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Effect of tailings treatment on stability of tailings dams

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ABSTRACT

The main objective of this study is to establish an efficient soil treatment scheme that can help enhance the stability of tailings dams constructed using the upstream method. To achieve this objective, the beneficial effects of different soil additives, both non-traditional and traditional are investigated to evaluate the enhancement of tailings strength and hence the stability of tailings dams. This paper only reports on the results for the traditional additives. An experimental program was conducted, which involves the study of employing different additives to improve the shear strength of tailings material in a laboratory setup. It covers both the characterization of tailings materials used and the testing of tailings treated with different additives to improve its stiffness and strength. Tailings tested were two types from mines in Northern Ontario, denoted tailings1 and tailings2. Tailings2 was only used for optimization work with traditional additives utilizing unconfined compression strength (UCS) testing. The rest of the tests are conducted with tailings1. The tailings treatment efficiency is then evaluated in terms of the increase in shear strength and improvement in consolidation behaviour of treated tailings. The treated tailings properties established from the experimental program could be used in studies of tailings dams stability.

Keywords: tailings dams, stability, soil treatment, chemical analysis, unconfined compression strength

1 INTRODUCTION

Significant research conducted on conventional earth dam performance enabled a deep scrutiny of the adopted practice for their design and construction, which lead to establishing sound design, management guidelines, and construction practices. Unlike conventional earth dams, tailings dams have received little attention by researchers until recently, perhaps motivated by reported tailings dams' failures (Rico et al., 2008; Davis, 2002). Nonetheless, the number of tailings dam failures has doubled in the past 20 years; on average, two to five major tailings dams fail each year (Armstrong et al. 2019), which is much higher than the failure rate of conventional earth dams. Therefore, thorough analysis and assessment are necessary to find out the prevailing modes of failures and their causes.

Villavicencio et al. (2013) investigated the tailings dams failures that took place over 100 years and reported that both active and abandoned tailings dams failed due to one of the following causes. The construction method (upstream method accounts for the majority of sand tailings dams' failure); poor compaction, high fine contents in the cyclone sand, and the elevated pore water pressure. Failure may happen when excessive deformation occurs at the crest or toe of the embankment due to construction on weak foundation material such as soft clay, or when the construction sequence does not allow the excess pore water pressure to dissipate, leading to elevated water table in the dam body, especially if not considered or predicted in the design stage. Failure can also happen due to earthquake loading, which causes cyclic shearing forces that could liquefy all or part of the dam body or its foundation soil and, consequently, reduces the available shear strength. Furthermore, static liquefaction can take place when the time laps between two consecutive layer placements is not adequate to allow for pore water pressure generated to dissipate resulting in full or partial liquefaction for the dam body and/or the foundation due to the negation of effective stresses. It is believed that this phenomenon accounts for the majority of reported failure of tailings dams that are normally consolidated and their stability depends on the effective shear strength provided at the slip surface; when the effective strength decreases, the factor of safety decreases (Riveros & Sadrekarimi, 2021). This clearly indicates the importance of good design and construction practice. Therefore, it is of utmost importance for the mining industry to design tailings dams to meet safety requirements implementing construction methodologies that ensure satisfactory performance under different loading conditions.

2 EXPERIMENTAL PROGRAM

2.1 Chemical analysis

Inductively Coupled Plasma (ICP) and X-Ray Fluorescence (XRF) analyses were conducted on the received tailings to define their chemical composition and identify sources of hazardous material. The ICP test can detect heavy metals such as (Cr, Ag, Fe, Co, Cd, Pb, Bi, Ba, V, As, Ni, Cu, Mn, Al, Zn, etc.) and Alkali elements like (Na, Mg, Ca, K). Figure 1 reveals the detected elements and minerals within the tailings liquid. The tailings liquid had a broad range of materials; however, they are not evenly present within the liquid. The dominant materials were Calcium and Potassium (very high concentrations of 1264 and 447 mg/L, respectively). Thus, they were removed from the chart presented in Figure 1 in order to allow the graphical representation of the small range fluctuation of materials presence in the tailings liquid. Of significant, was the presence of some hazardous materials, including: Arsenic, Cadmium, Chromium, and lead. Their concentrations in tailings1 liquid were found to be higher than of the maximum acceptable limits (MAC) found in Canadian Drinking Water Guidelines (CDWG). Accordingly, it is of utmost importance to have a robust lining and filtration systems around the TSF to ensure that no leaks, concentrated flow of water due to existence of fissures or cracks that create preferred path for water flow, or seepage, spatial flow of water due to difference in energy level to the ground water. It is also of more importance to maintain a robust tailings impoundment to safeguard the surrounding environment from any slope instability.

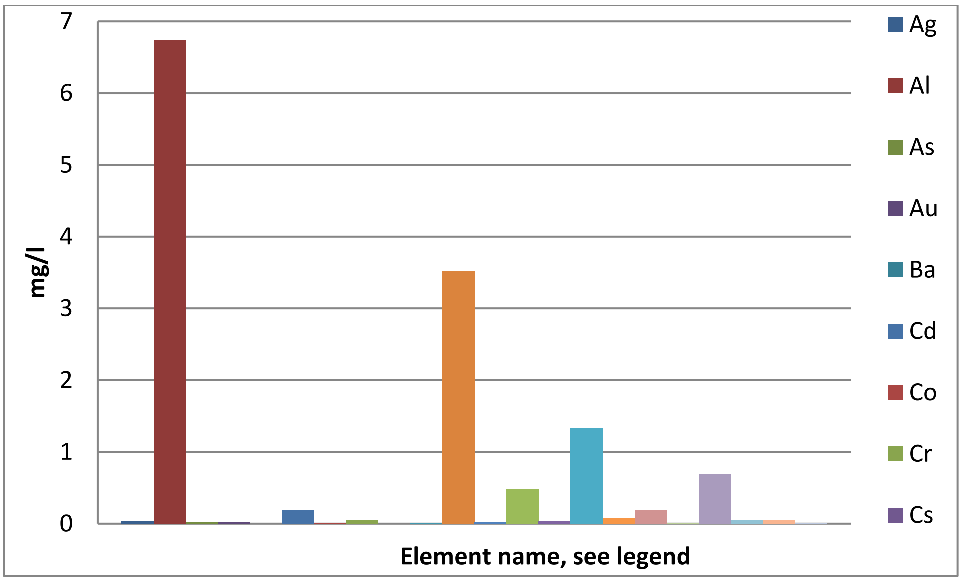

Figure 1. ICP test's results

X-Ray Fluorescence tests were performed to identify the general chemical composition of the materials used. The pressed bullet method was employed because it can screen up to 72 major elements. The tests were conducted on two types of tailings, as well as recycled gypsum and plaster that were used for treatment of tailings. Table 1 summarizes the results of this test, which demonstrate that all tested materials are rich in calcium. However, the plaster was richer than recycled gypsum (67.4 and 53.7% by total weight, respectively), which indicates plaster is more likely to offer increased strength to the treated tailings. Moreover, both types of gypsum are rich in sulfur trioxide, which is harmful to the environment as they can contribute to acid rain. Furthermore, it is seen that the tailings are rich on Silicon oxide and Aluminum, which are light materials. The measured specific gravity of tailings1 was 2.69, which lies within the range of silty clay materials; however, many tailings are reported to have higher specific gravity range due to the existence of heavy metals in them, which was not the case for these tailings. It was also noted that Arsenic, which is a hazardous material, was found in the plaster in high concentration, 0.024 g/1000 g, which is higher than 0.01 mg/L specified as MAC in CDWG.

Table 1. XRF analysis results

	Recycled gypsum		Plaster		Tailings1		Tailings2	
13.72	Wt%	StdErr	Wt%	StdErr	Wt%	StdErr	Wt%	StdErr
CaO	53.7	0.25	67.48	0.23	44.05	0.25	13.72	0.17
SO3	44.91	0.25	26.7	0.22	1.72	0.07	1.34	0.06
SiO2	0.543	0.027	1.82	0.07	32.38	0.23	44.63	0.25
Fe2O3	0.268	0.013	0.133	0.007	1.88	0.07	18.13	0.19
Al2O3	0.192	0.019	0.591	0.029	10.81	0.16	10.82	0.16
MgO	0.168	0.008	2.48	0.08	4.2	0.1	3.48	0.09
K2O	0.0576	0.0029	0.371	0.018	2.36	0.08	5.01	0.11
TiO2	0.0463	0.0041	0.0482	0.0046	0.822	0.041	0.58	0.029
Sc	0.0287	0.0027	0.034	0.003	0.0201	0.0024	0	0
La	0.0243	0.0058	0.0344	0.0068	0.0187	0.0058	0.04	0.0049
Sr	0.0228	0.0012	0	0	0.068	0.0034	0	0
Na2O	0	0	0	0	1.07	0.05	0.86	0.043
MnO	0	0	0	0	0.258	0.013	0.17	0.008
P2O5	0	0	0	0	0.1	0.005	0.07	0.0033
Cl	0	0	0.0172	0.0024	0.0421	0.0024	0.7	0.035
Zr	0	0	0	0	0.0264	0.0017	0.01	0.0009
Br	0	0	0.0882	0.0026	0.035	0.0011	0.06	0.0019
Cu	0	0	0.0113	0.0017	0.0195	0.0015	0.03	0.0014
Ba	0	0	0	0	0.0194	0.0035	0	0
Pb	0	0	0	0	0.0176	0.0044	0	0
Cr	0	0	0	0	0.0096	0.001	0	0
As	0	0	0.0246	0.0079	0	0	0.04	0.0064
SrO	0	0	0.129	0.006	0	0	0	0
Sm	0	0	0	0	0	0	0.02	0.0024
Rb	0	0	0	0	0	0	0.016	0.008
Er	0	0	0	0	0	0	0.015	0.0012
Yb	0	0	0	0	0	0	0.07	0.0044
Dy	0	0	0	0	0	0	0.01	0.0014
Ho	0	0	0	0	0	0	0.04	0.0022
Tb	0	0	0	0	0	0	0.02	0.0021

2.2 Sedimentation column

The soil behaviour was investigated from its first phase, the liquid phase, up to its plastic state after consolidation. For the liquid phase, only the time to effective stresses formation is of interest to ensure that laboratory testing mimics the field condition. Dimitrova and Yanful (2011) and Gan et al. (2011) discussed the concept of effective stress initiation after sedimentation, thereby initial void ratio at zero effective stress is achieved. The sedimentation and consolidation processes continue until all excess pore pressure is dissipated and the soil grains become in contact with each other. This concept was verified by pouring the tailings in slurry state into a graduated cylinder 6 cm in diameter to a height of 30 cm. The sedimentation process was monitored until the soil top surface level had not changed for a week and the tailings coefficient of permeability was evaluated. The results demonstrated qualitatively how long the tailings deposit took to change from slurry state into a soil stratum ponded by water from top, which was analogous to field condition where tailings deposits are successively placed on top of each other, and sedimentation and consolidation processes occur. Figure 2 depicts the interface level (i.e., height of soil-water mix) change versus time. The slurry behaved as a viscous liquid during the first hour, when fastest change occurred in interface height. It then transferred to a much thicker, paste like, material that had excess pore pressure (EPP) which dissipated with time and effective stress increased. The required time for self-weight consolidation was 7.6 hours, which is almost 7 times higher than the results of Dimitrova and Yanful (2011). This is attributed to the properties of tailings such as the particles fineness and amount of fines, which affect the drainage properties. However, the same trend was observed in terms of the line that defines the primary consolidation and the slightly descending line thereafter that constitutes the secondary consolidation phase. For a layer of 30 cm high (height considered in the test) is placed on impervious layer, the time required for contact stresses between soil particles would be around one day. The interface level change indicates that the coefficient of consolidation of soil was 0.548 cm^2/min. which lies close to the boundary established from the Oedometric test results reported later. As the slurry thickness increased, the time for the soil particles to sediment and for the effective stresses to form would increase. However, slurry thickness can be smaller as the reported heightening rates are in the range of 3 to 5 m per year which translates to 42 cm per month maxima. Meanwhile, some mining companies use a quite shorter time for constructing layers, e.g., 3 m layers were constructed in 10 days (Zardari, 2013). Hence, assessing the excess pore pressure development is of utmost importance for stability reasons. Furthermore, the sedimentation process is affected by the particle arrangements, angularity, specific gravity, size, and electrochemical repulsive/attractive forces. Therefore, caution should be exerted as to not rely on this estimate and map it to other tailings.

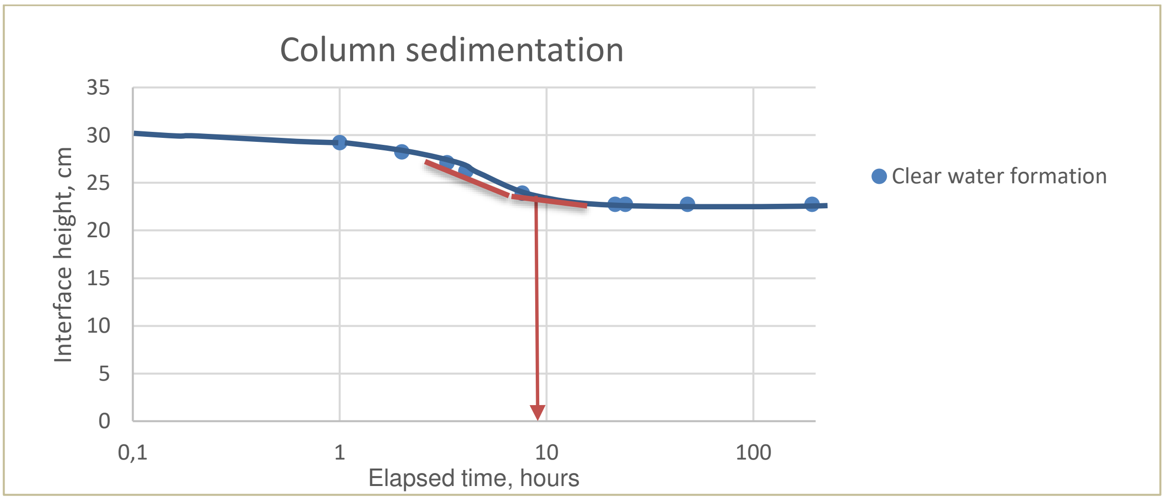

Figure 2. Sedimentation or self-consolidation of tailings and clear water formation for tailings 1.

2.3 Characterization tests

2.3.1 Sieve analysis and hydrometer tests

Sieve and hydrometer analyses established the gradation of tailings1 as shown in Figure 3. The mean particle size, $D_{50\%}$, effective particle size $D_{10\%}$, Coefficient of uniformity, C_u, and Coefficient of curvature and C_c are presented in Table 2. In addition, the specific gravity G_S was found to be 2.69 (ASTM D 854).

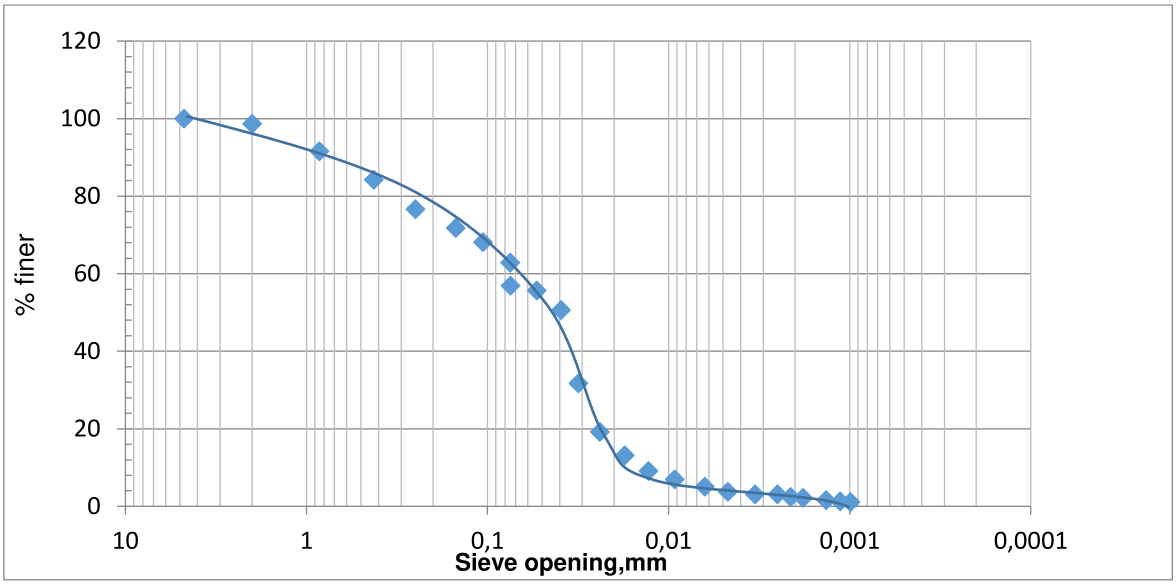

Figure 2. Sieve analysis test and hydrometer test's graph for tailings1.

2.3.2 Atterberg's limits tests

Oven-dried tailings1 sample was sieved through #40 U.S sieve, crushed gently with a pedestal for 10 minutes. The specimen was then tested to determine its liquid limit (LL) and plastic limit (PL) and plasticity index (PI) using Casagrande's apparatus in compliance with ASTM standard (ASTM D4318). The soil was non-plastic with LL = 48%. The results are also listed in Table 2. The soil is classified as low plasticity silt, ML according to the ASTM D2487 standard.

Table 2. General physical properties of tailings1.

Index parameters	Value
USCS of the tailings	ML
Mean particle size, D_{50}(mm)	0.045
Effective particle size, D_{10}(mm)	0.018
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

2.4 Consolidation and strength testing

2.4.1 Oedometer Test

The tailings were received in a slurry form (LI = 1.34). Therefore, the sedimentation column testing was done first. The tailings void ratio was determined from Oedometer test results. The soil slurry was placed in a bottom-perforated cylindrical mold and allowed to self-settle for a day. To reduce its water content and establish grain-contact between soil particles, it was pressurized with 0.25k Pa for 24 h (based on soil behaviour observed during the sedimentation column). After 24 h of dewatering, the soil was transferred to the Oedometer ring. The water content W_c was measured and the oedometer test was conducted according to ASTM (D2435). The sample was allowed to consolidate in the oedometer for 12 h and the initial water content was 51.1%. Figure 4 shows the e-log σ' curve for the untreated soils.

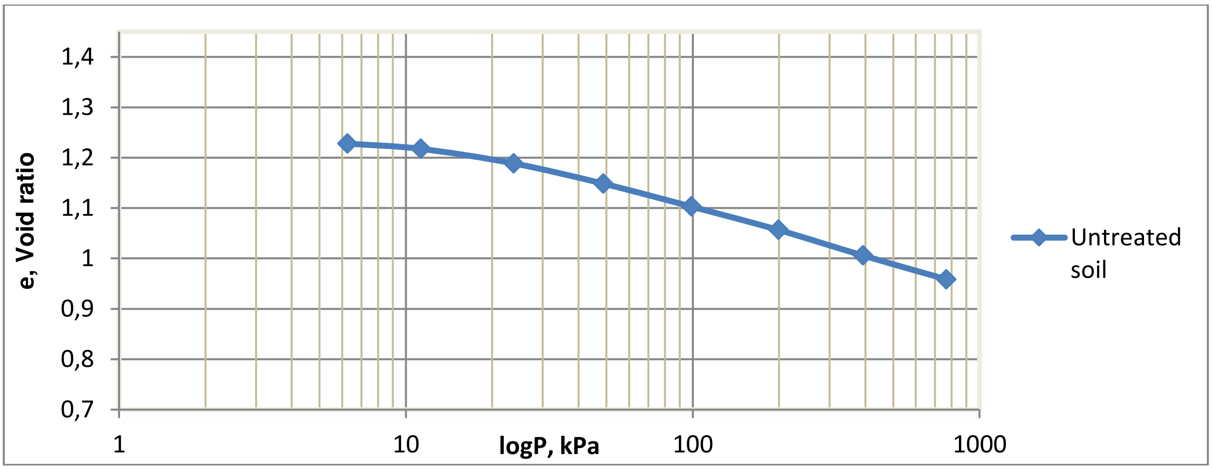

Figure 4. *e-log σ' curve of the untreated tailings 1*

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

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

where e is void's ratio and σ' is effective stress, subscripts 1&2 are arbitrary points on the virgin consolidation line. C_c ranges from 0.1 to 0.2 for silty soils and 0.2-0.3 for clayey soils (Vick, 1999). No rebound measurements for the untreated materials were recorded. Therefore, only Cs values were compared to treated tailings. The measured Cc value was 0.1548. Figure 5 presents the volumetric strain of untreated tailings versus log σ', which indicates the amount of consolidation settlement. It should be noted that one of the desired outcomes of treating the tailings is to reduce the coefficient of compressibility of the treated tailings to minimize the consolidation settlement.

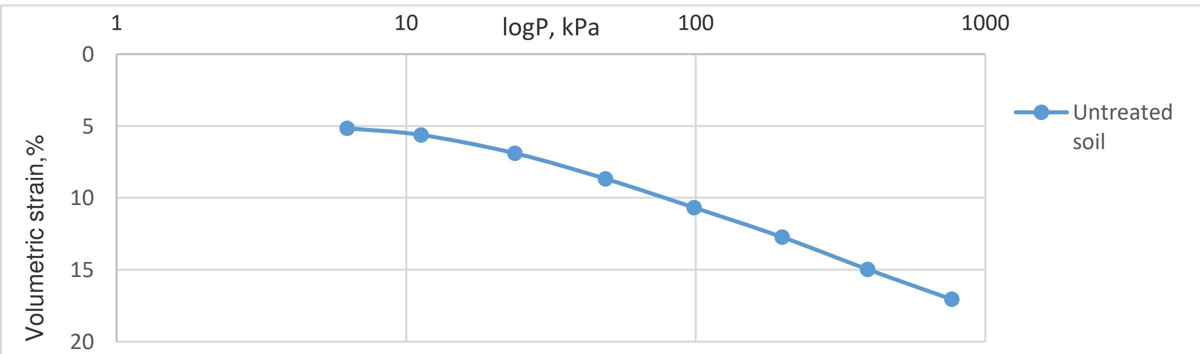

Figure 5. *Volumetric strain against effective stress of untreated tailings 1*

The coefficient of consolidation, C_v, measurements were taken for the untreated tailings at different loading steps to establish lower and upper bounds. The C_v values were established and plot with e-log σ' and a general increase of their value was observed as effective stresses increase. The coefficient of consolidation, C_v, ranged from 0.1 to 0.5cm^2/minute as shown in Figure 6. C_v measurements were done using Taylor's method (Das, 2006). Figure 6 shows that C_v obtained from the sedimentation column is much higher than the average C_v value of 0.38 cm^2/min. It is noted that the tailings exhibited a volumetric reduction of 17.05% of the original volume when the tailings material was consolidated to 765 kPa.

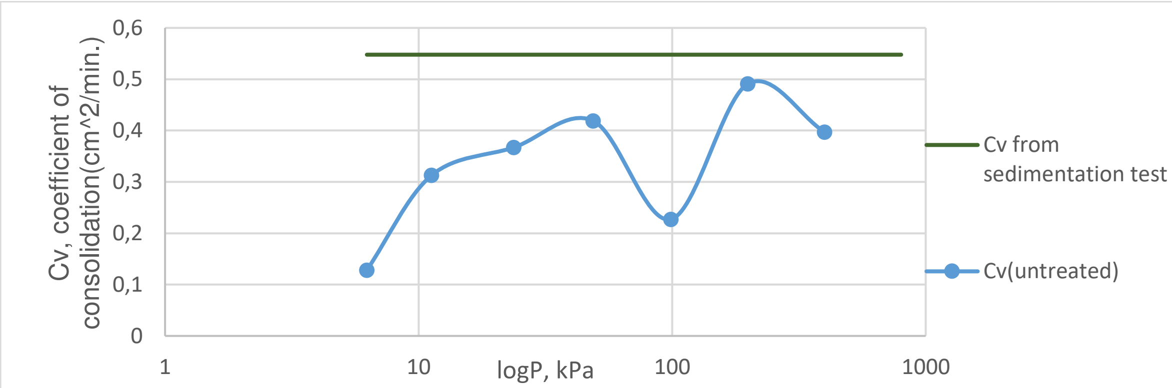

Figure 6. *C_v values at different effective stresses of untreated tailings 1.*

2.4.2 Shear strength

The shear strength parameters of untreated and treated tailings were measured through two laboratory tests: direct shear test (DST) and unconfined compression strength test (UCS). These tests measure the strength parameters in accordance with anticipated soil behavior: drained or undrained, and consolidated or unconsolidated. The expected tailings behavior in the field is neither fully drained nor undrained because of the unpredictable soil gradation a specific distance away from the discharge point. However, the effective stress analysis, ESA, is considered where the resulting EPP is accounted for in the numerical model along the potential slip surface length. Therefore, it was decided to use drained DST to determine the strength parameters of the treated and untreated tailings.

Direct shear test (DST): The device used in this testing had a square box 60x60 mm with fully computerized data logging system. It had two LVDTs (accuracy (_-^+)0.01 mm), for vertical and horizontal displacements, which are hocked to the Daisy lab logging program. The machine was equipped with two normal loading cells, one vertical to the box and one was shifted to make use of the mechanical loading using a lever arm. The maximum normal pressure that could be applied is 0.6 MPa.

The test was conducted in accordance with ASTM (D3080) using strain-controlled loading with a rate of 0.03 mm/min. At least three samples of each material were prepared and tested at 3 different normal stress values to establish the shear strength envelope of the material tested. The ratio of the inner dimension of the shear box to the largest particle size encountered was 30, which is higher than the minimum established ratio of 10 in laboratory standards; and thickness to maximum particle size was 20 which is higher than the minimum value of 6 (Benson et al., 2008; ASTM D 3080).

2.5 Tailings treatment investigation

Two types of additives were used: traditional and non-traditional admixtures. Traditional additives are commonly used in practice such as lime, cement, fly ash, gypsum, cement kiln dust and slag furnace. The non-traditional additives have been used quite recently such as polymeric derivatives, fibers, and emulsified polymers. Most failure incidents were attributed to the weakness of tailings material. Therefore, some additives were examined in the laboratory study to evaluate their strengthening effects on the tailings, which was evaluated through change in shear strength.

2.5.1 Non-traditional additives

A non-traditional additive (polymeric emulsion product) was employed in the study. The water soluble polymer was previously used in concentration of 20% in expansive soil and improved the erosion resistance (the soil erosion potential upon rain event and expansive potential were reduced, Liu & Huang, 2012. Examples of polymer emulsions used to treat tailings include: vinyl acetate and acrylic-based copolymer (Tingle et al., 2007); lignosulfonate with polyvinyl alcohol and polyacrylamide (Liu & Huang, 2012) and polycarboxylated acrylic acid polymer (Moghaddam, 2010). The emulsified polymer used in the current study was 53% water and 47% solids. It increased the bonds between soil particles and had a low viscosity that enabled it to permeate through the soil particles therefore facilitating good mixing condition. The soil improvement employing polymeric emulsions was evaluated. The supplier indicated this material is quick hardening material and attains its full strength in 1 day. The measured unconfined compression strength (UCS) of this material was 1MPa. Even though the polymer improved the behaviour of the treated soil, the strength improvement did not reach the target strength, so the results are not presented here and the polymer was not pursued further.

2.5.2 Traditional additives – optimization study

The effectiveness of traditional additives in improving the tailings consolidation behaviour and strength was evaluated initially in an optimization study. Recycled gypsum, B, mixed with CKD in different ratios was mixed in different percentages with tailings2. The percentages of the additives were 5, 10, and 20% of the total weight of the tailings samples. Batches were casted in plastic molds and tested for UCS at 7 and 14 days. This study investigated the effects of increasing recycled gypsum percentages in the mix proportion. Once the effects of gypsum are evaluated considering different percentages, the optimum proportions of B: CKD were selected and implemented in the remainder of the study.

2.5.3 Shear strength

Unconfined compressive strength (UCS) tests were conducted in accordance with ASTM (D2166) on the treated tailings specimens prepared with additive (CKD: B mixture) three different percentages: 5, 10 and 20% to the total weight of the tailings2. The additive was slowly added to the slurry while stirring. The slurry was mixed with hand mixer thoroughly for 5 minutes, then casted in three lifts into greased cylindrical molds 50 mm in diameter and 100 mm high. Each lift was tapped 10 times with a 2mm diameter rod, ensuring the tapping is distributed evenly across the area of each lift, then placed on the shaking table for 2 min. The casted samples were exposed to air at normal room's temperature for 24 hours, then capped with lids till testing after7 and 14 days curing. UCS tests were carried out using strain-controlled machine with strain rate of 4.3mm/min. Soil treated using gypsum achieves most of its maximum strength in the first 14days (Ahmed et al., 2012); therefore, the treated soil was tested after 7 days and after 14 days. In total, thirty samples were casted, half of them were tested after 7 day and the other half was tested after 14 days. After the specified curing time, the samples were placed in the UCS test machine. The failure plane in most tests was not well-defined for sheared samples. After shearing, the water content was measured to establish the dry unit weight.

2.5.4 Final tailings treatment scheme

The traditional additives were attempted to achieve the target strength improvement. Kamei et al. (2017) reported that a mixture of recycled Gypsum, Bassanite (B), and cement kiln dust (CKD) resulted in substantial improvement to tailings. Therefore, B, and CKD were considered as candidates for tailings treatment in the current study. Unconfined compression strength testing was employed to determine the strength of soil treated with the CKD: B admixture. Based on the results of the optimization study, two different treatment schemes involving cement kiln dust (CKD), basanite (B) and ordinary cement (OC) were applied to tailings 1. The treated tailings were prepared by mixing the tailings1 slurry with: 7.5% of admixture (1CKD:1 B: 1OC); and 7.5% of admixture (0.45CKD:0.45B:0.1OC). Ordinary cement was added to the mix because the DST samples were soaked in water one day before testing and it was observed that those samples without cement disperse almost immediately after being placed in water. Ahmed et al. (2018) made similar observation and attributed that behaviour to the fact that the calcium sulfate dehydrate is soluble in water. The slurry was first poured into the bowl of the kneader and the admixture was slowly poured in while stirring the slurry. The rotating speed of the kneader was increased gradually. The time of mixing was set to be 5 minutes to avoid bleeding or segregation of the mixture.

The resulting batch was then poured into specially fabricated square boxes 62 x 62 x 20 mm. The batch was kept in the normal room temperature.

3 RESULTS

3.1 Oedometer test

Figure 7 compares the consolidation behaviour for the treatment schemes along with the untreated tailings. The admixture combination (0.45 CKD: 0.45 B: 0.1 OC) at 7.5% did not increase the stiffness. This is because the bonds were weak and intangible; or the bonds collapsed when the effective stress exceeded 50kPa. However, substantial improvement was achieved when the tailings were treated with the 7.5 % admixture of (1CD:1B:1OC). The volumetric strains were drastically reduced from 17% to 2% as observed in Figure 7b. This huge reduction is attributed to the higher percentage of cement. On the other hand, the treatment increased the solids in the slurry volume, reducing the water content and void ratio, and thereby increased the dry unit weight. This has also reduced the hydraulic conductivity.

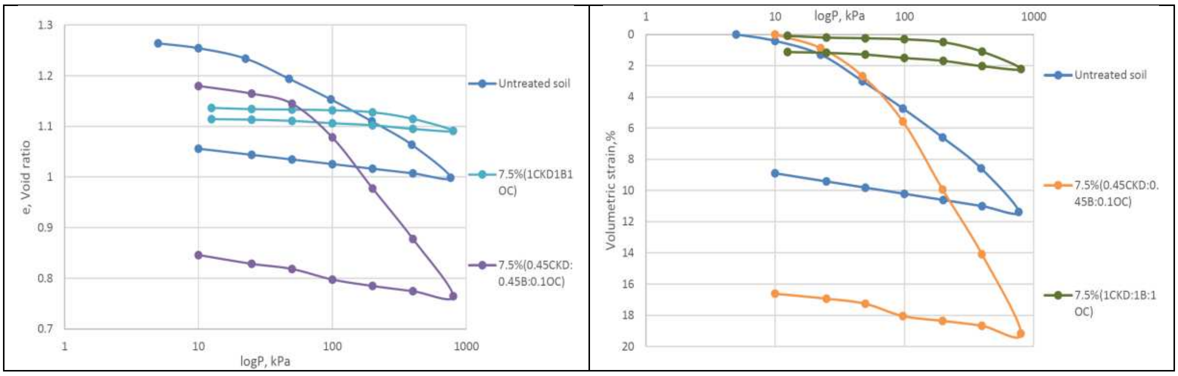

***Figure 7**. Consolidation behaviour for treated and untreated tailings*

3.2 Direct shear test

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 0.03mm/min) was applied to ensure shear induced EPP is dissipated. Figure 8 compares the shear strength envelope of tailings treated with 7.5% admixture of (1CKD:1B:1OC) with that of the untreated tailings. As can be noted from Figure 8 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. 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 8. On the other hand, the admixture combination 0.45CKD: 0.45B: 0.1OC had minimal effect on the shear strength envelope (only 11kPa increase in cohesion). The cohesion increase is attributed to higher dry density and not to cementitious bonds.

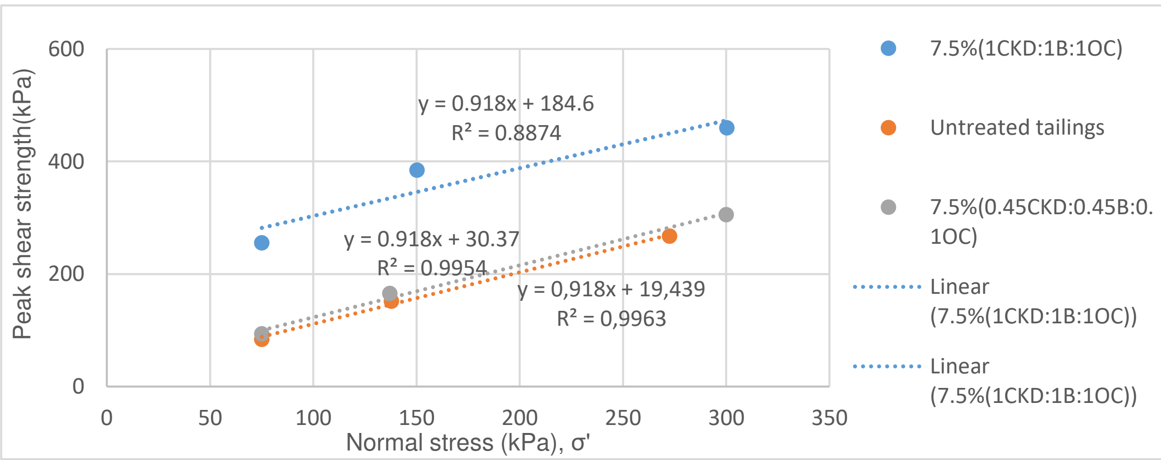

***Figure 8**. Shear strength envelope of both treated and untreated tailings*

Based on the shear strength tests conducted in this study, the strength properties of treated and untreated tailings are provided in Table 5. 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.

Table 3. 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

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:

1. Use of cementitious materials that increase the shear strength and stiffness is desirable.
2. 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.
3. 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.
4. In field applications, sufficient curing time should be allowed for the material to gain its strength. Sufficient curing should be allowed before adding another layer to avoid the adverse impact of water and to enable most of the shear strength gain before loading the treated tailings in the staged construction.

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