 14 further compare the results of consolidation tests for treated and untreated tailings.

It is evident from Figure 13 that the effect of a 7.5% admixture of (0.45CKD:0.45B:0.1OC) did not enhance the stiffness of the treated tailings significantly, possibly due to weak or unstable bonds leading to bond collapse under increasing effective stresses. However, analysis of shear strength envelopes for untreated and treated tailings (0.45CKD:0.45B:0.1OC) revealed an increase in cohesion of the treated material by approximately 11 kPa. This enhancement in cohesion is attributed to the quasi-over-consolidation resulting from the admixture's addition to the tailings. Nonethelzess, these acquired cohesive forces were not sustained in a water environment, as indicated later in the subsection 3.8.

Conversely, considerable improvement was achieved when the tailings were treated with a 7.5% admixture of (1CD:1B:1OC). Volumetric strains were drastically reduced from an average strain of 17% to almost 2.21%, as depicted in Figure 14.

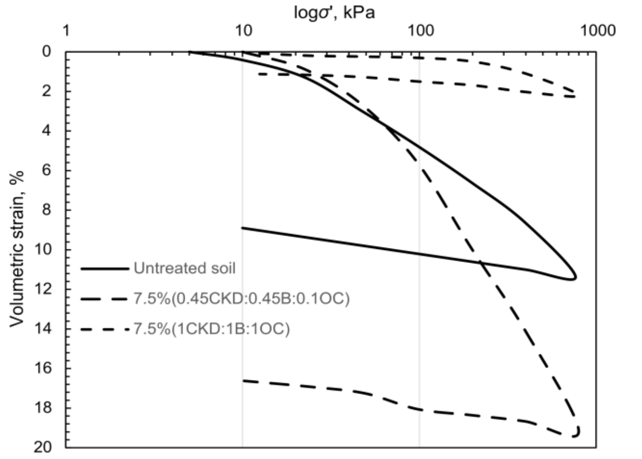

Figure 14. Volumetric strain-logarithmic effective stress relationship of all treated and untreated tailings

This significant reduction can be attributed to enhanced particle bonding resulting from the higher percentage of cement in the mixture. Additionally, the treatment increased solids in the slurry volume, reducing water content and void ratio, consequently leading to a lower void ratio compared to untreated tailings at any normal stress, thereby creating a stronger material. This also resulted in a lower hydraulic conductivity, as observed in Figures 15 and 16. Finally, the tailings properties used in modeling, both for untreated and 7.5% treated tailings, are presented in Table 3.

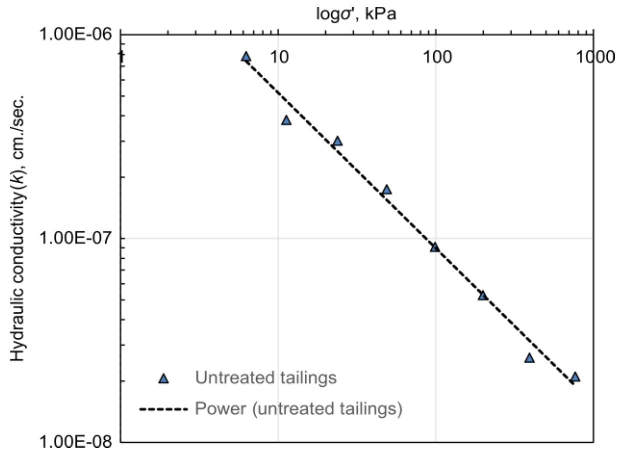

Figure 15. Hydraulic conductivity of the untreated tailings versus effective stress

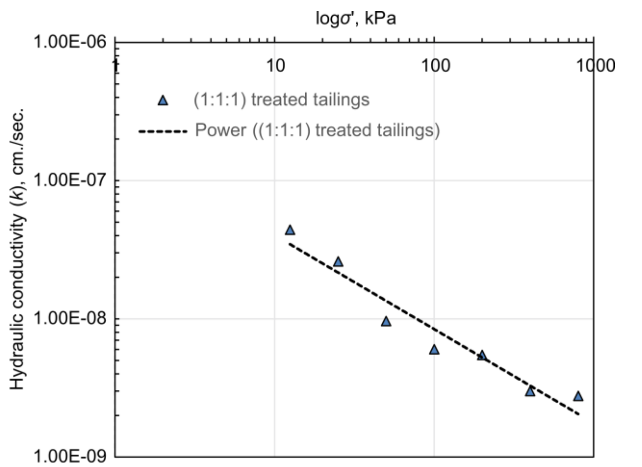

Figure 16. Hydraulic conductivity- effective stress relationship for (1CKD:1B:1OC) treated tailings

Table 3. Combination made for optimization work for traditional admixture

Percentage of CKD:B	Ratio B:CKD	Combination
5%	1:1	5-1
10%	1:1	10-1
	2:1	10-2
	4:1	10-3
20%	1:1	20-1

3.5. Effects of tailings treatment on the *k* value

Figures 15 and 16 display the effect of the vertical effective stress on the hydraulic conductivity values. It is worth noting that the binder had a substantial impact, one order of magnitude, on the *k* value due to the combined bonding and filler effects.

From Figure 15 and 16, it is proved that the addition of admixtures resulted in a reduction, around one order of magnitude, in the hydraulic conductivity of the treated tailings compared to those of untreated tailings due to the smaller initial void ratio of the treated tailings. Hydraulic conductivity chosen for modeling was selected based on the average effective stress anticipated in the field in the numerical modelling part of the current study. E_{oed}, was taken to be the secant modulus between 100-400 kPa based on the effective stresses anticipated in the field as well. Untreated tailings were assumed to be normally consolidated with effective cohesion of zero. The cohesion amount of 19.6 kPa exhibited by the untreated tailings was also subtracted from the effective cohesion of treated tailings.

3.6. Shear strength

The shear strength characteristics of both untreated and treated tailings were evaluated using two laboratory tests: the direct shear test (DST). These tests are designed to determine strength parameters based on expected soil behaviors, considering factors such as drained or undrained conditions, and consolidated or unconsolidated states. The anticipated behavior of tailings in the field typically falls between fully drained and undrained conditions due to variations in soil gradation at specific distances from the discharge point and the method of tailings disposal, whether it be saturation (subaqueous, thickened tailings, or dry tailings). These factors must be considered when assessing the stability condition of a tailing's storage facility.

Since the objective of this study is to compare the long-term behavior of the tailing's treatment plan, a drained DST was conducted. Figure 17 illustrates the stress-strain relationships for untreated tailings. It can be observed that the behavior of the tailings exhibited a strain-hardening response, wherein the shear stress initially increases proportionally to the strain levels up to a yield point, followed by a disproportionate increase in strain with minimal stress increase. A hyperbolic relationship can be fitted to represent the shear response of the tailings. It is worth noting that no definitive peak was obtained for any of the shear samples.

As can be noted from Figure 18, the shear stress-normal stress relationship was linear with a constant slope representing an angle of internal friction equal to 42°C. However, the shear stress-normal stress relationship exhibited an intercept, which suggests the untreated tailings material has some cohesion. The observed apparent cohesion may be attributed to two possible reasons.

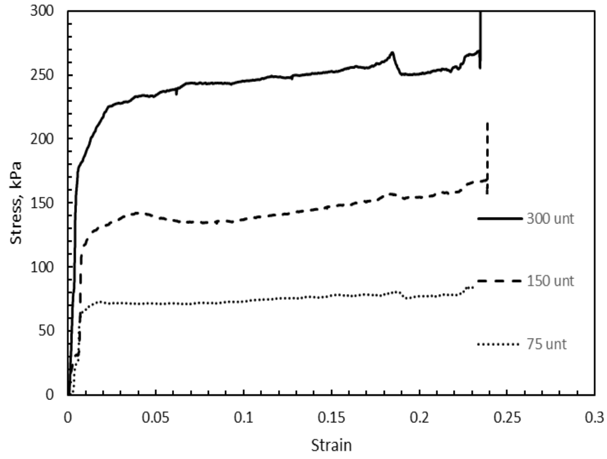

Figure 17. Untreated tailings stress strain relationships from DST

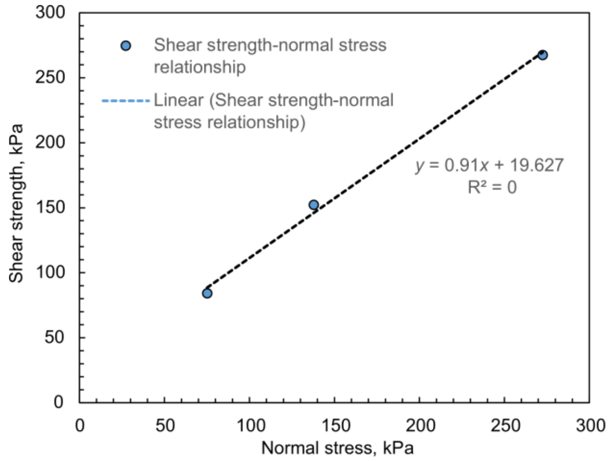

Figure 18. DST results of untreated tailings

Effects of thixotropy: Janzak et al. (2007) and Rout et al. (2013) reported that the tailings exhibited some cohesion intercept. This also could be supported by the observation from e-log σ' curve (Fig. 13) which exhibits an initially curved line at low stresses but became straight line at pressure higher than 25 kPa. This observation, however, might be attributed to the fact that the sample was tested at water contents higher than its LL and the initial part of the curve does not necessarily have to be a straight line.

The c' intercept is a result of test's errors related to varying dry density and void ratio of tested specimens. Indeed, achieving a specific dry density at confining pressure and high void ratio is almost impossible to attain. The tailings were prepared at low dry densities, in the order of 1200-1400 kg/m^3, and they were soaked in water and loaded to reach the desired normal stress. This led to inevitable settlement, which in turn altered the initial void ratio and consequently the dry density which led to some over consolidation of the specimen that resulted in the apparent c' intercept. The author is of this opinion this is a more plausible explanation. This is supported by the fact that the e values established after shearing the samples were all around 8% lower than the initial void ratio at which the samples were prepared.

Another important aspect is that Figures 18 shows that the peak shear stress (τf) – normal stress relationship for the untreated tailings is not linear, but rather is semi-exponential, which entails that the friction angle and cohesion of the treated tailings are not constants as typically assumed. The τf-N best fit line might flatten at high stresses, which means that there could be a limiting effective stress beyond which the shear strength becomes constant. Thesis [18] reported that [21] had a similar observation where he noted that the friction angle decreased until it stabilized at normal stresses higher than 276 kPa [18]. This may be an important observation for assessment of tailings dams' stability, especially for high dams of more than a hundred meters, i.e., effective stresses that could reach a few MPa. If a constant friction angle is assumed in the numerical modeling to assess the stability of such tailing's dams, then it might be possible that the safety factor is overestimated.

3.7. DST treated samples preparation

Three distinct treatment schemes utilizing cement kiln dust (CKD), bassanite (B), and ordinary cement (OC) were employed. The treated tailings were prepared by blending the tailings slurry with three different admixture ratios: 10% of admixture (1CKD:1B); 7.5% of admixture (1CKD:1B:1OC); and 7.5% of admixture (0.45CKD:0.45B:0.1OC). Ordinary cement was introduced into the mixture due to observations that DST samples soaked in water one day before testing, without cement, dispersed almost immediately upon immersion. Papers [15], [23] attributed this behavior to the water solubility of calcium sulfate hemihydrate.

The process began by pouring the slurry into the kitchen kneader bowl, followed by the gradual addition of the admixture while stirring the slurry. The rotational speed of the kneader was then increased gradually. Mixing was carried out for a predetermined 5-minute duration to prevent bleeding or segregation of the mixture. The resulting batch was subsequently poured into specially fabricated square boxes measuring 62×62×20 mm. These batches were left to cure at normal room temperature. Figure 19 depicts freshly cast treated samples.

Figure 19. Improved tailings DS samples

Initially, two treatment approaches were implemented for tailings: one with 10% admixture by total weight (1CKD:1B), and the other with 7.5% admixture by total weight (0.45CKD:0.45B:0.1OC). These samples were cast and left to cure at room temperature for 3 days before being soaked in water for saturation prior to testing. However, it was observed that the samples treated with 10% admixture of (1CKD:1B) dispersed in the water shortly after immersion, indicating weak bond formation. Conversely, the samples treated with 7.5% admixture of (0.45CKD:0.45B:0.1OC) maintained their shape. Consequently, a third treatment scheme was introduced, where another set of samples were prepared with 7.5% admixture by total weight (1CKD:1B:1OC) using the same procedure, but with a curing period of 7 days.

Once the specified curing period elapsed, the treated samples were subjected to direct shear testing at various normal stresses to assess their shear strength. The normal stresses were incrementally applied, starting from 10 kPa and doubling with each increment until reaching the desired stress level. Additionally, treated samples were placed in oedometer rings to investigate their consolidation behavior. All samples underwent dry curing at room temperature and were plastic wrapped to prevent moisture-induced desiccation.

3.8. Direct shear test results of treated tailings

It should be mentioned that for the treated materials tested in the DST, each load increment was kept constant for one hour, which is long enough for all excess pore water pressure to dissipate. This is based on the lowest coefficient of consolidation that was obtained from the oedometer tests to measure the time for full dissipation. The untreated tailings, however, were prepared from oven-dried tailings that were crushed and compacted to achieve void ratios, which correspond to the effective stresses from e-log σ' curve. Consequently. They were kept under pressure and soaked with tap water and left to saturate for 24 hours. Each load increment in DST was kept constant for one hour to allow all EPP to dissipate. In addition, very slow loading (strain rate of 0.03 mm/min) was applied to ensure shear induced EPP is dissipated. It should be mentioned that the water used her is a tap water for both tests to avoid result's bias. The tailings are usually submerged in acidic environments and the effect of this acidity should be given consideration. It is reported that pH variation has an effect on the shear strength parameters of the soil [24]. Figure 20 shows one sample after it was sheared.

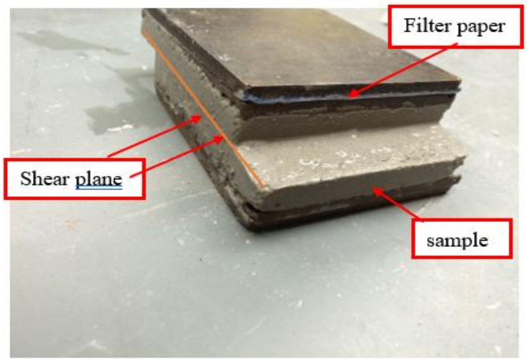

Figure 20. Treated tailings sheared DST sample

The failure plane was horizontal along the contact of the upper and lower parts of the untreated sample; however, there was some deviation from the horizontal failure plane for the treated soil, which was caused by the cementitious bonds that forced the failure to happen on the weakest plane, deviating slightly from the horizontal direction, Figure 20. Figure 21 displays the shear strength envelop for the treated tailings with 7.5% (1CKD:1B:1OC) [3], [25].

Figure 22 compares the shear strength envelope of tailings treated with 7.5% admixture of (1CKD:1B:1OC) with that of the untreated tailings. It can be seen from Figure 22 that the shear strength of the treated soil is substantially higher than that of untreated tailings due to the cementitious bonds established by the additive used.

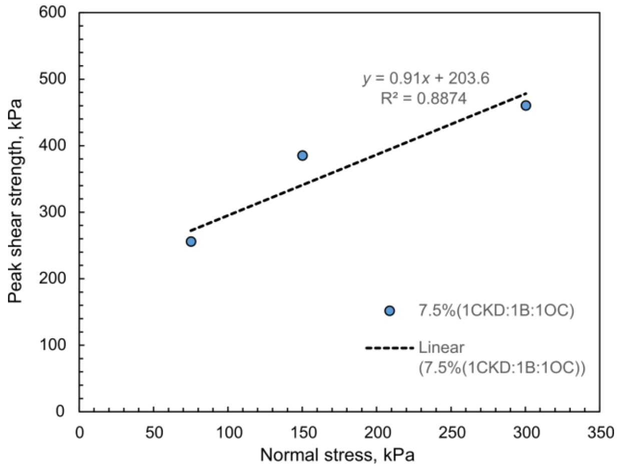

Figure 21. Shear strength envelope of 7.5% (1CKD:1B:1OC) treated tailings

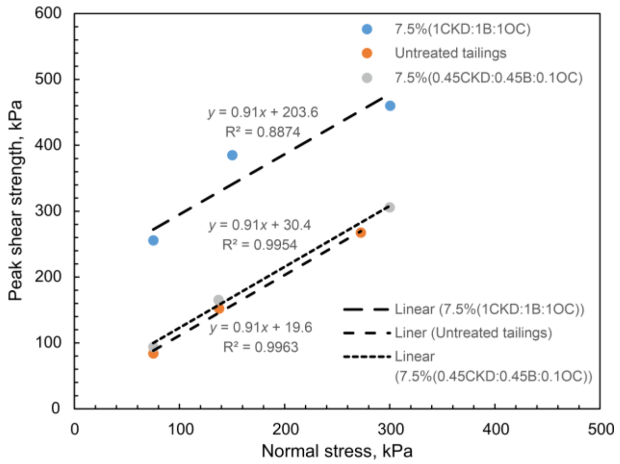

Figure 22. Shear strength envelope of both treated and untreated tailings

The 7.5% admixture of (1CD:1B:1OC) treatment resulted in substantial cohesive bonds that were manifested by cohesion intercept of 184 kPa, considering a straight line curve fit as shown in Figure 22. The 7.5% (0.45CKD:0.45B:0.1OC) had little to no effect on the shear strength envelope other than 11 kPa increase in cohesion. The cohesion gain in this case is attributed to higher dry density and not to cementitious bonds [26]-[28].

Based on the shear strength tests conducted in this study, the strength properties of treated and untreated tailings are provided in Table 4.

Table 4. Tailings properties

Material	*C'*	*Φ'*	E_{oed}	*k*, cm/sec
Untreated tailings	0	38	9400	9.12357E-08
Treated tailings (1:1:1)	184	38	300284	6.01838E-09

These properties can be used in developing proper treatment schemes and numerical models that can aid in assessing the stability of tailings dams treated with the proposed admixture combination.

3.9. Further research

Further research on mine tailings geotechnical improvement and recycling will be undertaken with the aim to reduce the environmental risks associated with these tailings and to enhance the efficiency of our globe natural resources. Polymeric emulsions and other industrial and naturally occurring materials will be studied with the aim of finding alternative uses for tailings, assess their potential as raw materials for various industrial and infrastructure applications such as brick manufacturing and liner materials for earthen dams.

4. Conclusions

The experimental program involved treating mine tailings with different traditional and non-traditional additives to improve their engineering properties. The improvement was assessed in terms of deformation shear strength parameters. Based on the results of the experimental investigation, the following conclusions may be drawn.

Use of cementitious materials that increase the shear strength and stiffness is desirable.

Traditional additive of recycled gypsum with cement kiln dust (1:1) was proven to be the best tested proportion in terms of adding cohesive strength to the non-cohesive tailings and enhancing its stiffness. However, soaking in water may affect its integrity.

Adding ordinary cement to the admixture at the proportions 1CKD:1B:1OC prevented the adverse impact of water. The admixture at 7.5% by total weight has substantially improved the shear strength parameters and resulted in cohesive strength of 184 kPa.

Based on experimental observations, the change of shear strength parameters with confining pressure increases should be considered in numerical modeling/design calculations.

In field applications, sufficient curing time should be allowed in order for the material to gain its strength. At least 7 days of curing should be allowed before adding another layer to avoid the adverse impact of water and enable most of the shear strength gain before loading the treated tailings in the staged construction.

Author contributions

Conceptualization: YAA; Data curation: YAA; Formal analysis: YAA; Investigation: YAA, MHEN; Methodology: YAA, MHEN; Project administration: YAA, MHEN; Writing – original draft: YAA; Writing – review & editing: YAA, MHEN. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

References

[1] Alsharedah, Y.A., & El Naggar, M.H. (2023). Effects of tailings treatments scheme on tailings dam. *Proceedings of the 9th International Congress on Environmental Geotechnics*, 1-6.

[2] Alsharedah, Y.A., El Naggar, M.H., & Ahmed, A. (2023). Improving tailings dam safety via soil treatment. *Sustainability*, *15*, 15276. https://doi.org/10.3390/su152115276

[3] Alsharedah, Y.A. (2015). *Slope stability enhancement of an upstream tailings dam: Laboratory testing and numerical modelling*. PhD Thesis. London, Canada: The University of Western Ontario, 159 p.

[4] Rico, M., Benito, G., & Díez-Herrero, A. (2008). Floods from tailings dam failures. *Journal of Hazardous Materials*, *154*(1), 79-87. https://doi.org/10.1016/j.jhazmat.2007.09.110

[5] Armstrong, M., Langrené, N., Petter, R., Chen, W., & Otávio, P.C. (2019). Accounting for tailings dam failures in the valuation of mining projects. *Resources Policy*, *63*, 101461, https://doi.org/10.1016/j.resourpol.2019.101461

[6] Alsharedah, Y.A., El-Naggar, M.H., Ahmed, A., & Soliman, A.M. (2016). Mining tailing stabilization using waste materials. *Proceedings of the Canadian Society for Civil Engineering Conference*, 1-7.

[7] Jantzer, I., Bjelkevik, A., & Pousette, K. (2008). Material properties of tailings from Swedish mines. *Proceedings of the Nordiska Geoteknikermötet Conference*, 229-235.

[8] Chen, Y., & Wei, Z. (2024). Stability of tailings dam constructed by both upstream and centerline methods. *Geotechnical and Geological Engineering*, 1-5.

[9] Villavicencio, G., Espinace, R., Palma, J., Fourie, A., & Valenzuela, P. (2014). Failures of sand tailings dams in a highly seismic country. *Canadian Geotechnical Journal*, *51*(4), 449-464. https://doi.org/10.1139/cgj-2013-0142

[10] Riveros, G.A., & sadrekarimi, A. (2021). Static liquefaction behaviour of gold mine tailings. *Canadian Geotechnical Journal*, *58*(6), 0209. https://doi.org/10.1139/cgj-2020-0209

[11] Ahmed, A., Ugai, K., & Kamei, T. (2011). Investigation of recycled gypsum in conjunction with waste plastic trays for ground improvement. *Construction and Building Materials*, *25*(1), 208-217. https://doi.org/10.1016/j.conbuildmat.2010.06.036

[12] Anderson, C., & Eldridge, T. (2010). Critical state liquefaction assessment of an upstream constructed tailings sand dam. *Tailings and Mine Waste*, 101-112. https://doi.org/10.1201/b10569-15

[13] Ateş, A. (2013). The effect of polymer-cement stabilization on the unconfined compressive strength of liquefiable soils. *International Journal of Polymer Science*, 1-8. https://doi.org/10.1155/2013/356214

[14] Nicolas, B. (2015). *Development of a tailings management simulation and technology evaluation tool*. PhD Thesis. Edmonton, Canada: University of Alberta, 481 p.

[15] Bery, A.A., & Saad, R. (2012). Correlation of seismic P-wave velocities with engineering parameters (N value and rock quality) for tropical environmental study. *International Journal of Geosciences*, *03*(04), 749-757. https://doi.org/10.4236/ijg.2012.34075

[16] Boulanger, R.W., & Idriss, I.M. (2006). Liquefaction susceptibility criteria for silts and clays. *Journal of Geotechnical and Geoenvironmental Engineering*, *132*(11), 1413-1426. https://doi.org/10.1061/(asce)1090-0241(2006)132:11(1413)

[17] Liu, L., & Huang, H. (2012). Application of water-soluble polymers in soil quality improvement. *Civil Engineering and Urban Planning 2012*, 123-129. https://doi.org/10.1061/9780784412435.022

[18] Zardari, M.A. (2013). *Stability of tailings dams*. PhD Thesis. Luleå, Sweden: Luleå University of Technology, 200 p.

[19] Benson, C.H., Edil, T.B., & Bareither, C.A. (2008). Comparison of shear strength of sand backfills measured in small-scale and large-scale direct shear tests. *Canadian Geotechnical Journal*, *45*(9), 1224-1236. https://doi.org/10.1139/T08-058

[20] Gan, J., Ebrahimi-Birang, N., & Haug, D.M. (2011). *Consolidation and hydraulic conductivity testing of slurries*. *Proceedings Tailings and Mine Waste*, 1-7.

[21] Vick, S.G. (1990). *Planning, design, and analysis of tailings dams*. Vancouver, Canada: Bitech Publishers Ltd., 381 p.

[22] Das, B.M. (2006). *Principles of geotechnical engineering*. New York, United States: Thompson, 683 p.

[23] Kamei, T., Ahmed, A., & El Naggar, M.H. (2017). Performance of ground improvement projects incorporating sustainable reuse of geocomposite wastes. *Transportation Geotechnics*, *14*(1), 22-28. https://doi.org/10.1016/j.trgeo.2017.09.003

[24] Dimitrova, R.S., & Yanful, E.K. (2011). Undrained strength of deposited mine tailings beds: Effect of water content, effective stress and time of consolidation. *Geotechnical and Geological Engineering*, *29*(5), 935-951. https://doi.org/10.1007/s10706-011-9428-7

[25] Ahmed, A., Nagy, N.M., El Naggar, M.H., & Kamei, T. (2018). Stabilisation of soft soil with recycled plaster admixtures. *Ground Improvement*, *171*, 12-20. https://doi.org/10.1680/jgrim.16.00038

[26] Sun, S.-W., Zhu, B.-Z., & Wang, J.-C. (2013). Design method for stabilization of earth slopes with micropiles. *Soils and Foundations*, *53*(4), 487-497. https://doi.org/10.1016/j.sandf.2013.06.002

[27] Simon, D., Murray W., Grabinsky, M.W., & Bawden, W. (2011). Effect of polycarboxylated acrylic acid polymer-based superplasticizer on cemented paste backfill. *Proceedings of the 14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering & 64th Canadian Geotechnical Conference*, 1-6.

[28] Tingle, J.S, Newman, J.K., Larson S.L., Weiss, C.A., & Rushing, J.F. (2007). Stabilization mechanisms of nontraditional additives. *Transportation Research Record: Journal of Transportation Research Board*, *1989-2*(1). https://doi.org/10.3141/1989-49

Розкриття переваг використання перероблених відходів при геотехнічній обробці хвостосховищ: сталий підхід

Я.А. Альшаредах, М.Х. Ель Наггар

Мета. Дослідження ефективної стратегії обробки ґрунту з метою покращення геотехнічних характеристик хвостосховищ. У роботі оцінюється ефективність різних ґрунтових домішок, зокрема, як традиційних, так і нетрадиційних, для зміцнення дамб хвостосховищ.

Методика. Розроблено комплексну експериментальну програму, у межах якої до хвостів в лабораторних умовах додавали полімерну смолу та комбінацію переробленого гіпсу, пилу цементних печей і звичайного цементу. Для оцінки ефективності обробки застосовували випробування на одновісний стиск (UCS) з метою визначення оптимального вмісту домішок. Виконувалися випробування для оцінки жорсткості та властивостей ущільнення, а також випробування на прямий зсув для аналізу реакції матеріалу на зсувні навантаження.

Результати. Встановлено, що традиційна домішка з переробленого гіпсу з цементним пилом (1:1) виявилася найкращою випробуваною пропорцією з точки зору додавання міцності зчеплення до незв'язних хвостів та підвищення їх жорсткості, проте, замочування у воді може вплинути на їхню цілісність. Встановлено, що додавання звичайного цементу в суміш у пропорціях 1ЦП:1Г:1ЗЦ запобігло несприятливій дії води, де ЦП – цементний пил, Г – гіпс, ЗЦ – звичайний цемент. Домішка у кількості 7.5% від загальної ваги суттєво покращила параметри міцності на зсув та призвела до міцності зчеплення 184 кПа. Визначено, що оброблені хвости демонструють покращені механічні властивості, що надає важливі дані для числового моделювання та оцінки стійкості дамб хвостосховищ.

Наукова новизна. Виявлено нові закономірності щодо обробки хвостосховищ, зокрема, комбінації пилу цементних печей і звичайного цементу, переробленого гіпсу та звичайного цементу. Отримані результати сприяють кращому розумінню механізмів підвищення стійкості дамб хвостосховищ, що раніше не було достатньо висвітлено у науковій літературі.

Практична значимість. Результати дослідження сприяють покращенню управління хвостосховищами та впровадженню найкращих екологічних практик. Оптимізація методів обробки ґрунту дозволяє ефективніше використовувати природні ресурси та підвищує безпеку та стійкість конструкцій дамб хвостосховищ.

Ключові слова: *хвостосховища, геотехнічні ризики, покращення ґрунту, управління відходами, переробка*

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