A survey study on hydro geotechnical properties of mines

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ABSTRACT: To response some problems in soil engineering it requires a detailed knowledge of the mechanical properties of soils that is probably among the most complex materials to be studied from this point of view. This paper examines the hydro-mechanical behavior of soil for mines according to different data. The present paper tries to present a reasonably comprehensive account of the relations governing the response of soils to applied forces. The main objective of this paper is to characterize the tailings deposit at mines in terms of its hydro geotechnical properties and present their vertical and horizontal distribution. In this study, relationship between each parameter has also been identified. According to the data collected from different mines, the investigation has been done from various levels. These evaluations include: particle density termination, Proctor compaction, permeability and grain size analysis. According to result, the horizontal hydraulic conductivity has been found to have a good correlation to fine fraction and void ratio.

Keywords: Hydro Geotechnical, Mines, soil engineering, permeability

INTRODUCTION

This research is aiming at defining the hydraulic conductivity of the tailings deposit comparatively with a good reliability. Along with the determination of hydraulic conductivity, it covers a number of geotechnical properties of the deposit material. These geotechnical properties are highly related to the hydrologic behavior of the tailings. By doing this investigation on a large portion of the deposit, it anticipates or provides the general trend of different parameters using empirical relations as well as graphical representations. Aims of the study could also be listed as the following:

- Determination of horizontal and vertical hydraulic conductivity of the tailings using direct laboratory measurement.
- Comparison of the measured values of hydraulic conductivity with predicted ones using existing empirical relations.
- Identify the distribution of hydro-geotechnical properties throughout the investigated area of the deposit.
- Identify and present substantial relationships between the measured parameters and the existing hydraulic conductivity predicting relations.

Literature review

This particular paper research has theoretical support from a number of previous studies in similar topics. Among these previous works, some of the main literatures are reviewed below. These literatures are written based on different experiments on tailings material in many different places. Alike this paper, their main concern is hydro geotechnical, geotechnical, physical and hydro geological characteristics of tailings material for specific tailing deposits or mine wastematerials in general. Finally, few works will be reviewed on determination of hydraulic conductivity of soils based on their grain size analysis.

Geoffrey Blight (2010): He has covered many aspects of geotechnical investigations and a characteristic of mine wastestorage facilities in general and tailings impoundment in particular. Mainly, he dealt with particlesize
analysis, permeability of the whole material and of its coarse and fine fractions, shear strength characteristics of the waste, in situ void ratio or density and particle relative density.

He summarized the particle size analyses for a number of tailings from the extraction of various mineral products. The actual particle size distribution for tailings depend on factors such as the fineness to which the ore is milled, the mineralogy and degree of weathering of the ore, the type of milling process, the separation or extraction process, etc. Grading may be very variable both at a single mine and from mine to mine, as well as being variable on a single tailings storage.

The need of determination of both vertical and horizontal hydraulic conductivities is due to their high difference between them. This difference is common as a result of hydraulic deposition. During deposition there is high potential of formation of layers or stratifications as well as grading down the length of the hydraulic beach. Ultimately, this difference in permeability will influence not only the shape of the seepage or phreatic surface at the perimeter of the wastestorage, but also possible seepage losses through the floor (or footprint) of the storage.

Blight stated that, in situ void ratio or density of tailings materials usually shows loose state as a result of mode of deposition is hydraulic. A loose structure combined with a high state of saturation may render the material liable to static or dynamic liquefaction.

He also mentioned that, particle relative density \( G \) has an influence on the density or unit weight of the waste and hence on volume/mass calculations. For many wastes the particle relative density has values in the range 2.65 to 2.75. Depending on mineralogy, the particle relative density may be as high as 3.5 to 4.

Jantzer et al (2008): They presented the general material properties of tailings from Swedish mines. Properties which were emphasized in their paper are shear strength and hydraulic conductivity. According to this paper, tailings are particles of crushed rock with particle sizes ranging from clay to sand. This paper states that size of tailings material varies from 0.01 mm to 1.0 mm, but up to 20 % of clay-sized particles, i.e. 0.002 mm, can be found. Such variations occur dependent on sedimentation, site and processing methods. Like Blight, Jantzer et al said that characteristics of tailings material could be dependent on origin and processing of the ore, as well as deposition methods. The origin affects the size and the gradation of the grains, the internal friction angle and the particle density; whereas the deposition method is responsible for bulk density, void ratio and porosity, and the hydraulic conductivity. Tailings generally have high water content and porosity, a low to moderate hydraulic conductivity and a low plasticity when compared to natural geological materials [1-3].

Based on this paper, tailings generally have a relatively low uniformity coefficient \( Cu \) between 3 and 8. The value is not constant, as it varies with the distance to the discharge point because of the sorting effect of sedimentation. Results from study on tailings of mine are included.

<table>
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<tr>
<th>Site</th>
<th>Measured Kv ( (10^{-6} \text{m/s}) )</th>
<th>Calculated Hazen ( (10^{-6} \text{m/s}) )</th>
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<td>1.41</td>
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These are measured and calculated hydraulic conductivity results and their comparison. (Table 1) The report concluded that measurement and calculation of the hydraulic conductivity of tailings appears to be difficult as the study shows that obtained values have a large variation and that increased void ratio does not always correspond to increased hydraulic conductivity.

A. Shamsai et al (2007): A research by A. Shamsai et al (2007) covered the geotechnical characteristics of tailings specifically for copper. They took one mine as a case study. In this research, many of the geotechnical and hydro geological parameters were determined. Comparison between grain size distribution curve of Iran whole tailings and other tailings from different mines are shown in figure 1. Mines that are included in this chart include Michigan whole tailings and Philippines whole tailings. Based on grind milling size of the extracted minerals, generally, the tailings are relatively coarse, with about only 45% finer than 0.075 mm on average.
One of the interesting concepts stated in this paper is the empirical relation between portion of tailing material finer than 0.075mm and void ratio and in turn hydraulic conductivity. Percentage of soil finer than 0.075mm, which is denoted as P200, is used to distinguish the characteristics of the soil in terms of its hydrologic behavior, [5,6]. Therefore, nine samples from tailings were chosen. After carrying out 9 tests for P200 = 55, 60, 65, 70, 75, 80, 85, 90, and 95%, values of hydraulic conductivity for different void ratios were determined indirectly through consolidation odometer test results. A mathematical relation has also been determined by Abolfazl et al. (2007) by fitting the curves above with R2 value of 0.984. This relation is shown as:

\[ K = 0.09 \times 10^{-0.009P200} \times \left( \frac{e^2}{e + 1} \right) \]

Equation (1)

Where: \( K \) = Hydraulic conductivity, in cm/sec, and \( e \) = Void ratio. Despite the simplicity of this equation, it has a limitation on P200 to be over 50%. However, it gives values of hydraulic conductivity for a wide range of void ratios between 0.3 and 1.1.[7].

R. Rodriguez in 2006 presented hydro-geotechnical characterization of a metallurgical waste. This study has given emphasis to chemical and mineralogical analysis, odometer test, tensile strength tests, determination of water retention curve, and shrinkage and permeability tests. Review of this study will be more of on the test results of saturated hydraulic conductivity and grain size distribution of tailings material from Ammoniac ammonium carbonate leaching (ACL) metallurgical waste (MW) in Moa mining district. Here, it is stated that, 99 percent of the residue has a grain size finer than 0.2mm, with a mean grain size of 20μm. (Figure 2) The material has an in situ density of about 2.30g/cm3, a particle density between 3.80 and 4.04, and a void ratio between 1.3 and 2.2.
It is also tried to show the relationship between saturate hydraulic conductivity and waste void ratio as in the figure 2. Based on the experiments, the tailings have a grain size distribution similar to that of silty soil. The relation between hydraulic conductivity and void ratio could generally be represented as:

\[ k_{sat} = e^y \]

Where: \( k_{sat} \) is saturate hydraulic conductivity (m/sec), \( e \) is void ratio and \( y \) is constant.

Hydraulic conductivity has important dependence on degree of saturation and varies significantly during drying process [9, 10].

Prediction of hydraulic conductivity for tailings from grain-size distribution might not be as successful as prediction on natural soils. This is because tailings are prone to several phenomena such as creation of new fines during compaction (if the test is done on disturbed soil sample) and chemical reaction during permeability testing. Moreover, shapes of tailings and natural soils are quite different while having equivalent diameters. Consequently, the predicted hydraulic conductivity must take these phenomenon into account.

A number of researches dealt with modeling and empirical formulation for hydraulic conductivity from grain size distributions. Hazen in 1893 proposed a formula which is oldest and originally developed for determination of hydraulic conductivity of uniformly graded sand but is also useful for fine sand to gravel range, provided the sediment has a uniformity coefficient less than 5 and effective grain size between 0.1 and 3mm [11, 12].

MATERIAL AND METHODS

Both field and laboratory investigations of the tailings deposit are carried out. Several data has been collected during these investigations. Based on the results of these investigations and analytical knowledge of both hydrogeology and geotechnical engineering, this study will come up with defined results and intellectual suggestions.

Field study comprises the following activities

- Making trial pits at different distances along selected three cross sections. Number and length of sections are controlled by accessibility of the digging machine and their representativeness of the section itself. Depths of test pit are affected by the presence of ground water and ice lenses. A maximum of 5m depth trial pit has been dug out.
- Detailed information will be provided in the later section.
- Logging of different soil layers according to their type and degree of compaction. This has to be carried out by measuring the thicknesses of every soil layer and giving detailed field descriptions.
- Records of field observations which might affect the general hydrogeotechnical properties of the deposit.

Determination of in place density using balloon density method. This test was conducted at an average interval of 0.5m vertically. The field density has numerous uses in determining the existing porosity and how stiff the deposit is.

- It is always important to follow certain test standards and procedures; therefore American Society for Testing and Materials (ASTM) standard was preferred to be used as the main basis and reference for this specific laboratory investigation. Although some modifications in the procedures are made, it has been seen that no test result is affected. Below are tests that are conducted in order to determine the parameter that helps to understand the hydrological setup of the deposit.

- Constant head permeability test is one of the major tests used in laboratory investigation of the tailings material. This test is mainly targeted in determining the hydraulic conductivity of the deposit in its different parts. It is carried out on 43 undisturbed soil samples taken in both vertical and horizontal directions. Permeability test has also been done on three disturbed samples after remolding it up to its field dry density. Particle size distribution test has been carried out on 35 samples which are taken from different depths in the three sections.
- Wet sieving using standard mesh sizes starting from 0.063mm to 2mm diameter have been used for part of samples coarser than silt size.
- Hydrometer and pipette analysis had to be used for the fine fraction depending on the amount of soil passing sieve size of 0.063mm. For those samples with less than 50 gram of this size, pipette analysis has been used, while hydrometer analysis was conducted on the samples having more than or equal to 50g of silty and clay particles.
- Modified proctor compaction test was supposed to be done for at least every 1.5-2m interval. This test helps to check the degree of compaction of the hydraulically deposited tailings by comparing maximum laboratory density moisture content of the soil collected from balloon density test has to be determined shortly after the test.
- Pycnometer test has been used to get the exact density of soil particles. This is very crucial for several phase relationship calculations such as porosity and void ratio that intern affect the ease of water flow through pores (permeability).
Particle density, porosity and void ratio results are in agreement with the range determined by [13-15] on different tailings deposit. Ice layers are encountered exactly above layers with higher silt and clay contents. Silty SAND is discovered to be the predominant soil type in the investigated area.

Because the study was able to cover only part of the whole deposit, further detailed investigation covering the whole area and depth of the deposit is recommended to be done in the future. Additionally, monitoring and continuous measurements are important to minimize uncertainty that could be caused by seasonal tailings property changes.

Sedimentation analysis (hydrometer, pipette, and buoyancy analysis) defines the grain size distribution curve of soils that are too fine to be tested by sieving. Sedimentation analysis sorts soil particles by size using the physical process of sedimentation, a process that is described by Stokes’ law (Stokes, 1891). The grain size is calculated from the distance of sedimentation of soil particles. The percent by weight finer is determined by measuring the unit weight of the soil fluid suspension.

This method further separates fine soil particles so that a complete grain size distribution curve can be produced by the end of this experiment. From this curve, many important aspects of the soil can be determined and a general classification of the soil can be made.

This test was conducted according to ASTM Designation: D 422 – 63, that deals about standard test methods for particle size analysis of soils. The hydrometer used was of type 151H. All the appropriate corrections such as dispersion agent correction, hydrometer reading correction, temperature correction, and hygroscopic correction have been done.

Diameter of soil particles was calculated according to stoker’s law as follows: (ASTM, Standard Test Method for Particle-Size Analysis of Soils, 1998.

\[ D = \sqrt{\frac{18\eta L}{(G_s - G_1)\rho_w T}} \]

Where: 
\( \eta \) = Viscosity of water at 20°C…10.09 mill poise
\( L \) = Depth at which the density of suspension is being measured, effective depth which is based on hydrometer. In this case for hydrometer 151H,
\( T \) = Interval of time from beginning of sedimentation to the taking of the reading, min,
\( G_s \) = Specific gravity of soil particles, and
\( G_1 \) = Specific gravity (relative density) of suspending medium

Ultimately, percentage of soil remaining in suspension at the level at which the hydrometer measuring the density of suspension was calculated as:

\[ P = \text{Percentage of soil remaining in suspension at the level at which hydrometer is measuring} \] (%) 
\( R_h \) = Corrected hydrometer reading

Figure 3. Hydrometer used type 151H (Left) and hydrometer testing on tailings (Right)
Hydrometer analysis was accomplished on 15 soil samples which are taken from section-A and Section-B. Among the fifteen samples, ten of them are from section-A, and the remaining five were from section-B. No samples were found to be enough for hydrometer test from section-C. This might give an implication of soil from section-C is coarser than soils in section-A and section-B.

Pipette Analysis: This is for the determination of the sub-sieve particle distribution in a soil sample by mechanical analysis. An analysis of this kind expresses quantity the proportions by weight of various sizes of particles present in the soil. Similar to hydrometer test, it is recommended as a standard procedure to use dispersion agent to avoid flocculation.

The apparatus used consists of regular sampling pipette, capable of measuring 10 ± 0.2 mL of liquid, with a lowering and raising support. (Figure 3), Dispersion apparatus (1000ml), 500 mlof stock solution of sodium prepared as in the hydrometer test, many sedimentation cylinders, thermometer, ranging from 0 to 50°C, accurate to 0.5°C, stopwatch, and balance which is accurate to 0.001 g. It is observed that, this method is much faster than hydrometer and gives opportunity to work on a smaller amount of samples than hydrometer.

Pipette analyses were used for most of the tailings material collected. This was due to the availability of fine fraction in the samples. In other words, more than 60% of the collected samples (25 in number) had not enough amount of fine fraction for hydrometer analysis (which should be a minimum of 50gm). Procedure and analysis of this test were adopted from [16], which is based on British Standard.

RESULT AND DISCUSSION

In this section of the report, summary of results and their interpretation according to the general trend and previously studied literatures will be provided. Moreover, the author will also make opinions based on experience and practical records during the field investigation of this study. Various properties of the deposited material with their lateral and vertical distribution will also be provided graphically, tabulated form and as a map using software like surfer. This will help to know and understand the hydro-geotechnical characteristics of tailings deposit. Many of the correlations and comparisons are seen along section-A, because of many reasons. One of them is; it is the longest and most accessible section. However, few analysis and correlations are made in the other remaining sections and the whole investigated area too.

Although the investigated depth is the top most 5m of the whole deposit, it is highly crucial to have precise information about it. This is because; the deposition is cyclic in which similar processes are taking place every time. The profile of the top layers could give a clue about the layers deep in the whole deposit as well as far into the pond.

Several layers with different color and texture are observed along the selected sections and vertically down through the test pits. Before any of the laboratory tests, field description and nomenclature of each layer are given. These names have been modified after determining the exact proportion of different particle sizes. Generally, the deposit is composed of Silty Sand soil intercalated with some thin layers of silty and clayey soils. The main difference between the observed layers is the amount of fine (silt and clay) content. In some parts of the investigated area, ice layer having thickness ranging from 10-40 cm were encountered. The ice layers are generally lying horizontally at a depth of 1-1.5m. Section—A is composed of light to dark gray silty sand. Ice layer is encountered at 320m from A-B dam at a depth of 1.1m. This ice layer possesses thickness ranging from 8 to 10 cm. and laterally the width of the ice is measured to be 3.5m. It has also been seen in other sections at different levels, forms and variable thicknesses. This thin layer of ice could possibly be a remnant of old waste water channel which is frozen during winter season and afterwards soil deposition took place on it.

Immediately below the ice layer; there is dark clayey silt which has a thickness of 1.4m and high water content. The existence of clayey silt layer could be one of the reasons for the formation of the ice layer. This might be due to low permeability of the clayey layer so that the water during winter period could take longer time to infiltrate before it is changed to ice. Ground water was not encountered in this section up to 5 meters except at test pitA5. Pit A5, 650m from A-B dam exhibited some sign of ground water at which the wall of the pit has been unstable due to high water content.

Field bulk and dry density were determined and presented in Appendixes D. Few explanatory graphs showing the distribution of bulk and dry density in the deposit and their description is provided in this section of the report. It is observed that the deposit has more consistent bulk density throughout the section at the surface than those at depth, (Figure 4).
Figure 4. Variation of field bulk density with distance from C-D dam along section B for depth ranges from 0 - 2.5m.

As it can easily be noticed from the chart, Figure 6, dry density of the deposit increases with depth. This increment is expected to be a result of consolidation and densification of soil found in the deeper level due to the weight of overlying layers. Generally, as the overlying layer is thinner, the increment of density with depth is comparatively very low.

Points possessing relatively higher density indicate the existence of thin layers of fine materials which are denser but located in the upper levels of the deposit. A very low dry density has also been observed in some of the levels. For example, sample taken from 2.0m depth at test pit A2 has a dry density of 1.27g/cm3 which is very low. The possible explanation for such an experience could be related to its high water content and stress history of the soil at that level. According to the test results, water content of soil at the level is about 25% and it is observed that the layer at this depth was frozen. Moreover, a very slight increment of density could be seen from the overall trend of the curves (Figure 7).
By making a trend line on the above graph, dry density is found to be higher at far inside the tailings impoundment than at the periphery of the deposit. For instance, horizontal variability in dry density from axis of dam A-B towards the center of the impoundment is shown in Figure 7.

**CONCLUSION**

Based on the results of laboratory and field investigations and some empirical analysis, conclusions and recommendations for future work have been drawn.

Silty SAND is discovered to be predominant soil type in the investigated area.

The horizontal hydraulic conductivity has been found to have a good correlation to fine fraction and void ratio. Similar to the results of Jantzer et al., the increased void ratio did not correspond to vertical hydraulic conductivity.

Determined particle density, porosity and void ratio results are in the range determined by [16] on different tailings deposit.

The existence of ice layers is directly related to the amount of fine fraction in the layer below it. In other words, ice layers are formed on top of layers which have relatively higher silt and clay content. Hazen formula has given 25 and 45 times more than measured values of vertical and horizontal hydraulic conductivity respectively. On the other hand, Chapuis et al. have not been succeeded for prediction of hydraulic conductivity of undisturbed samples. Generally, the horizontal hydraulic conductivity is 1.7 times higher than the vertical one.

Due to high water content low plasticity tailings deposit are not suitable for heavy investigation machines to ride on. So, it is highly recommended to use special types of machineries (For example, sort of snowmobile or a platform that can float on soft ground) for to facilitate access to different locations even on very soft areas.
Adequate monitoring and in situ testing of the whole deposited tailings are essential for the verification of geotechnical design parameters and performance assessment of tailings storage facilities in which the impounded tailings govern structural stability.

The in-situ methods of permeability measurement normally represent the hydraulic conductivity value of a larger volume of tailing bodies than the laboratory methods, so that the variability in the results is less. The size of sample for hydraulic conductivity matters on the effect of anisotropy of the stratified layers of tailings deposit, so large diameter samplers are recommended to get more reliable hydraulic conductivity values.

Further studies and detailed investigations have to be engaged in order to represent the whole area covered by the tailings. The future work has to be incorporating samples taken from reasonably all parts of the deposit with a small sampling interval.

Ground water monitoring is highly recommended as to know the actual gradient, pore pressure and flow directions. In addition, it is important to define the effects of ice layers on the general hydrological setup of the deposit.

REFERENCE