

## EXPERIMENTAL MODIFICATION OF A COPPER TAILINGS FOR IMPROVED WATER RECOVERY

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### ABSTRACT

Efficient water recovery is a key issue for mining, especially in arid and semi-arid environments. Klohn Crippen recently carried out a water reclamation study for a copper tailings facility located in a desert region. Material characterization revealed that the main cause of poor water release from the tailings was high clay content and the associated bookhouse fabric of the clay that retains pore water. To improve water release from the tailings, laboratory scale test work focused on modifying the soil fabric using mechanical and chemical methods. This paper presents self-weight settling tests for the copper tailings with the addition of sand and sodium hexametaphosphate (SHMP). Test data are studied in conjunction with inherent soil properties: tailings gradation, pore water chemistry, and the resulting microstructure. Results indicate possible improvements in water recovery of up to 56% for sand addition and up to 91% for SHMP addition.

### RÉSUMÉ

Dans le secteur minier l'extraction de l'eau dans les déchets est très importante, spécialement pour les régions désertiques et semi-désertiques. Récemment, Klohn Crippen a fait une étude sur l'assèchement de déchets produits par l'extraction du cuivre dans une région désertique. Des tests sur ce matériel ont révélé que le bas niveau d'assèchement est principalement dû à la haute concentration d'argile et à la structure en "château de carte" de l'argile qui retient l'eau dans les déchets miniers. Des tests en laboratoire ont été exécutés en se concentrant sur la modification des déchets miniers, en ajoutant des méthodes tant mécaniques que chimiques pour augmenter leurs capacités d'assèchement. Ce rapport démontre la façon dont les déchets miniers de cuivre se déposent par gravité en utilisant du sable et du sodium hexametaphosphate (SHMP). Les résultats de tests ont été étudiés en conjonction avec les propriétés existantes du sol: gradation des déchets miniers, la chimie de l'eau dans les pores, et la microstructure finale des déchets. Les résultats indiquent des améliorations de l'assèchement du sol jusqu'à 56% en ajoutant du sable et jusqu'à 91% avec en ajoutant du SHMP.

### 1. INTRODUCTION

Efficient water recovery is a key issue in mining operations throughout the globe. This is especially the case in arid and semi-arid environments where ambient rainfall is scant and sporadic, and fresh water sources are usually scarce (Chambers et al. 2003). Klohn Crippen recently carried out a research study of water reclaim from a copper tailings facility located in a desert region that receives an average annual rainfall of less than 25 mm. The main objective of this work was to provide a fundamental understanding of the mechanisms governing current tailings behaviour and to investigate modification methods for improved water release.

Based on laboratory investigations, this paper discusses self-weight settling test results in light of inherent material properties: tailings gradation, pore water chemistry, and the resulting microstructure. Tailings behaviour was improved using mechanical and chemical methods. To investigate coarser ore grinding, tailings gradation was altered by adding 5%, 10%, and 15% sand (screened tailings material coarser than 0.075 mm). To manipulate soil fabric by modifying pore water composition, various chemical additives were screened. These included hydrogen peroxide ( $H_2O_2$ ), sulfuric acid ( $H_2SO_4$ ), hydrochloric acid (HCl), alum ( $NaAl(SO_4)_2 \cdot 12H_2O$ ), table

salt (NaCl), and sodium hexametaphosphate (SHMP) ( $(NaPO_3)_6$ ). Based on performance, SHMP (a known dispersing agent) was selected for detailed testing and used in dosages of 27 g/L and 82 g/L. The potential for increased water recovery was evaluated by improved water release in jar setting tests. Soil microstructure was also analyzed for the sample with the higher SHMP dosage after the settling test and compared with that without the dispersant.

### 2. MATERIALS AND METHODS

Tailings samples were collected at two stages in the mining operation. Sample A, which was obtained from a drop box in the tailings distribution system in September 2003, had been treated with a polymeric flocculant as part of the thickening process. Sample B was retrieved pre-thickener in October 2003 and was not treated with flocculent agents. The gradation of both samples was similar; the sand content (material coarser than 0.075 mm) measured  $28\% \pm 2\%$ .

Sand was added to Sample A in increments of 5% leading to a total sand content of 35%, 40% and 45% in the test samples. SHMP was added to Sample B with dosages calculated on the basis of increasing known water

composition of the control sample to a pre-determined value that resulted in a distinct soil fabric. Using the definition given by Likos et al. (2003), ionic strength of 0.3 moles/L and 0.6 moles/L were chosen to obtain a loose structure with large flocs and a compact fabric with small flocs, respectively; the corresponding dosages were 27 g/L and 82 g/L of tailings slurry water.

Index properties were determined for a preliminary assessment of tailings materials. Specific gravity ( $G_s$ ) was measured according to the ASTM Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer (D 854-00). Similarly, the consistency limits were determined according to the ASTM Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (D 4318-00).

X-ray diffraction (XRD) analyses were undertaken to study the composition and particle association of the tailings samples using a Phillips diffractometer, Model Pw 1710. A centrifuge was used to separate the bulk fraction (material coarser than 3  $\mu\text{m}$ ) from the clay fraction (material finer than 3  $\mu\text{m}$ ). This separation allowed to distinguish between aggregated (bulk fraction) and dispersed (clay fraction) particles.

Sieve and hydrometer analyses were conducted according to the ASTM Standard Test Method for Particle Size Analysis of Soils (DG22-63 (1998)). This procedure was modified to account for the initial dry mass of the slurry that was unknown because pre-test drying was avoided. Therefore, the soil sample was divided into two sub-samples; one for determining dry mass of the soil and the other for grain size analyses (Dusseault & Scott 1983). Hydrometer analysis was performed on slurry specimens after dispersing the soil mass by agitation with dilute alkaline sodium hexametaphosphate. The hydrometer test was followed by a sieve analysis on the same material washed with deionized water.

To appreciate the influence of pore water chemistry on geotechnical behavior, pH, electrical conductivity (EC) and  $\text{Na}^+$  and  $\text{Ca}^{2+}$  ion concentration in soil water were determined before and after the additive introduction in the settling tests. An Accumet 50 instrument with  $\pm 0.1$  accuracy was used to measure pH and EC. The pH was determined as per ASTM Standard Test Method for pH of Soils (D4972-01) and the EC was measured according to ASTM Standard Test Methods for Electrical Conductivity and Resistivity of Water D1125-95(1999). Likewise,  $\text{Na}^+$  and  $\text{Ca}^{2+}$  ions were determined by the Inductively Coupled Plasma (ICP) method using a Thermal Jarrell Ash IRIS Advantage. With EC in units of dS/cm, the ionic strength (I, moles/L) was calculated according to the following equation:

$$I = 0.0127 \text{ EC} \quad [1]$$

Settling tests were conducted at an initial solids density of 50% in 2.0 L (123 mm internal diameter) and 0.25 L (58

mm internal diameter) flasks. The ratio between the inside diameter to the initial sample height was 0.75 and 1.0, respectively. To run the test, a known volume of the slurry was poured into the flask and the change in height of the sample was recorded at regular intervals of time. The test was stopped after five days when no observable change in settling under self-weight was noted.

Scanning electron microscopy (SEM) was used for fabric assessment of the slurries using the microscope JSM-6301FXV, manufactured by Japan Electron Optics Limited (JEOL). To ensure an intact fabric with minimal disturbance, samples were prepared using cryogenic method (Erol et al. 1976). This involved the insertion of a 5 mm circular straw for withdrawing the slurry specimen. The sample in the straw was immediately frozen using liquid nitrogen at  $-208^\circ\text{C}$ . The frozen sample was broken and, for clear visual observations, the exposed fresh surface was sputter coated with a fine gold film. The scanning and recording speeds were 450 frame/sec and 40 sec/frame, respectively. Likewise, the incident electron beam was at a vertical distance of 30 mm and the voltage was kept between 2.5 kV and 5 kV. The micrographs were taken at representative locations with enlargements of 500 and 2000 times.

### 3. TAILINGS CHARACTERISTICS

Table 1 summarizes the index properties of the tailings samples. The specific gravity for both samples is 2.73 and the consistency limits are almost identical. Both samples are classified as low plastic clays (CL) according to the Unified Soil Classification System (USCS).

Table 1. Summary of Tailings Index Properties

Sample	$G_s$	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	USCS Classification
A	2.73	29	20	9	CL
B	2.73	27	20	7	CL

Based on XRD analyses, Table 2 gives the mineralogy of the tailings samples in terms of bulk and clay fractions. Quartz and plagioclase mainly occur in the bulk fraction and, because of their electro-chemically inert nature, are considered to be in a deflocculated form. Conversely, muscovite and the clay minerals (that is, kaolinite, chlorite, illite, and smectite) exist in both aggregated and dispersed forms as indicated by their presence in both bulk and clay fractions.

Tailings mineralogy is related to the geology of the mine deposit. Muscovite is typically derived from sericite by metamorphism along cleavage planes in plagioclase

Table 2. Summary of Tailings Mineralogy

Sample	Fraction	Weight (%)	Qtz (%)	Plag (%)	Musc (%)	Kaol (%)	Chl (%)	Ill (%)	Smec (%)	Clay Minerals (%)
A	Bulk	79.0	54	8	18	9	2	9	0	20
	Clay	21.0	1	0	35	42	11	9	1	64
B	Bulk	80.5	58	3	18	7	7	7	0	21
	Clay	19.5	1	1	40	42	7	8	1	58

Notes: Qtz = Quartz, Plag = Plagioclase, Musc = Muscovite, Kaol = Kaolinite, Chl = Chlorite, Ill = Illite, Smec = Smectite

feldspar. Similarly, the clay minerals (kaolinite, chlorite, illite, and smectite) originated from argillic alterations in the ore. Muscovite, chlorite and illite are all micaceous minerals derived from mica. The addition of mica to sand is reported in the literature to reduce compressibility (Mitchell 1976).

The clay fraction in the tailings material depends on geology, ore crushing in the mill and dispersion during flotation and thickening. Table 2 indicates that 19.5% to 21% of the tailings samples are less than 3  $\mu\text{m}$  in size, and clays comprise most of the particles less than 3  $\mu\text{m}$ . It follows that defining material finer than 3  $\mu\text{m}$  as clay fraction is reasonable for the investigated tailings.

Figure 1 shows that the materials are fine grained with a maximum grain size of 0.85 mm. The sand size fraction measured 27.4% for Sample A and 29.9% for Sample B. The clay size fraction was 21.6% for the former sample and 22.5% for the latter sample. These values are consistent with those obtained from the centrifuge.

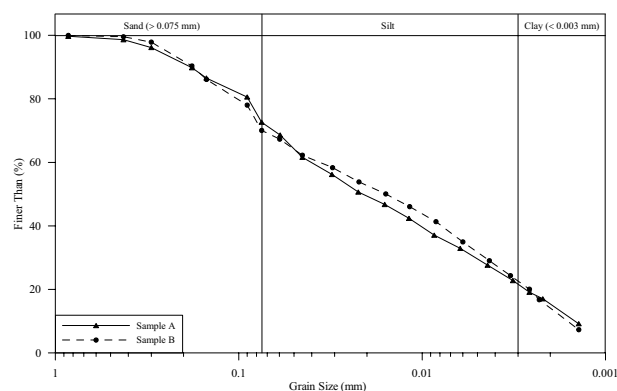


Figure 1. Tailings Gradation

Table 3 summarizes the pore fluid composition of the decant water from the tailings samples. The pore fluids of

both samples are basic with low ionic strengths. Theoretically, the higher ionic concentration of Sample B would result in thinner diffuse double layers of adsorbed water around clay surfaces. This would improve the rate and amount of the water release from the slurry undergoing self-weight settling.

Table 3. Summary of Tailings Pore Water Chemistry

Sample	pH	EC ( $\mu\text{S/cm}$ )	$\text{Na}^+$ (mg/L)	$\text{Ca}^{2+}$ (mg/L)	I (moles/L)
A	7.54	6850	848	691	0.09
B	8.24	8350	1150	747	0.11

Notes: EC = Electrical Conductivity  
I = Ionic Strength

#### 4. TAILINGS BEHAVIOUR AND MICROSTRUCTURE

Figure 2 presents the results of settling test in the form of height change as a function of the elapsed time. The dewatering curves for the investigated materials can be divided into three zones as defined by Pane & Schiffman (1997): the initial rapid decrease in height due to hindered sedimentation completes within the first day; this is followed by a slow height change during the transition zone that occurs between Day 1 and Day 2 of the test; finally, the slurry undergoes consolidation under self-weight at very low effective stresses. The slightly better dewatering of Sample B could be attributed to the higher ionic strength of the pore fluid as discussed above.

Most of the water recovery occurs during the first two days of the test. This means that the initial bleed is effectively completed within the first two days after slurry deposition. Additional water can be recovered during consolidation due to the surcharge of tailings layers deposited above.

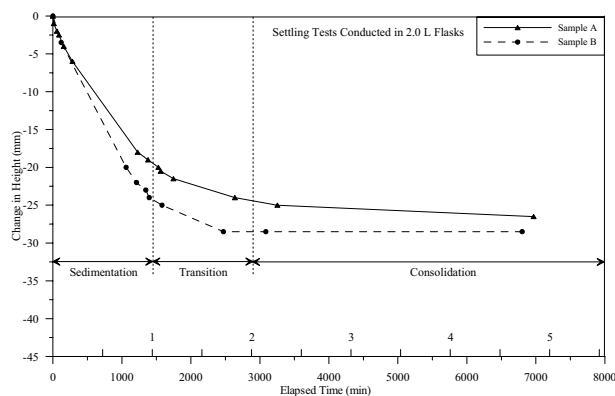


Figure 2. Settling Test Results

Figure 3 shows two SEM micrographs of Sample B. Micrograph (a) at a 500x magnification illustrates that the platy clay particles have assumed a preferred orientation whereas the occasional silt and sand grains are scattered in the clay matrix. Micrograph (b) at a 2000x magnification shows that the clay fabric is composed of a bookhouse arrangement of particles with bridging between the books thereby holding water within the successive layers. The aggregation of clay particles in the form of books (clay clods) is attributed to tailings gradation and the high ionic strength of the pore water. This observation provided the premise for this research work; altering gradation and/or pore water chemistry could improve water recovery from the tailings.

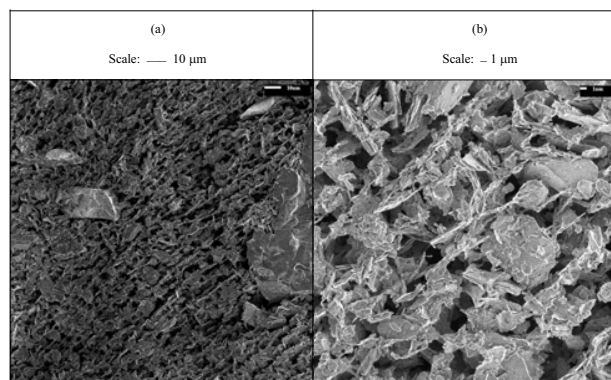


Figure 3. SEM Micrograph of Sample B

## 5. TAILINGS BEHAVIOUR MODIFIED WITH SAND

Figure 4 compares settling test results of Sample A with 0% to 15% additional sand content. The dewatering behaviour of the material is improved by the addition of sand which acts as a surcharge and facilitates the collapse of the clay fabric. The water recovery is directly proportional to the amount of added sand. The water recovery at test end improved by 56% when 15% sand was added to the slurry. The increase in sand content is verified by sieve analysis on the sample with 15% added

sand. Figure 5 shows that the total sand content of Sample A is increased to 45%.

Table 4 highlights the influences of clay/water ratio on the dewatering behaviour of the tailings samples. A consistent end of test clay/water ratio of about 0.28 was obtained for different amounts of added sand and this demonstrates that the pore water is predominantly associated with the clay phase. Therefore, coarser ore grinding in the mill to increase the sand fraction of the tailings is one of the viable options being considered to optimize water recovery.

## 6. TAILINGS BEHAVIOUR MODIFIED WITH SHMP

Figure 6 compares the settling test results of Sample B with those obtained by adding different dosages of SHMP to this sample. This figure shows that the sedimentation/transition phases of dewatering are completed within the first day of slurry deposition. It highlights that the dispersing agent starts interacting with the clay and the adsorbed water as soon as it is introduced into the system. This is because colloid-electrolyte interactions are at a maximum during the initial stages of hindered sedimentation (Azam 2003).

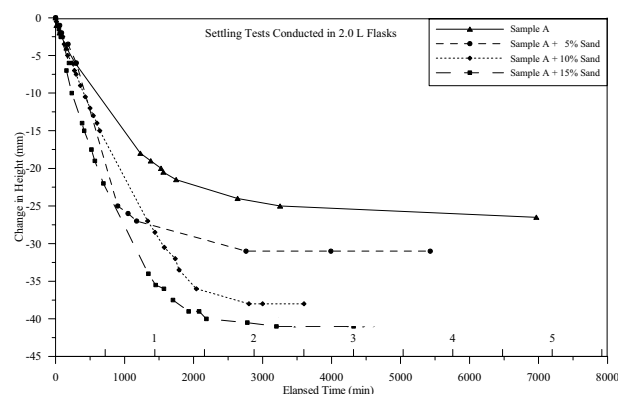


Figure 4. Settling Test Results for Sample A Modified with Sand

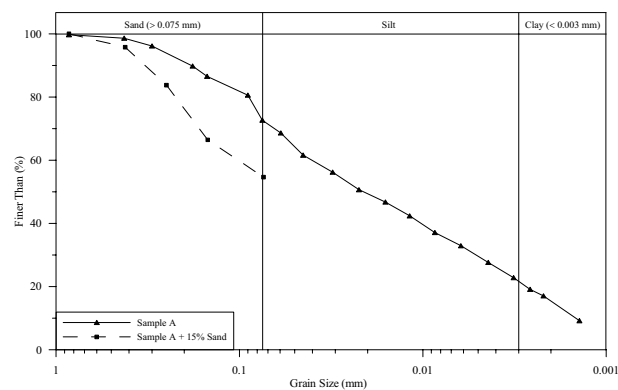


Figure 5. Gradation of Sample A Before and After Sand Addition

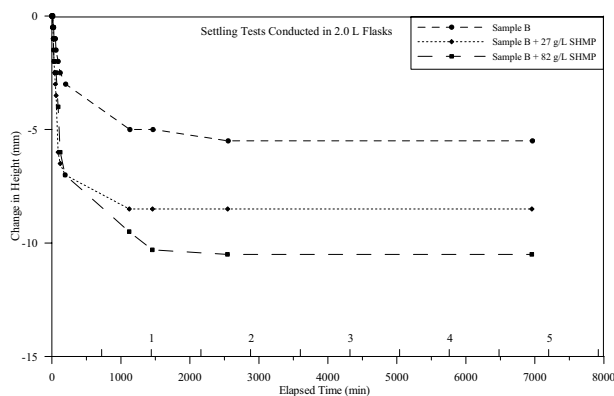


Figure 6. Settling Test Results for Sample B Modified with SHMP

Table 5 indicates that the dispersing agent reduces the pH of the system from basic to slightly acidic. This is because SHMP releases  $\text{Na}^+$  ion in solution and attracts  $\text{H}^+$  ion thereby producing phosphoric acid ( $\text{H}_3\text{PO}_4$ ). The large amount of dissociated  $\text{Na}^+$  ion depicted in Table 5 (about 4 and 8 times for the two dosages, respectively) is adsorbed onto the negatively charged clay surfaces thereby causing these surfaces to repel one another. However, some of the clay particles are still attracted at the edges due to unsatisfied charges. These interactions result in a dispersed clay fabric that allows a swift release of bound water. This water flows through channels (paths of least resistance) leaving behind a compressible soil matrix. Table 5 indicates that increasing the amount of SHMP in the investigated slurry improves water recovery. Water recovery at test end is increased by 91% when 82 g/L of SHMP was added to the slurry.

Figure 7 gives two SEM micrographs of Sample B modified with 82 g/L SHMP. Micrograph (a) at a 500x magnification illustrates that the clay particles are largely dispersed, and the clay fabric is devoid of any visible preferred orientation and contains silt and sand grains scattered in the soil matrix. Interpretation of micrograph (b) at 2000x magnification suggests that bridging between the bookhouses of clay particles may be reduced by the addition of SHMP. Similarly, a majority of the clay particles appear to be acting independently because of the disintegration of aggregated clay clods. These observations corroborate the above mechanism that explained SHMP interactions within the colloid-electrolyte system.

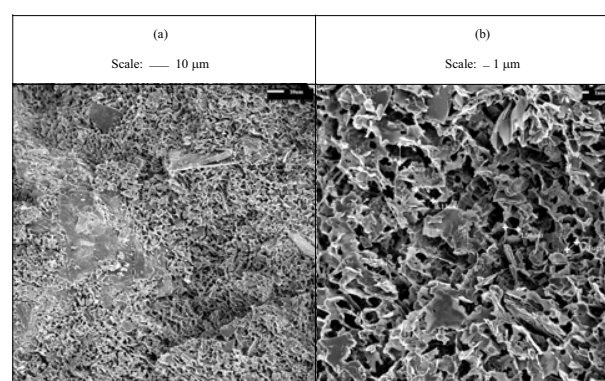


Figure 7. SEM Micrograph of Sample B Modified with 82 g/L SHMP

Table 4. Influence of Clay/Water Ratio on Water Recovery

Sample	Clay Fraction (%)	Water Content (%) At Test End	Clay/Water Ratio	Increase in Water Recovery (%) At Test End
A	21.60	80	0.270	-
A + 5% Sand	20.57 est	75	0.274	18
A + 10% Sand	19.64 est	69	0.285	45
A + 15% Sand	18.78 est	67	0.280	56

Table 5. Influence of Geochemical Interactions on Water Recovery

Sample	pH	EC ( $\mu\text{S}/\text{cm}$ )	$\text{Na}^+$ (mg/L)	$\text{Ca}^{2+}$ (mg/L)	Ionic Strength (moles/L)	Settlement (mm)	Increase in Water Recovery (%)
B	8.24	8350	1150	747	0.11	5.5	-
B + 27 g/L SHMP	6.44	16500	4250	167	0.30	8.5	55
B + 82 g/L SHMP	6.71	25100	8800	666	0.60	10.5	91

## 7. SUMMARY AND CONCLUSIONS

Efficient water recovery is a key issue for mining, especially in arid and semi-arid environments. Most of the reclaim water from the waste slurries is released during sedimentation after deposition. The amount of water recovered during sedimentation is governed by the size and arrangement of soil particles. Increased amount of large-size particles and chemical dispersion of the clay fabric creates flow channels, which improve water recovery. Based on both approaches, the main conclusions of this study are summarized as follows:

1. Both chemical and gradational modifications can manipulate a bookhouse clay fabric developed as a result of the high amount of clay (fraction and minerals) in the investigated copper tailings.
2. Sand addition improved water recovery by acting as a surcharge that facilitates compression of the clay-water matrix. Using 15% additional sand, a maximum improvement of 56% was observed in water reclaim from the slurry.
3. Sodium hexametaphosphate improved water recovery by dispersing the clay fabric thereby creating channels for water flow. Adding 82 g/L SHMP improved water recovery of the investigated materials by 91%.

## 8. REFERENCES

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