The Pennsylvania State University

The Graduate School

Department of Civil and Environmental Engineering

SYNTHESIS OF GEOTECHNICAL PROPERTIES OF TAILINGS

A Thesis in

Civil Engineering

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

May 2019

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ABSTRACT

Minerals and their products play a vital role in human's life after the 19th Century. In 2015, the value of coal, metals, and industrial minerals mined in the United States was over $100 billion according to the report of U.S Geological Survey (USGS). Tailings dams that are usually used to store these wastes encountered several structural failures in the past century. These catastrophes not only affect human's life but also pollute the environment. Recently, an iron tailings dam failure in Brazil on Feb 1, 2019 caused more than 60 deaths and significant economic loss. This study synthesizes the data that were presented in the previous publications in last 40 years along with the coal tailings data that were obtained by the Penn State (PSU) research team. This thesis compared the basic geotechnical properties of different mineral tailings and derived correlations of these properties. The results indicate that fine and coarse coal tailings tend to have lower specific gravity than other minerals. Most of the classifications of fine coal tailings belong to CL and ML. Copper tailings generally have higher hydraulic conductivity than gold tailings. Compared with other mineral tailings, fine coal tailings have the lowest hydraulic conductivity. This study also found that for fine coal tailings the percentage of clay size particles has higher impact on *PI* than fine content. The percentage of clay size particle and fine content, on the other hand, have very similar impact on *LL*. A relationship equation between fine content and coefficient of consolidation of fine coal tailings that are classified as SM or ML was derived in this study. The collected database showed that most of the mineral tailings still lack information in both basic properties (i.e. liquid limit and plastic index) and advanced laboratory testing. Even the existing data showed high variability. Compared to the large amount of usage in minerals, the information of mineral tailings is still very limited.

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ACKNOWLEDGEMENTS

First, I would like to thank my advisor Dr. Ming Xiao, who has been always supportive during my graduate study. I won't be able to accomplish what I did without his guidance and encouragement. It's an honor to work with him. I would like to show my appreciation to my thesis committee members Dr. Tong Qiu and Dr. Shimin Liu for their advice in developing the thesis.

Secondly, I would like to thank my research team, Min Liew, Sajjad Salam, Jintai Wang, and Rong Zhao. They have been very helpful and supportive in the past two years. Their suggestion and contribution to this thesis is unignorable. The journey of this research is always full of joy because of them.

Finally, I would like to sincerely thank my parents for their unconditional support so that I can indulge myself in the research. Thanks to Tina Wang, Jo Wang, and Jethro Ma, my siblings and brother in law, who have always provided their support in my ups or my downs. Thanks to Yi-Xuan Zeng, who has been taking care of me for the past two years and giving me some advice so I can smoothly finish the thesis.

CHAPTER 1 INTRODUCTION

1.1 Background

Mining became a major industry in the 19th century when new minerals were discovered, this led to series of mining rushes. Minerals affect our lives in many ways. Coal mineral is used to generate heat or electricity, which is one of the major reasons that led to the industry revolution. Iron, aluminum, and copper products are used in different industries and make our lives and work more convenient. In 2015, the value of coal, metals, and industrial minerals mined in the United States was over $100 billion; more than 15 thousand workers were employed by the mining industry (USGS 2016).

Among all the minerals, coal is the origin of all the mineral extractions since it is the most widely used energy source in the world. However, with the large usage comes with lots of problems. The process of producing coal generates coal waste so called “coal slurry”, the procedure of using coal brings another coal waste called “coal ash.” Large amount of the coal waste generates several problems since they might pollute the environment and affect the human life. How to store these wastes properly and how to efficiently reutilize these wastes remain unsolved problems.

1.2 Research Motivation

The losses of lives and economic and environmental losses caused by tailings dam failures are significant in the past century. The Buffalo Creek dam failure in 1972 and the Kingston Fossil plant’s slurry spill in 2008 showed how destructive these failures are. Even early this year, an iron mine tailing in Brazil collapsed, causing more than 60 deaths. A study by the International Commission of Large Dams (ICOLD) and the United Nations Environment Programme (UNEP) found that one major tailings incident happens each year on average (ICOLD 2001). According to the National Inventory of Dams, there are more than 700 coal waste tailings in the United States. Over 200 coal waste tailings impoundments that store coal slurry, according to the Federal Emergency Management Agency's hazard rating system, are classified as high hazard; this means that the facilities failures could cause loss of human life, severe damage to buildings, roads, and the environment (FEMA 2011).

Failures of coal waste tailings can be triggered by different conditions, including seismic motion such as earthquake or blasting and loading change due to the upstream construction on settled fine coal refuse. Therefore, it is important to know the properties of different coal tailings and other mineral tailings in order to adequately analyze the impoundments stability. The need of a large database to record these properties from different minerals at different locations is vital and urgent.

1.3 Research Scope

This thesis compile and synthesize a database including approximately 40 years references on field or laboratory tests of mineral tailings properties. The database includes the properties of tailings of nickel, gold, copper, iron, zinc, fine coal, and coarse coal. This research also carries out the results of laboratory tests from PSU research team on the coal slurries from a coal tailing in Pennsylvania.

1.4 Thesis Outline

This thesis consists of four chapters. Chapter 1, where this thesis outline is located, summarizes the research motivation and the scope of this study.

Chapter 2 provides an overview of the geotechnical properties of various tailings given by previous publications.

Chapter 3 presents the data from PSU research team and the database established by this study with all the data from previous publications and PSU research team. The comparison and analysis of different mineral tailings are also provided in this chapter.

Chapter 4 provides conclusions derived from this research.

CHAPTER 2 LITERATURE REVIEW

2.1 Previous Geotechnical Investigations on Mineral Tailings

Large amounts of studies have been published in the past on the geotechnical properties of coal tailings. Busch et al. (1975) conducted field sampling in a coal waste impoundment to retrieve relatively undisturbed samples to perform laboratory testing. The goal was to investigate problems associated with drainage, liquefaction, strength, and stability. The chosen site was inactive so that it was accessible and available for field sampling. Busch et al. (1975) using light, hand-operated drilling equipment for sampling as the bearing capacity of the ground surface of coal tailings was poor. The laboratory testing by Busch et al. (1975) included measurements of permeability, grain size distribution, specific gravity, maximum density, optimum moisture content, Atterberg's limits, and shear strength. Other tests such as chemical composition of ash, X-ray diffraction, and spectrographic analyses were also performed to determine the future development potential and the uses of coal tailings. Busch et al. (1975) concluded that the instability of coal minerals impoundment was mainly because of its low shear strength. They also suggested that the coal tailings could be suitable for a construction material once the alumina deposits in the coal tailings are extracted.

Ullrich et al. (1991) used a simplified method of slope stability for coal tailings dams for earthquake loading and excess pore water pressure within the embankment. A conventional method of slices was used to analyze the slope stability under dynamic loading and a pseudo-static force was applied to each slice. Cyclic triaxial test results showed that none of the six sites in the reference was expected to liquefy under dynamic loading. Another phenomenon that Ullrich et al. (1991) observed was that the sites that used fine coal cleaning had pore pressure ratio from 1% to 20%; on the other hand, the site without using fine coal cleaning had pore pressure ratio ranging from 40% to 60%.

Qiu and Sego (2001) carried out a series of laboratory testing to determine the geotechnical properties of four different types of mine tailings: coal, copper, gold tailings, and consolidated oil sand tailings. The basic properties included grain size distribution, Atterberg's limits, specific gravity, and pH value. The reference also presented the consolidation behavior, shear strength, hydraulic conductivity, and water retention characteristics of the mine tailings samples. Qiu and Sego (2001) concluded that there was a linear relationship between void ratio and the logarithm of effective stress. The relationship between the void ratio and the logarithm of saturated hydraulic conductivity of the tailings was almost linear. Strain-hardening behavior was observed in the coal tailings and the consolidated oil sand tailings samples but not in the other two types of tailings. Qiu and Sego (2001) also concluded that it was important to address pore-pressure increase in designing the tailings facilities.

Zeng et al. (2008) performed a series of resonant column tests and cyclic triaxial tests to determine the shear modulus and damping ratio versus shear strain curves for coal tailings samples. The excess pore water pressure generated in the coal tailings samples was measured during the cyclic triaxial loading. The coarse coal tailings samples were mixture of gravel and sand while the fine coal tailings samples were mixture of sand, silt, and clay-sized particles with a low plasticity and specific gravity slightly larger than 2.0. Based on the laboratory testing results, Zeng et al. (2008) concluded that the possibility of liquefaction could not be ruled out even though there is no liquefaction during the laboratory testing since the variation in the index properties of the coal tailings samples are significant.

A laboratory testing program was conducted by Hu et al. (2017) to evaluate the static and cyclic behaviors of fine and coarse coal tailings. Hu et al. (2017) concluded that the liquefaction susceptibility of the coal tailings agreed with the results determined from the cyclic triaxial tests. This conclusion was inferred based on the regression model of cyclic resistance ratio (CRR) as a function of number of cycles that caused liquefaction.

Wijewickreme et al. (2005) conducted constant-volume cyclic direct simple shear (DSS) tests to simulate the loading mode expected under earthquake loading conditions in three different types of fine-grained mine tailings: laterite tailings, copper-gold tailings, and copper-gold-zinc tailings. Wijewickreme et al. (2005) reported that fine-grained tailings usually appear a cumulative decrease in effective stress (or increase in equivalent excess pore-water pressure) with an increase in the number of load cycles, which is associated with progressive degradation of shear stiffness. The test results showed a clear tendency for laterite and copper-gold-zinc tailings that with the increase of post cyclic maximum shear strength ratio ($S_{u\text{-}PC}/\sigma'_{vc}$) the void ratio decreased. This tendency was fitted with liquefied strength ratio versus normalized standard penetration resistance correlations based on back-analysis of field case histories.

Geremew and Yanful (2013) carried out a series of stress-controlled isotropic and undrained cyclic triaxial tests on copper-zinc, and gold tailings to examine the dynamic properties and the influence of clay mineral types on their cyclic strength. SEM and standard laboratory testing were conducted. Geremew and Yanful (2013) pointed out that the dynamic shear modulus decreased, whereas the damping ratio increased, with increasing number of loading cycles and cyclic stress ratio. In addition, the effect of void ratio on shear modulus was significant in the small strain range (0.1%~1.5%).

Al-Tarhouni et al. (2011) used a simple-shear apparatus (Norwegian Geotechnical Institute (NGI) type) to investigate the mechanical behavior of gold tailings under monotonic, cyclic, and post-cyclic loading. They pointed out that the monotonic behavior of tailings is highly dependent on initial void ratio and consolidation pressure. There is no specific relationship between void ratio and mobilized shear strength. However, the shear strength normalized by consolidation pressure showed a strong correlation with void ratio.

James et al. (2011) evaluated the dynamic response of gold mine tailings, which are classified as nonplastic silt and sand, by using cyclic laboratory testing. The samples from the tailings were prepared as slurries, consolidated to vertical effective stress from 100 to 400 kPa, and subjected to cyclic direct simple shear tests with cyclic stress ratio (CSR) between 0.075 and 0.15. The dynamic response of the tailings was similar to that of sands with respect to shear modulus reduction and liquefaction resistance.

Bonin et al. (2014) used a 300 mm-high settling column to assess the self-weight consolidation behavior of gold mine tailings deposited to 68% of solids. The monitoring of the total pore-water pressure showed that self-weight consolidation ends after 24 hr and it was confirmed that the sample would experience mainly self-weight consolidation. The void ratio corresponds to this solids content is far below the critical void ratio reported by de Oliveira-Filho, W. L., and van Zyl (2006) and Bartholomeeusen et al. (2002) for silty materials

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Zhao et al. (2014) applied cyclic loading on three kinds of copper tailings, fine sand, silty sand, and floury soil and analyzed the dynamic parameters of elastic modulus and damping ratio. Zhao et al. (2014) concluded that with the increase of the strain, the dynamic modulus decreased. At 100 kPa confining pressure, the dynamic modulus of floury soil was greater than the other two; while at 200 and 300 kPa confining pressure, the dynamic modulus of silty sand was larger than the other two. For the same sample, there was a relationship between dynamic modulus and confining pressure. The higher the confining pressure, the greater the dynamic modulus. Zhao et al. (2014) also pointed out that the damping ratio increased with the shear strain increases; the damping ratio progressively reached a fixed value.

CHAPTER 3 RESEARCH DATA SYNTHESIS AND ANALYSIS

3.1 Data Organization and Category

Qiu and Sego (2001) carried out a series of laboratory testing to gather properties from different kind of tailings, such as copper, gold, coal wash, and oil sand consolidated tailings. The study conducted tests for specific gravity, Atterberg limits, grain size distribution, and soil classification (Qiu and Sego 2001). The consolidation tests and hydraulic conductivity tests were also run in the study. Qiu and Sego (2001) presented the basic properties of these mining waste tailings (Table 3.1).

Table 3-1 Properties of Mining Waste Tailings (Qiu and Sego 2001)

Mineral	Gs	LL	PI	USCS Classification	Cc
Copper	2.75	N/A	N/A	SM	0.056~0.094
Gold	3.17	N/A	N/A	ML	0.083~0.156
Coal	1.94	40	16	CL	0.370~0.396
CT	2.6	N/A	N/A	SM	0.271~0.319

Hu et al. (2017), just like what Qiu and Sego (2001) did, ran several laboratory testing to gather the static and cyclic characteristics of Yuhezhai iron tailings and Bahuerachi copper tailings. The difference between the two studies is that Hu et al. (2017) separated each mine tailing into two groups based on the particle size, which can help to describe the characteristic of mine tailings more precisely. Hu et al. (2017) also collected a large amount of data not only from the tests he conducted but also from previous publications in order to compare the results of the tests.

These two publications give a great model of what kind of tests should be conducted in order to present the basic properties of mining waste tailings. The way they assorted the mineral also show a path for this thesis to follow. These two publications establish the foundation of this thesis not just because of the methods they used but also because of the data that were presented become part of the database in this study.

This thesis compiled a large database with different types of tailings materials. Each reference is classified into one or multiple categories based on the materials they used and each of the category includes all the properties that are given in the references. The properties in the database not only include some basic properties such as specific gravity, void ratio, and water content, but also cover the results of cyclic triaxial tests, cone penetration tests. In addition, our research team (denoted as PSU team) conducted series of experiments for coal slurry (also known as fine coal refuse) from two of the Jeddo Coal Basins; the laboratory testing included basic soil indices; triaxial tests, consolidation tests, resonant column tests.

3.3.1 Laboratory Testing of Drilled Samples Obtained at Jeddo Coal Slurry Impoundments

For the first group of samples, PSU team used the boring samples from Jeddo coal slurry impoundments. These sample were classified using the Unified Soil Classification System (USCS). Classification tests such as sieve analysis, hydrometer tests, and Atterberg limits tests were carried out to determine the soil type of the drilling samples. PSU team labeled the samples based on its impoundment, borehole, and depths and gives total 9 different types of samples (Table 3-2).

Table 3-2 Label and depth for drilling samples

Impoundment	Borehole	Depth (m)	Label
S1	B1	0-1.5	PSU-1
		4.5-6	PSU-2
		10.5-12	PSU-3
	B2	0-1.5	PSU-4
		4.5-6	PSU-5
		10.5-12	PSU-6
S2	B1	0-1.5	PSU-7
		4.5-6	PSU-8
		7.5-9	PSU-9

The groundwater depth in the field was measured by lowering a measuring tape into the borehole. The drilling samples that were retrieved from drilling and tested in this thesis were all below groundwater table. Table 3.3 presents some of the basic index properties (i.e. specific gravity, plastic index), hydraulic conductivity, and classification of the samples that were used for the static triaxial tests. The Atterberg limits tests were conducted several times until repetitive and consistent results for each sample were reached. The reported moisture contents are the average values with standard deviation of 3%. All the samples can be considered as non-plastic to low plasticity, as the plasticity indexes were less than 7. The moisture content of all the other samples was higher than their liquid limit except for PSU-4 and PSU-7. Specific gravity (G_s) shown in Table 3.3 is the average values, with standard deviation of 0.03.

Table 3-3 Index properties of drilling samples

Sample	*LL* (%)	*PL* (%)	*PI*	G_s	*k* (cm/s)	Moisture Content (%)	Density (kN/m^3)	e_{ini}	Saturation Degree (%)	USCS Classification
PSU-1	27	21	6	2.1	N/A	35	N/A	N/A	N/A	CL-ML
PSU-2	33	29	4	2.1	3.3e-6	35	15.6	0.8	92	SM
PSU-3	34	30	4	2.1	5.1e-7	49	12.9	1.4	73	ML
PSU-4	N/A	N/A	0	2.3	N/A	15	N/A	N/A	N/A	SM
PSU-5	31	27	4	2.1	8.8e-7	35	14.6	0.9	82	ML
PSU-6	27	25	2	2.1	1.3e-4	36	16.1	0.8	94	SM
PSU-7	N/A	N/A	0	2.3	N/A	10	N/A	N/A	N/A	SW-SM
PSU-8	20	19	1	2.2	3.6e-7	25	15.4	0.7	75	SM
PSU-9	35	33	2	2.2	1.0e-6	48	15.6	1.0	100	ML

Figure 3-1 showed the particle size distribution of the drilling samples. As shown in Table 3.3, the classifications of drilling samples were classified as either silty sand (SM), low plasticity silt (ML), clayey silt (CL-ML), or well graded sand with silt (SW-SM).

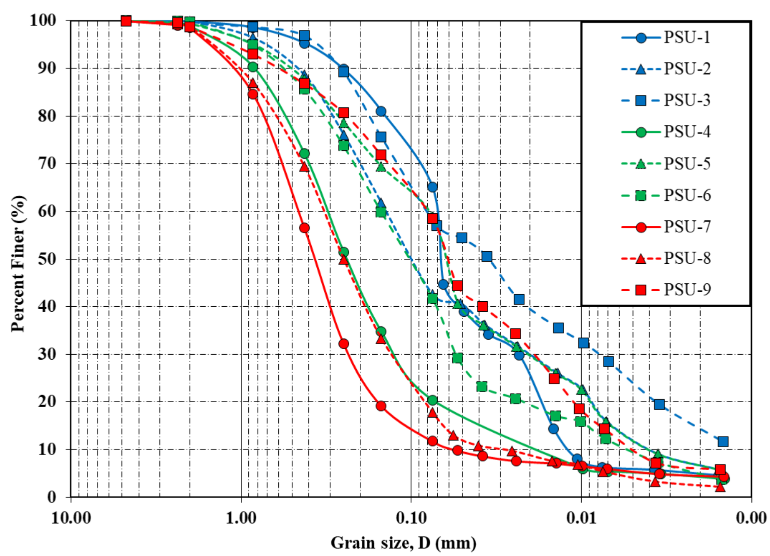
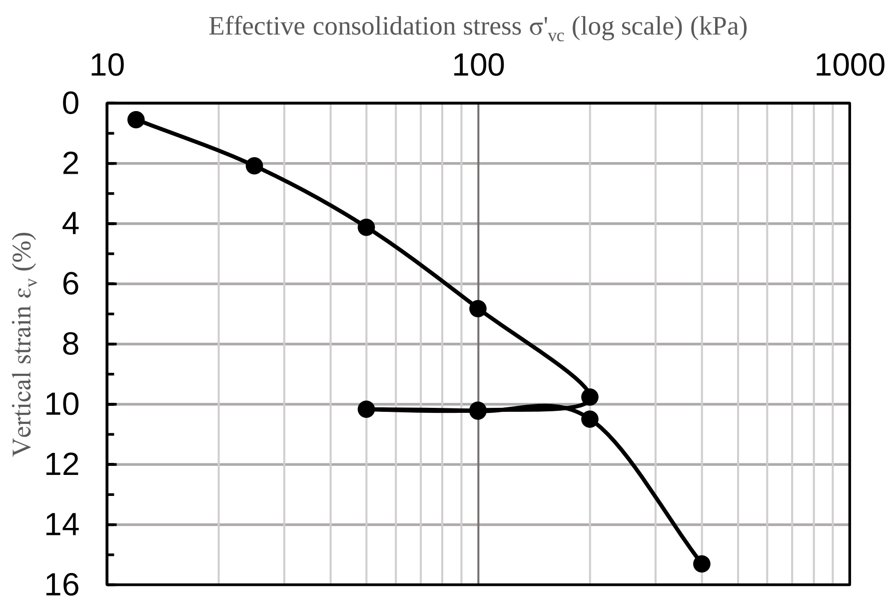


Figure 3-1 Particle size distribution of drilling samples

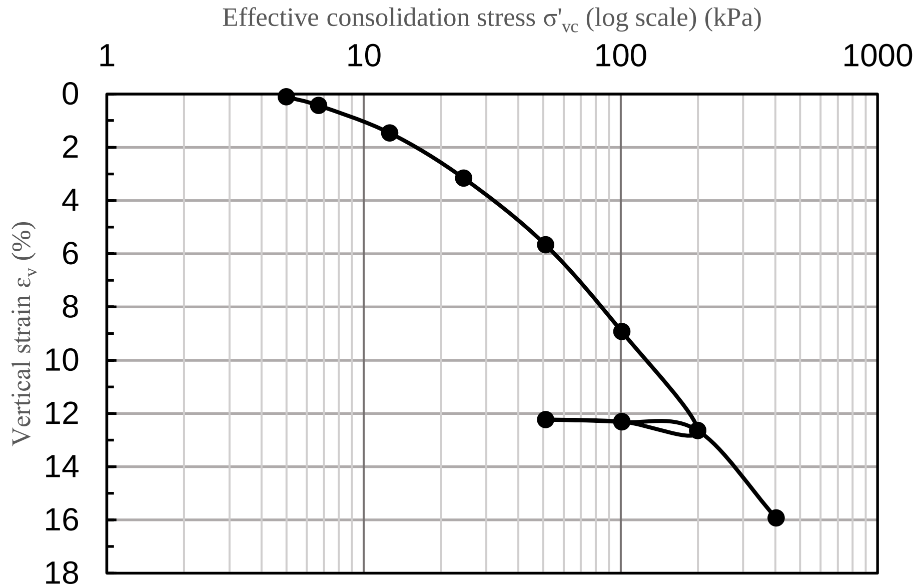
One-dimensional consolidation tests were conducted on the drilling samples. The results of consolidation tests for drilling samples are presented in Table 3.4. As what shown in Table 3.4, the compression index (*Cc*) ranged from 0.134 to 0.453 and the swell index (*Cs*) ranged from 0.003 to 0.013. The coefficient of consolidation ranged from 0.75 to 2.36 cm^2/min. Figure 3-2 (a-f) shows the consolidation curves for the fine coal refuse samples at different sites and depths.

Table 3-4 The results of consolidation tests

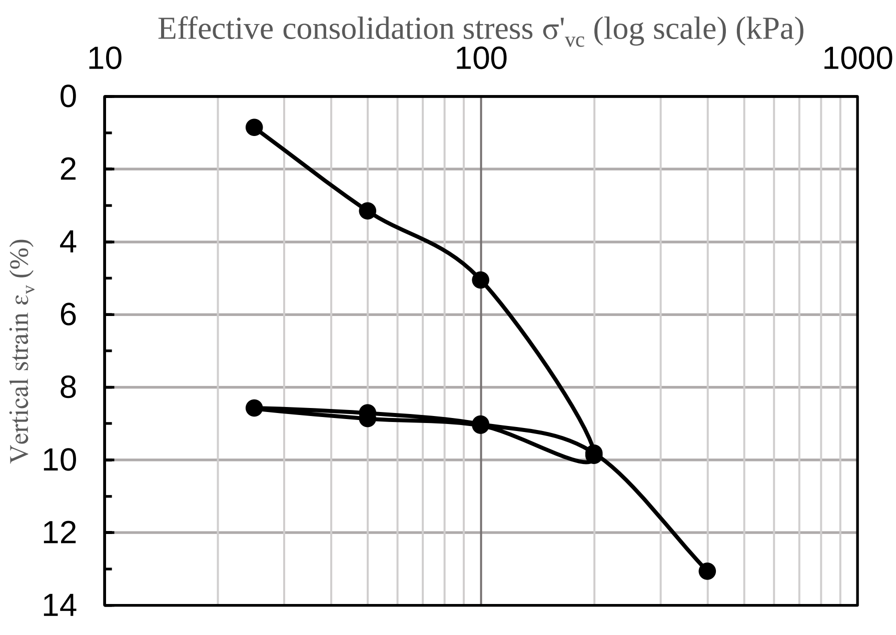
Sample	Compression Index, C_c	Swell Index, C_s	Coefficient of consolidation, C_v cm^2/min
PSU-1	0.234	0.005	1.06
PSU-2	0.134	0.003	1.70
PSU-3	0.200	0.013	1.17
PSU-7	0.242	0.007	0.75
PSU-8	0.453	0.010	2.36
PSU-9	0.200	0.013	0.89



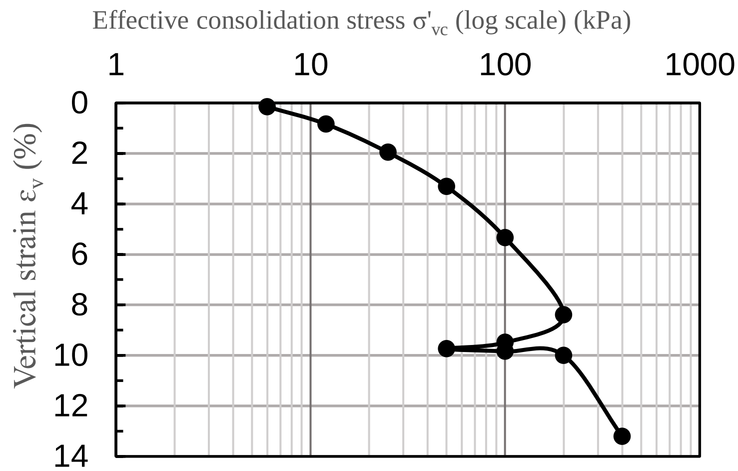
(a). PSU-1


Effective consolidation stress σ'vc (log scale) (kPa)
1
10
100
1000
0
2
4
6
8
10
12
14
16
18
Vertical strain εv (%)

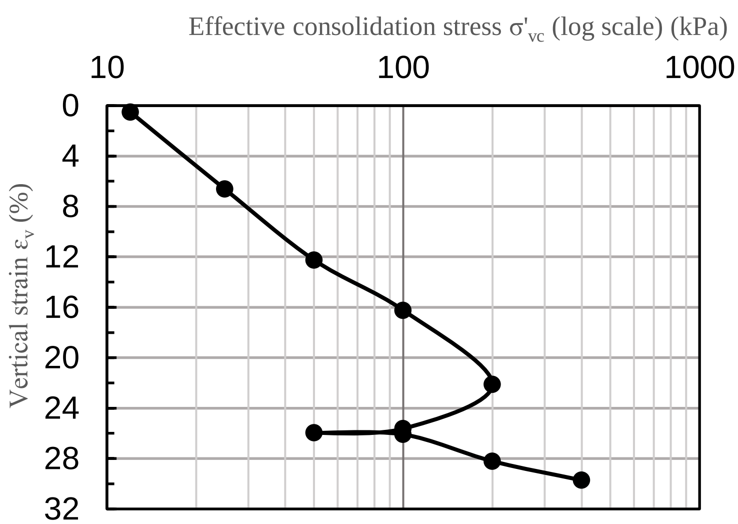
(b). PSU-2


Effective consolidation stress σ'vc (log scale) (kPa)
10
100
1000
0
2
4
6
8
10
12
14
Vertical strain εv (%)

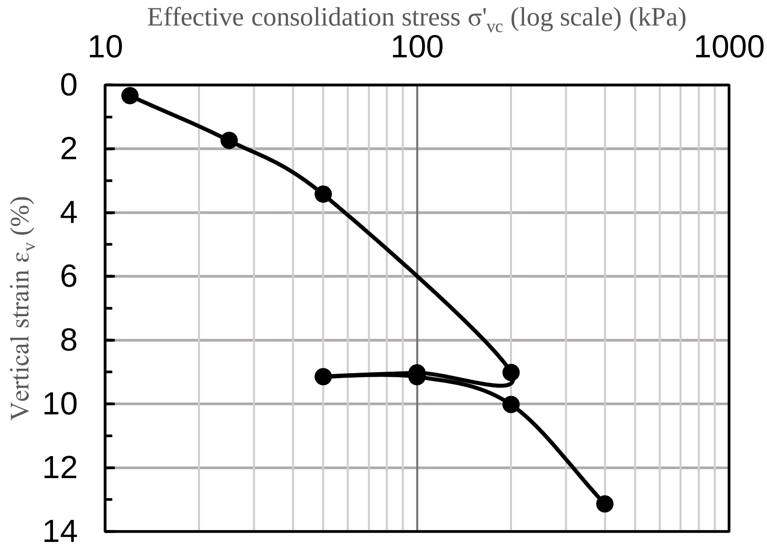
(c). PSU-3


Effective consolidation stress σ'vc (log scale) (kPa)
1
10
100
1000
Vertical strain εv (%)
0
2
4
6
8
10
12
14

(d). PSU-7


Effective consolidation stress σ'vc (log scale) (kPa)
10
100
1000
Vertical strain εv (%)
0
4
8
12
16
20
24
28
32

(e). PSU-8



(f). PSU-9

Figure 3-2 Consolidation curves for the samples obtained at different sites and depths in Jeddo coal slurry impoundments

Static consolidation-drained (CD) tests and consolidation-undrained (CU) triaxial tests were carried out on these samples to determine the shear strength of the samples under monotonic loading. Table 3.5 shows the results of effective shear strength properties of all the specimens. The cohesion of CU tests ranges from 13.8 kPa to 25.5 kPa, and ranges from 13.4 kPa to 16.5 kPa under CD conditions.

Table 3-5 Static triaxial test results

Test	Sample	c' (kPa)	$\varnothing'$ (deg.)
CU	PSU-2	13.8	29
CU	PSU-3	25.5	26
CU	PSU-5	24.8	30
CU	PSU-6	20.7	31
CD	PSU-8	16.5	36
CD	PSU-9	13.1	38

3.3.2 Laboratory Testing of Bulk Samples Obtained at Jeddo Coal Slurry Impoundments

A second group of coal slurry samples were retrieved from the same slurry impoundment in November 2018. The team ran the sieve analysis, hydrometer tests, and Atterberg limits tests to classify the samples. With the grain size distribution (Figure 3.4) and the results of Atterberg limit, it can be concluded that all the samples, except for D1S1, were classified as ML (silt), CL (lean clay), or CL-ML (silty clay) (Table 3.6).

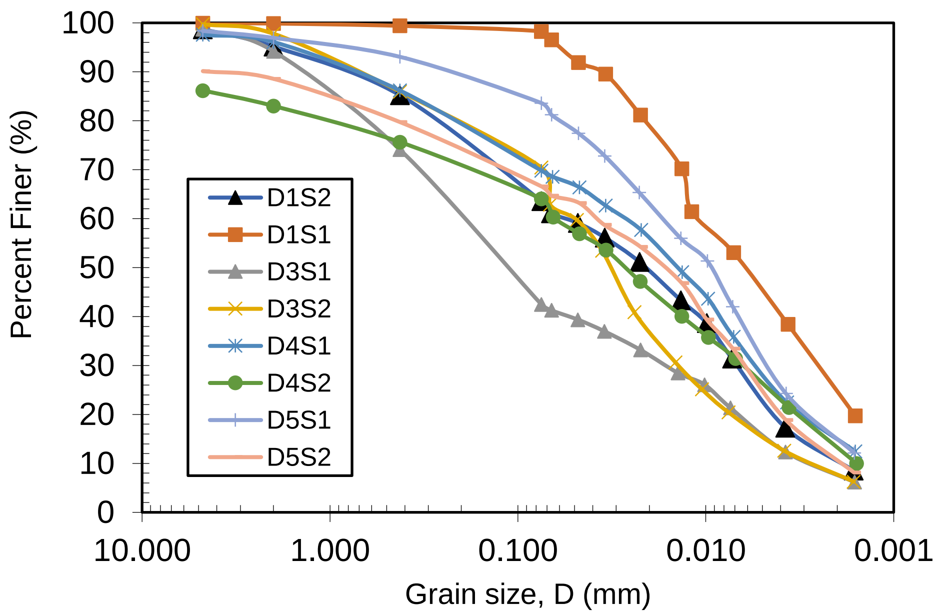


Figure 3-3 Grain size distribution of bulk samples

Table 3-6 Results of Atterberg limits and soil classification for bulk samples

	LL	*PL*	*PI*	USCS Classification
D1S1	55.36	35.29	20.09	CH
D1S2	39.4	28.57	10.83	CL
D3S1	35.07	33.33	1.74	ML
D3S2	35.62	29.41	6.21	CL-ML
D4S1	33.03	27.5	5.53	CL-ML
D4S2	37.43	27.5	9.93	CL
D5S1	33.38	32.14	1.24	ML
D5S2	31.98	28.26	3.72	ML

For the resonant column tests, the team classified the samples into two groups based on the grain size distribution, one is silty sample, the other is sandy sample. The silty samples tend to have larger shear modulus and shear velocity than sandy samples. The range of the shear modulus for the silty samples is from 5.751 to 10.134 MPa and for the sandy samples the range is from 3.735 to 6.685 MPa. For the shear wave velocity, the silty samples range from 53.62 to 71.18 m/s and the sandy samples range from 43.21 to 57.81 m/s. The test parameters and results are showed in Table 3.7.

Table 3-7 Results of resonant column tests for bulk samples

	Sandy Sample			Silty Sample		
Mass (kg)	1.454	1.763	1.832	1.582	1.648	1.744
Void ratio	1.074	0.755	0.689	0.956	0.878	0.774
Frequency (Hz)	32.2	34.9	45.4	40.1	49.5	55
Vs (m/s)	43.21	45.01	57.81	53.62	65.29	71.18
G (MPa)	3.735	4.051	6.685	5.751	8.524	10.134

3.4 Mineral Tailings Properties

The data that were collected from previous publications along with the test results from PSU research team were presented in Table 3.9 to Table 3.15. Each Table presents one type of mineral with the properties. The category of each table is in the sequence of fine coal, coarse coal, gold, copper, nickel, zinc, and iron. The tables show all the properties and tests results that were provided in the references, such as specific gravity, plastic index, USCS classification, void ratio, compression index. The label of each sample is based on the reference. Some of the properties may not be included in the table if no data were presented in the references. The grain size distribution of each mineral can be seen in the Appendixes based on the Notes provided in the tables. Some of the terminologies may differ in different publications. In order to avoid misunderstanding, explanation of the terminologies is listed in Table 3.8. With all the data that were included in the database, the comparison of properties from each mineral is conducted in the next section.

Table 3-8 Terminology for Table 3-9 to Table 3-15

C_{cu} (m^2/MN)	Cohesion from CU test
c'	Effective Cohesion from CU test
c_{cd} (kPa)	Cohesion from CD test
CCR_{20}	CRR Correspond to 20 cycles required to produce 5% double amplitude axial strain
CCR_{10}	CRR Correspond to 10 cycles required to produce 5% double amplitude axial strain
σ'_{vo} (kPa)	Estimated in-situ vertical effective stress
σ'_{vc} (kPa)	Vertical effective stress prior to cyclic loading
$\tau_{\mathrm{cy}}/\sigma'_{\mathrm{vc}}$	Cyclic stress ratio from cyclic DSS
NL	Number of cycles to reach max shear strain
γ_{peak} (%)	Shear strain at max shear stress Su-pc in postcyclic shear stress
S_{u}-PC/σ'_{vc}	Ratio of max shear stress to initial vertical effective stress reached in postcylcic shear tests
CSR	Nondimensional cyclic stress ratio
N_{init} (%)	Number of cycles required to reach initial liquefaction
N_5% (%)	Number of cycles required to produce 5% double amplitude axial strain
q_t (MPa)	Cone penetration resistance
f_s (MPa)	Friction sleeve resistance
S_u (kpa)	Field vane shear strength
R_c	Roundness coefficient
A_r	Aspect ratio

Table 3-9 Fine coal tailings

Reference	Qiu and Sego (2001)	Zeng et al. (2008)				Ullrich et al. (1991)					
Name	Coal	Sample 1	Sample 2	Sample 3	Sample 4	Abner Fork	Bennetts Branch	Gum Branch	TCC NO.1	Meigs	Muskingum
GSD (Note 1)	GSD 1-1	GSD 1-2				GSD 1-3					
Gs	1.94	2.02	2.02	2.16	2.1	1.85	N/A	1.87	1.97	2.49	1.79
LL	40	36	27	32	34	35.9	43.6	NP	NP	NP	31.1
PI	16	10	3	11	11	9.3	2.7				7.6
Water Content (%)	N/A	13.5	13.6	8.7	12.5	N/A	N/A	N/A	N/A	N/A	N/A
Void Ratio	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Shrinkage limits	21.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Clay size particle (%)	22.5	30.8	12.3	33.8	37	42.6	36	N/A	42.6	16	20
Sand Content (%)	40	43	61	45	40	18	24	69	14	76	56
Fines Content (%)	66.4	57	39	55	30	82	76	31	86	24	44
D_{10} (μm)	1.31	N/A	2	N/A	N/A	N/A	N/A	N/A	N/A	1.6	N/A
D_{30} (μm)	4.13	4.77	26.5	3.92	3.32	N/A	N/A	83	2.92	131	13
D_{50} (μm)	29.2	21.2	144	28.8	16	7.79	13.7	211	7.05	378	109
D_{60} (μm)	60	84.5	221	98.6	59.6	15.4	26.3	263	11.7	430	190
USCS Classification	CL	ML	SM	CL	CL	CL	ML	ML	ML	ML	CL
Cc	0.37~0.396	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cv (m^2/yrs)	1.48~17.26	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
mv (m^2/MN)	1.08~188.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
k_s (cm/s)	4.0E-7~1.1E-5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N_L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	30
CSR	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.3

Note 1 See Appendix A

Table 3-9 Fine coal tailings (continued)

Reference	Busch et al. (1975)				Wong et al. (2008)	PSU								
Name	WDH-1	WDH-2	BDH-1	BDH-2	Fine	PSU-1	PSU-2	PSU-3	PSU-4	PSU-5	PSU-6	PSU-7	PSU-8	PSU-9
GSD (Note 2)	GSD 1-4	GSD 1-5	GSD 1-6	GSD 1-7	GSD 1-8	GSD 1-9								
Gs	1.61	1.6	1.58	1.87	N/A	2.1	2.1	2.1	2.3	2.1	2.1	2.3	2.2	2.2
LL	41.7	38	34.3	51.1	N/A	27	33	34	N/A	31	27	N/A	20	35
PI	8.7	2.7	0	13.1	N/A	6	4	4	0	4	2	0	1	2
Water Content (%)	55.4	53.4	35	60.6	141.4	35	35	49	15	35	36	10	25	48
Void Ratio	N/A	N/A	N/A	N/A	3.746	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Shrinkage limits	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Clay size particle (%)	49~64	35~53	1.8~20.8	50.1~78.6	35	5.52	11	23.1	5.1	11	9.19	4.68	3	9.19
Sand Content (%)	6.1~12.7	10~25	38.1~86.2	<5.2	14	35.3	58.5	44.7	81.2	58.8	6	89.15	82.8	44.1
Fines Content (%)	87.3~93.9	75~90	10.1~58.2	>94.8	86	64.7	41.5	55.3	19.8	41.2	42.8	10.85	17.2	55.9
Bitumen Content (%)	N/A	N/A	N/A	N/A	1.6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D_{10} (μm)	0.47~0.64	0.57~1.38	1.3~72	0.34~0.96	N/A	12.2	3.95	1.46	20.8	3.95	5.06	58.8	40.6	5.27
D_{30} (μm)	1.3~2.1	1.75~3.79	10.4~249	0.8~2.16	N/A	23.9	23.9	7.93	139	21.4	58.6	246	139	19.5
D_{50} (μm)	3.2~5.4	4.48~10.6	40.4~467	2.07~4.8	6.93	72.1	107	37.5	252	65.5	107	385	266	65.5
D_{60} (μm)	5.17~8.16	6.86~18.1	82.8~662	2.88~6.08	16.6	74.1	150	86.1	336	86.1	161	506	355	86.1
USCS Classification	CL	ML	ML	CL	N/A	CL-ML	SM	ML	SM	ML	SM	SW-SM	SM	ML
Cc	N/A	N/A	N/A	N/A	N/A	0.234	0.134	0.200	N/A	N/A	N/A	0.242	0.453	0.200
Cv (m^2/yrs)	N/A	N/A	N/A	N/A	N/A	55.71	89.35	61.49	N/A	N/A	N/A	39.42	124.04	46.78
k_s (cm/s)	N/A	N/A	N/A	N/A	N/A	N/A	3.3e-6	5.1e-7	N/A	8.8e-7	1.3e-4	N/A	3.6e-7	1.0e-6
NL	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CSR	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note 2 See Appendix A

Table 3-9 Fine coal tailings (continued)

Reference	Hegazy et al. (2004)	PSU							
Name	FCR	D1S1	D1S2	D3S1	D3S2	D4S1	D4S2	D5S1	D5S2
GSD (Note 3)	GSD 1-10	GSD1-11							
Gs	1.52	2	2	2	2	2	2	2	2
LL	31.2	55.36	39.4	35.07	35.62	33.03	37.43	33.38	31.98
PI	11.2	20.09	10.83	1.74	6.21	5.53	9.93	1.24	3.72
Water Content (%)	33	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Void Ratio	N/A	0.689~1.074							
Shrinkaga limits	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Clay size particle (%)	27	49.1	25	17.3	17.3	30.9	28.8	34.7	27.5
Sand Content (%)	43.1	1.653	35.137	56.2	29.306	27.743	22.146	14.731	23.54
Fines Content (%)	56.9	98.27	63.576	42.491	70.428	69.818	64.034	83.622	66.597
Bitumen Content (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D_{10} (μm)	10	N/A	1.58	2.15	2.15	N/A	2	N/A	1.58
D_{30} (μm)	37	2.22	6.12	13.8	12.4	4.86	5.49	4.36	5.49
D_{50} (μm)	127	5.24	17.9	97	29.2	11.6	23.2	8.06	13.6
D_{60} (μm)	196	9.26	43.4	168	43.4	21.2	51.7	14.2	32.1
USCS Classification	CL	CH	CL	ML	CL-ML	CL-ML	CL	ML	ML
Cc	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cv (m^2/yrs)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
k_s (cm/s)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
NL	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CSR	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note 3 See Appendix A

Table 3-10 Coarse coal tailings

Reference	Zeng et al. (2008)	Hegazy et al. (2004)	Saxena et al. (1984)	Wong et al. (2008)
Name	Coarse	CCR	Coarse	Coarse
GSD (Note 4)	N/A	GSD 2-1	GSD 2-2	GSD 2-3
Gs	2.5	2.02	2.56	N/A
LL	31	N/A	27	N/A
PI	20	N/A	11.5	N/A
Water Content (%)	11.2	6.4	N/A	N/A
Void Ratio	N/A	N/A	N/A	0.88
Shrinkage limits	N/A	N/A	N/A	N/A
Clay size particle (%)	N/A	N/A	N/A	Nil
Sand Content (%)	N/A	N/A	13	88~90
Fines Content (%)	N/A	N/A	N/A	10~12
Bitumen Content (%)	N/A	N/A	N/A	0.4
D_{10} (µm)	N/A	N/A	3,000	118
D_{30} (µm)	N/A	350	10,000	156
D_{50} (µm)	N/A	1,230	17,970,	206
D_{60} (µm)	N/A	2,020	22,820	230
USCS Classification	SC	N/A	GW	N/A
Cc	N/A	N/A	N/A	N/A
Cv (m^2/yrs)	N/A	N/A	N/A	N/A
k_s (cm/s)	N/A	N/A	N/A	N/A
NL	N/A	N/A	N/A	N/A
CSR	N/A	N/A	N/A	N/A

Note 4 See Appendix B

Table 3-11 Gold tailings

Reference	Qiu and Sego (2001)	Bonin et al. (2014)	Geremew and Yanful (2013)	Al-Tarhouni et al. (2011)				James et al. (2011)			
Name	Gold Tailings	Gold Tailings	Musselwhite	PSD 1	PSD 2	PSD3	PSD 4	Sample 1	Sample 2	Sample 3	Sample 4
GSD (Note 5)	GSD 3-1	N/A	GSD 3-2	GSD 3-3				GSD 3-4			
Gs	3.17	2.76	3.32	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LL	N/A	29.00	24.48	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PI	N/A	4.0	4.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Void Ratio	N/A	N/A	0.70~0.95	0.7	0.8	0.9	1.1	N/A	N/A	N/A	N/A
Shrinkage limits	21.6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Clay size particle (%)	5.3	11	5.96	N/A	N/A	N/A	N/A	14.6	12.3	7.69	7.23
Sand Content (%)	33.3	8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Silt Content (%)	N/A	81	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fines Content (%)	81.3	N/A	57.8	18.3				54.3	59.8	73	82
D_{10} (μm)	5	1.8	12.1	N/A				8.2	7.7	4.2	3.6
D_{30} (μm)	19	N/A	28.7	13				36	33.2	15	11.7
D_{50} (μm)	44.8	N/A	69.2	51				65	60	35	25
D_{60} (μm)	54	21	78.2	82				82.6	75.1	47.3	36.6
USCS Classification	ML	ML	ML	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cc	0.083 ~ 0.156	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cv (m^2/yrs)	13.58 ~ 80.07	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
mv (m^2/MN)	0.29 ~ 162.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
k_s (cm/s)	2.7E-5 ~ 6.7E-5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CCR20	N/A	N/A	0.173~0.344	N/A	N/A	N/A	N/A	CRR=0.15M^-0.19			
CCR10	N/A	N/A	0.196~0.389	N/A	N/A	N/A	N/A				
CSR	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.075~0.15			

Note 5 See Appendix C

Table 3-12 Copper tailings

Reference	Qiu and Sego (2001)	Hu et al. (2017)		Zhao et al. (2014			Geremew and Yanful (2013)
Name	Copper Tailings	Fine	Coarse	#1	#2	#3	Mattabi (Copper-Zinc)
GSD (Note 6)	GSD 4-1	GSD 4-2		N/A	N/A	N/A	GSD 4-3
Gs	2.75	2.76	2.77	N/A	N/A	N/A	3.29
LL	N/A	28	N/A	N/A	N/A	N/A	20.1
PI	N/A	15	N/A	N/A	N/A	N/A	12.6
Water Content (%)	N/A	67	39	28.4	27.8	28.1	N/A
Void Ratio	N/A	1.03	0.84	0.861	0.858	0.856	0.60~0.92
Shrinkage limits	24.4	N/A	N/A	N/A	N/A	N/A	N/A
Clay size particle (%)	1.3	10	Nil	N/A	N/A	N/A	N/A
Sand Content (%)	74.5	39.5	85	N/A	N/A	N/A	N/A
Fines Content (%)	31.3	60.5	15	N/A	N/A	N/A	39.3
D10 (μm)	16.28	5	65	N/A	N/A	N/A	37
D30 (μm)	72.25	28	90	N/A	N/A	N/A	62.4
D50 (μm)	120.6	60	120	N/A	N/A	N/A	86.9
D60 (μm)	153.5	74	140	N/A	N/A	N/A	101
USCS Classification	SM	CL	N/A	N/A	N/A	N/A	CL
Cc	0.056 ~ 0.094	0.085	0.025	N/A	N/A	N/A	N/A
Cv (m^2/yrs)	22.32 ~ 104.23	N/A	N/A	N/A	N/A	N/A	N/A
mv (m^2/MN)	0.63 ~ 19.76	N/A	N/A	N/A	N/A	N/A	N/A
ks (cm/s)	4.5E-5 ~ 9.8E-5	N/A	N/A	N/A	N/A	N/A	N/A
Ccu (m^2/MN)	N/A	0	71	N/A	N/A	N/A	N/A
C'	N/A	0	32	N/A	N/A	N/A	N/A
CCR20	N/A	N/A	N/A	N/A	N/A	N/A	0.141~0.441
CCR10	N/A	N/A	N/A	N/A	N/A	N/A	0.157~0.517

Note 6 See Appendix D

Table 3-12 Copper tailings (continued)

Reference	Wijewickreme et al. (2005)			
Name	CG-01 (Copper-Gold)	CG-02 (Copper-Gold)	CG-03 (Copper-Gold)	CG-04 (Copper-Gold)
GSD	N/A	N/A	N/A	N/A
G_s	2.78	2.78	2.78	2.78
LL	27	27	27	27
PI	Nonplastic	Nonplastic	Nonplastic	Nonplastic
Clay size particle (%)	6.3	8.0	11.7	13.6
Sand Content (%)	3.0	1.5	0.4	3.0
σ'_{vo} (kPa)	99	99	99	99
σ'_{vc} (kPa)	100	100	100	100
τ_{cy}/σ'_{vc}	0.130	0.155	0.190	0.250
N_L	43	50	29	5
γ_{peak} (%)	23.0	20.0	17.0	17.0
$S_{u\text{-}PC}/\sigma'_{vc}$	0.640	0.610	0.420	0.480

Table 3-13 Nickel tailings

Reference	Geremew and Yanful (2013)						
Name	SEBEC-01	SEBEC-02	SEBEC-03	SEBEC-04	SEBEC-05	SEBEC-06	SEBEC-07
GSD (Note 7)	GSD 4-3						
Gs	3.22	3.22	3.22	3.22	3.22	3.22	3.22
LL	12	12	12	12	12	12	12
PI	1	1	1	1	1	1	1
Water Content (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Void Ratio	0.75	0.800	0.746	0.745	0.782	0.718	0.707
Fines Content (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CCR_{20}	0.305	0.267	0.267	0.267	0.207	0.305	0.305
CCR_{10}	0.319	0.295	0.295	0.295	0.221	0.319	0.319
CSR	0.305	0.208	0.140	0.217	0.231	0.333	0.277
Ninit (%)	19	59	2081	46	18	31	25
$N_{5\%}$ (%)	15	31	2081	40	13	16	25

Note 7 See Appendix D

Table 3-13 Nickel tailings (continued)

Reference	Geremew and Yanful (2013)							
Name	SEBEC-08	SEBEC-09	SEBEC-10	SEBEC-11	SEBEC-12	SEBEC-13	SEBEC-14	SEBEC-15
GSD (Note 8)	GSD 4-3							
Gs	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22
LL	12	12	12	12	12	12	12	12
PI	1	1	1	1	1	1	1	1
Water Content (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Void Ratio	0.775	0.799	0.733	0.686	1.060	0.980	1.075	1.007
Fines Content (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CCR_{20}	0.207	0.207	0.267	0.305	0.207	0.144	0.144	0.144
CCR_{10}	0.221	0.221	0.295	0.319	0.221	0.16	0.16	0.16
CSR	0.178	0.163	0.166	0.214	0.113	0.073	0.098	0.179
Ninit (%)	24	323	485	4169	49	3257	108	11
$N_{5\%}$ (%)	24	295	484	4145	46	3189	108	17

Note 8 See Appendix D

Table 3-14 Zinc tailings

Reference	ME Quille (2010)		Wijewickreme et al. (2005)								
Name	Fine	Coarse	CGZ-01	CGZ-02	CGZ-03	CGZ-04	CGZ-05	CGZ-06	CGZ-07	CGZ-08	CGZ-09
GSD (Note 9)	GSD 4-4		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Gs	2.82	2.78	3.62	3.62	3.54	3.72	3.60	3.93	3.63	4.42	3.42
LL	75	N/A	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0
PI	60	N/A	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Water Content (%)	20	15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Void Ratio	0.61	0.63	1.130	1.320	1.310	1.220	1.210	0.840	1.250	0.720	0.740
Sand Content (%)	N/A	N/A	3.1	6.4	0.0	0.0	0.0	0.0	2.4	0.0	16.0
D_{10} (μm)	less than 2	8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D_{30} (μm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D_{50} (μm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D_{60} (μm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
USCS Classification	N/A	N/A	ML	ML	ML	ML	ML	ML	ML	ML	ML
CCR_{20}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CCR_{10}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
$\sigma'vo$ (kPa)	N/A	N/A	177	85	125	144	172	98	110	117	254
$\sigma'vc$ (kPa)	N/A	N/A	347	181	265	253	338	144	223	147	461
$\tau cy/\sigma'vc$	N/A	N/A	0.124	0.125	0.128	0.128	0.127	0.110	0.130	0.107	0.117
NL	N/A	N/A	20	16	13	13	13	13	14	9	15
$\gamma peak$ (%)	N/A	N/A	20.0	16.0	18.0	19.0	18.0	25.0	19.0	19.0	15.0
$Su\text{-}PC/\sigma'vc$	N/A	N/A	0.179	0.144	0.132	0.170	0.157	0.375	0.157	0.401	0.130

Note 9 See Appendix D

Table 3-14 Zinc tailings (continued)

Reference	Wijewickreme et al. (2005)										
Name	CGZ-10	CGZ-11	CGZ-12	CGZ-13	CGZ-14	CGZ-15	CGZ-16	CGZ-17	CGZ-18	CGZ-19	CGZ-20
GSD	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Gs	3.36	3.69	3.54	3.94	3.79	3.65	4.17	3.78	3.57	3.75	4.00
LL	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0
PI	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Water Content (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Void Ratio	0.590	0.915	1.289	0.640	0.716	1.318	0.976	1.719	1.380	0.904	0.732
Sand Content (%)	43.1	3.1	0.9	11.4	37.3	0.6	0.0	0.0	3.3	9.3	5.3
D_{10} (μm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D_{30} (μm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D_{50} (μm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D_{60} (μm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
USCS Classification	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
CCR_{20}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CCR_{10}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
$\sigma'vo$ (kPa)	117	202	127	111	297	170	163	100	129	76	236
$\sigma'vc$ (kPa)	209	352	248	149	452	357	183	236	295	115	314
$\tau cy/\sigma'vc$	0.112	0.121	0.126	0.110	0.120	0.121	0.128	0.137	0.137	0.125	0.129
N_L	12	14	21	29	24	18	9	11	9	13	17
$\gamma peak$ (%)	20.0	15.0	15.0	15.0	9.3	15.0	22.0	18.0	20.0	18.0	24.0
$Su\text{-}PC/\sigma'vc$	0.287	0.205	0.198	0.940	0.367	0.171	0.339	0.169	0.203	1.070	0.525

Table 3-15 Iron tailings

Reference	Hu et al. (2017)		Baoshan and Chopin (1983)		
Name	Fine	Coarse	Site A	Site B	Site C
GSD (Note 10)	GSD 4-2		N/A	N/A	N/A
Gs	3.08	3.23	N/A	N/A	N/A
LL	28	N/A	N/A	N/A	N/A
PI	9	N/A	N/A	N/A	N/A
Water Content (%)	43	43-54	N/A	N/A	N/A
Void Ratio	0.74	1.41	0.857~0.931	0.863~0.922	0.857~0.906
D_{10} (μm)	5	51	N/A	N/A	N/A
D_{30} (μm)	12	93	N/A	N/A	N/A
D_{50} (μm)	30	120	62	83	83
D_{60} (μm)	45	160	N/A	N/A	N/A
USCS Classification	CL	N/A	N/A	N/A	N/A
Cc	0.046	0.26	N/A	N/A	N/A
Ccu (m^2/MN)	13.8	194	N/A	N/A	N/A
C'	7.4	8.8	N/A	N/A	N/A
Ccd (kPa)	28.5	30.1	N/A	N/A	N/A
qt (MPa)	N/A	N/A	4.12~6.67	5.00~8.43	5.30~8.63

Note 10 See Appendix D

3.5 Data Analysis

Figure 3-4 is the box plot of specific gravity for all the mineral tailings included in the database. For the specific gravity, fine coal tailings range from 1.52 to 2.49 with the average about 2.0, the coarse coal tailings are between 2.02 to 2.56, the gold tailings are in range of 2.76 to 3.32, the copper tailings are about 2.77 with an outlier 3.29, the nickel tailings have specific gravity of 3.22, the zinc tailings between 2.78 to 4.42, and the iron tailings from 3.08 to 3.23.

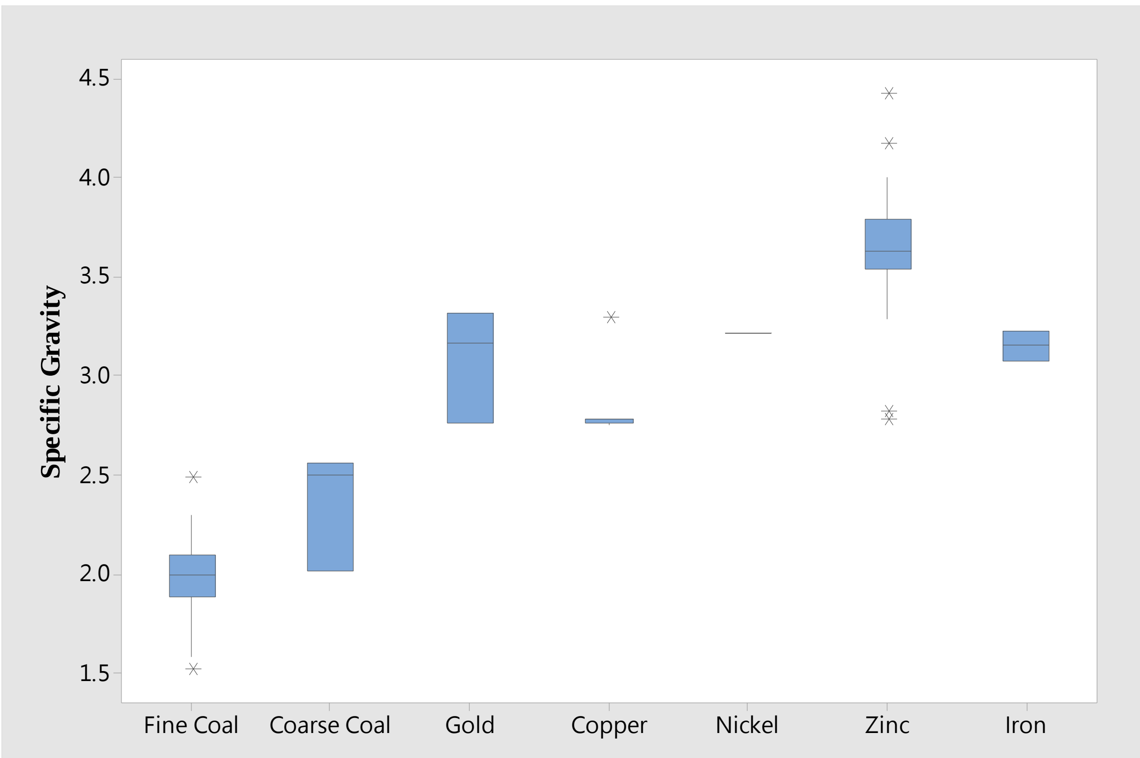


Figure 3-4 Specific gravity of mineral tailings

Although the results and comparison of specific gravity of different mineral tailings are shown in Figure 3-4, some tailings contain more than one kind of minerals (e.g. copper-zinc, copper-gold). Such mixing tailings give a different aspect of specific gravity, which is presented in Figure 3-5. Figure 3-5 compares copper, gold, zinc and its mixed tailings' specific gravity. Pure copper tailings have specific gravity about 2.76, pure zinc tailings ranged from 2.78 to 2.82, and the pure gold tailings range from 2.76 to 3.32. The mixed tailings, copper-zinc, have specific gravity of 3.29, which is much higher than both pure copper and pure zinc tailings. Copper-Gold tailings, on the other hand, have the value of 2.78, which is between the amount of pure copper and pure gold tailings. Copper-Gold-Zinc tailings have relatively high specific gravity than any other tailings, which is in the range of 3.36 to 4.17 with an average 3.74. The reason of this uncertainty results is that for the mine tailings, the factors that affect the specific gravity are not only its mineral but also related to its mother rocks.

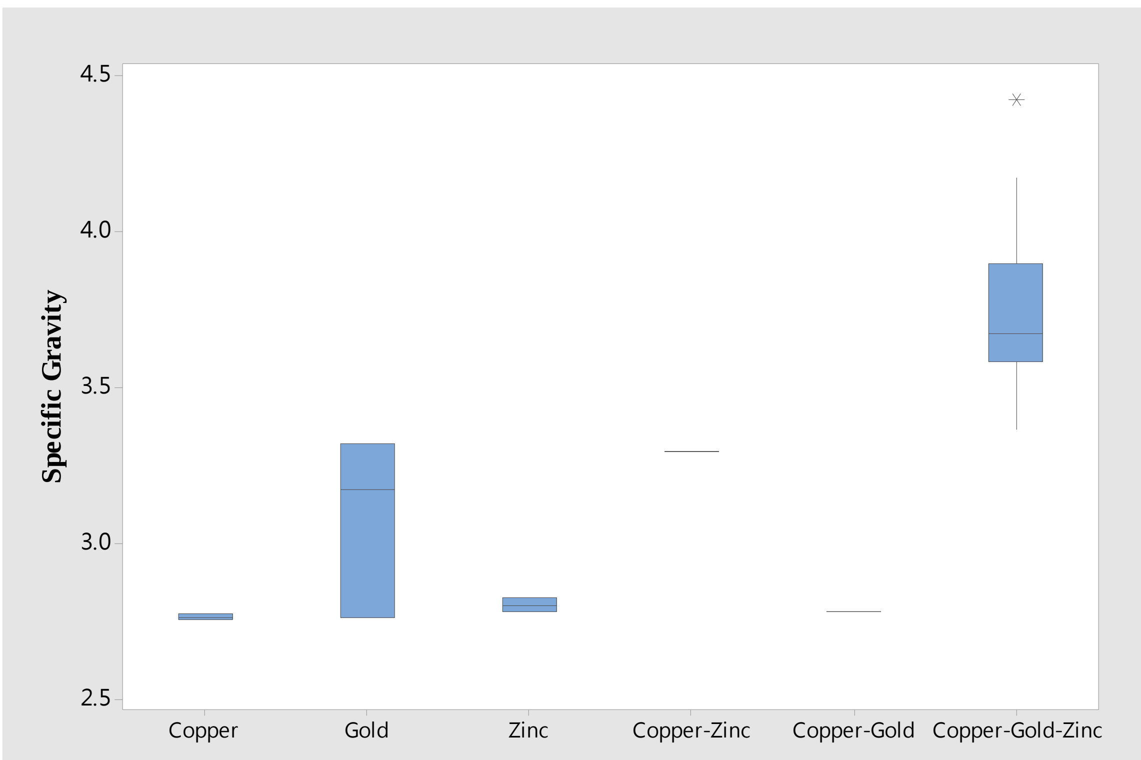


Figure 3-5 Specific gravity of copper, gold, zinc tailings and their mixed tailings

PSU research team conducted several tests with the fine coal tailings samples from Jeddo coal slurry impoundments. With the results of these tests and the data from previous publications, this study carried out a chart of USCS classification for fine coal slurry (Figure 3-6). Most of the classifications range from lean clay (CL) to silty sand (SM) with one as fat clay (CH) and one as well-graded sand with silt (SW-SM).

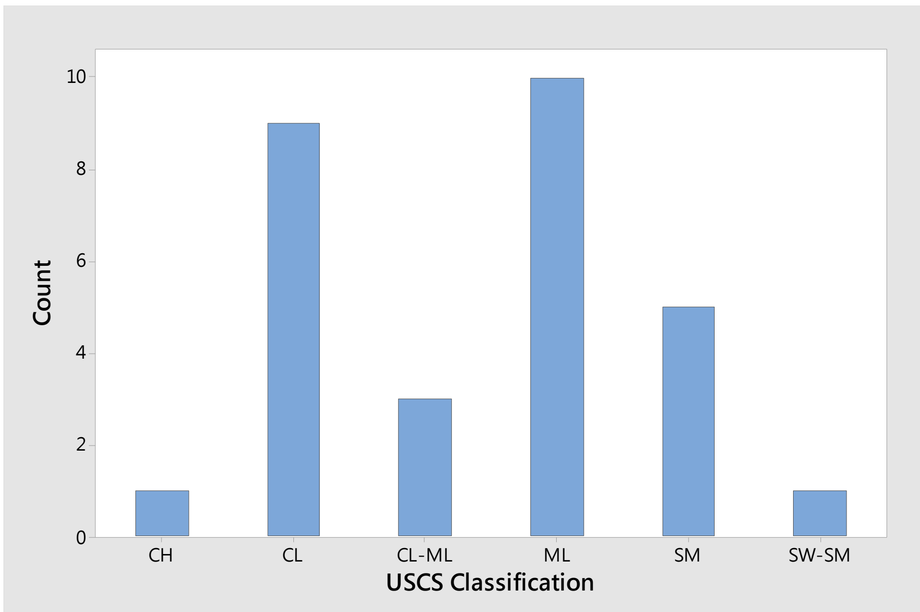


Figure 3-6 USCS classification of fine coal tailings

Figure 3-7 shows the USCS classification for all the mine tailings that were included in the database. We can see that most of the mine tailings are classified as ML.

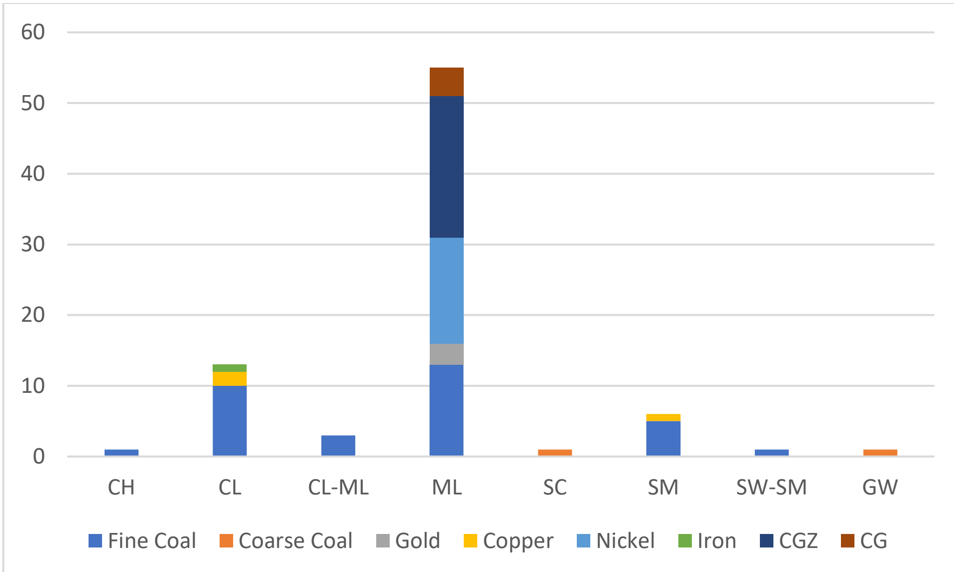


Figure 3-7 USCS classification for various tailings
(CGZ: copper-gold-zinc mixed tailings, CG: copper-gold mixed tailings)

Figure 3-8 and 3-9 show the void ratio of minerals in the data base. The different between these two figures is that Figure 3-9 removes the result from Wong et. al (2008) since the void ratio is much larger than other fine coal tailings and is considered an outlier by the Minitab software. For the void ratio, fine coal tailings range from 0.689 to 1.074 with an outlier 3.746, coarse coal tailings are about 0.88, nickel tailings are between 0.686 to 1.075 with the average of 0.82, copper tailings are between 0.84 to 1.03, gold tailings are in the range of 0.7 to 1.1, zinc tailings are between 0.61 to 0.63, and iron tailings range from 0.857 to 0.931 with two outliers, 0.74 and 1.41. The void ratio for the mixed tailings, copper-gold-zinc is from 0.59 to 1.719 and copper-zinc tailings range from 0.6 to 0.92.

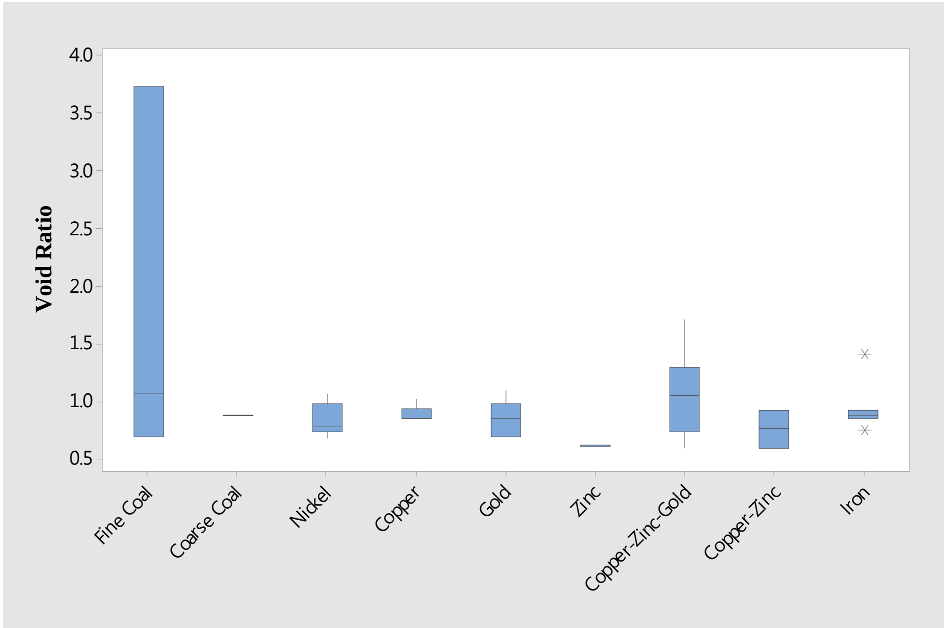


Figure 3-8 Void ratio of various mineral tailings

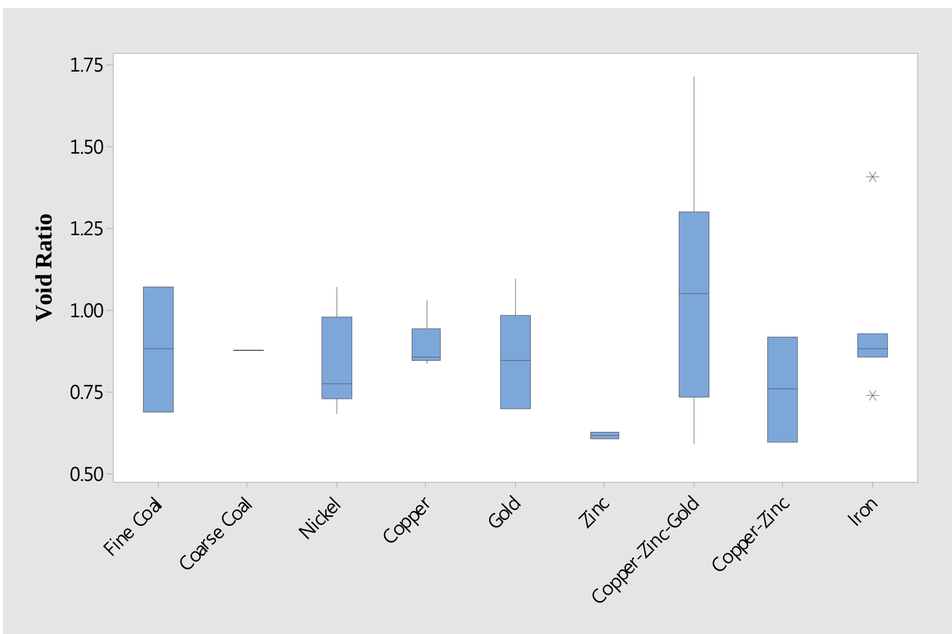


Figure 3-9 Void ratio of various mineral tailings (without outlier)

For the compression index (*Cc*), most of fine coal tailings have a higher value than other mineral tailings. The value of the compression index of fine coal tailings is between 0.134 to 0.453. The copper tailings have the value from 0.025 to 0.094. The compression index of gold tailings ranges from 0.086 to 0.156. For the iron tailings, the compression index is between 0.046 to 0.260 (Figure 3-10).

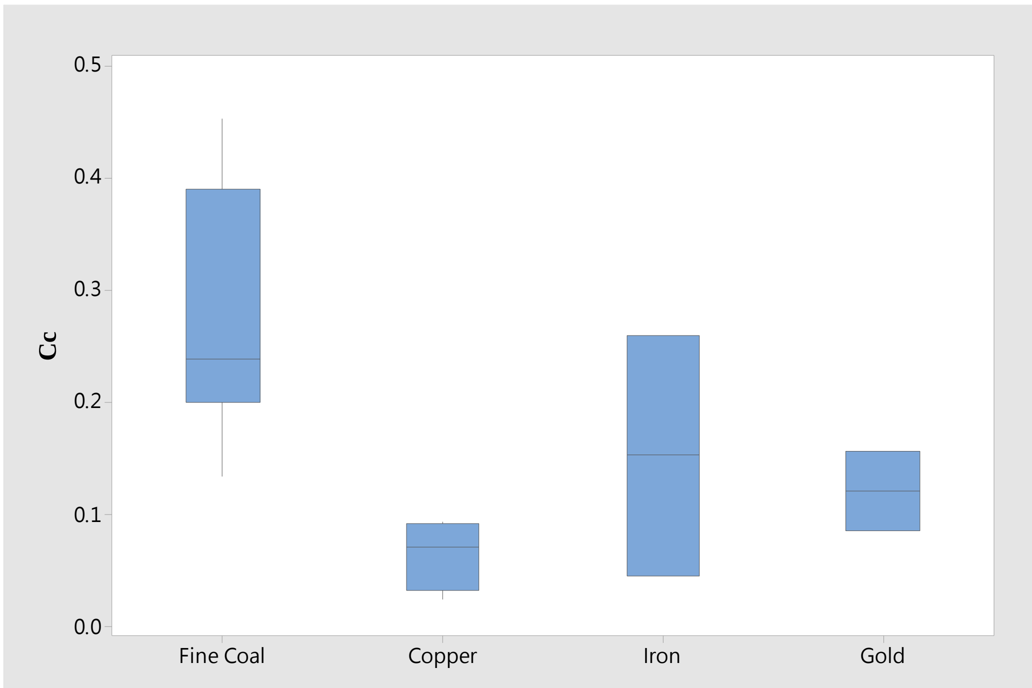


Figure 3-10 Compression index (*Cc*) of various mineral tailings

Figure 3-11 and Figure 3-12 compares the hydraulic conductivity from PSU research team and Qiu and Sego (2001). Figure 3-12 removes one data from PSU team, which is considered as an outlier by the Minitab software. The hydraulic conductivity of fine coal from PSU research team has the amount from 4×10^{-7} cm/sec to 3.3×10^{-6} cm /sec with an outlier 1.3×10^{-4} cm/sec. Qiu and Sego (2001) gave the same lower bond of 4×10^{-7} cm/sec with a higher upper bond of 1.1×10^{-5} cm/sec. Compares to fine coal tailings, gold tailings and copper tailings have higher hydraulic conductivity ranged from 2.7×10^{-5} cm /sec to 6.7×10^{-5} cm/sec and from 4.5×10^{-5} to 9.8×10^{-5} cm/sec, respectively.

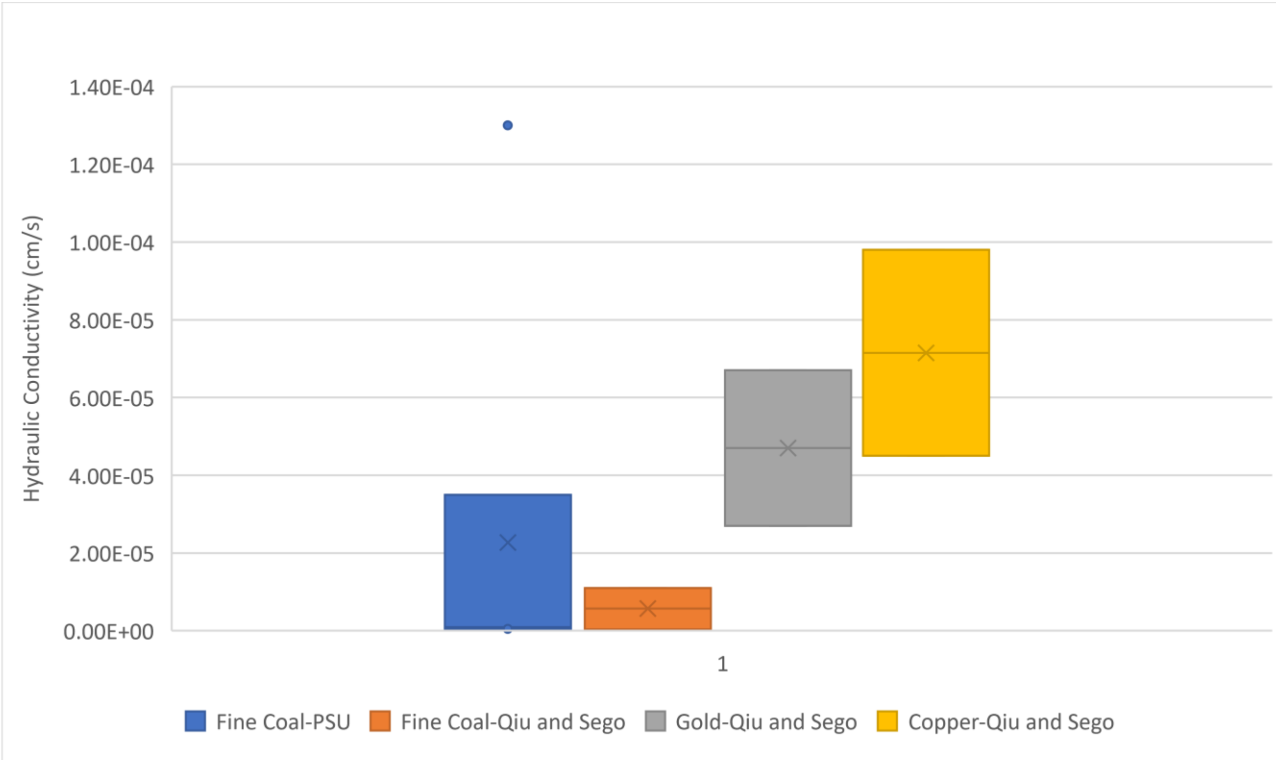


Figure 3-11 Hydraulic conductivity of various mineral tailings

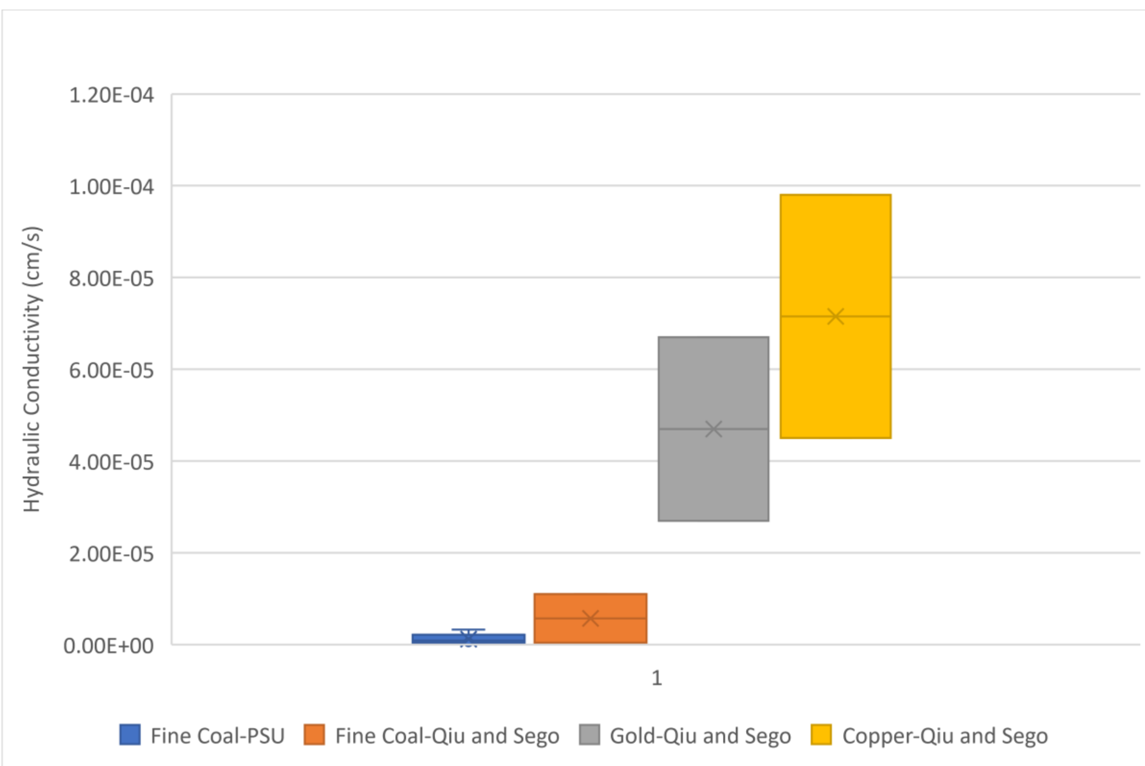


Figure 3-12 Hydraulic conductivity of various mineral tailings without outliers

This study attempted to find the effect of fines content (i.e., particles passing #200 U.S. sieve) of fine coal tailings on plasticity index (*PI*) and liquid limits (*LL*). Figure 3-12 and Figure 3-13 present the data given in Table 3-9 (fine coal) to study the relationship between them. In Figure 3-13, although the regression line seems a positive linear correlation, the correlation coefficient is 0.446. However, in Figure 3-14, liquid limit shows a stronger correlation to the percentage of fines content with correlation coefficient 0.768. In the range approximately 30% to 90% of fines content, the liquid limit of fine coal tailings falls mainly into 30 to 40. If the fines content is over 90%, the liquid limit increases drastically to over 50.

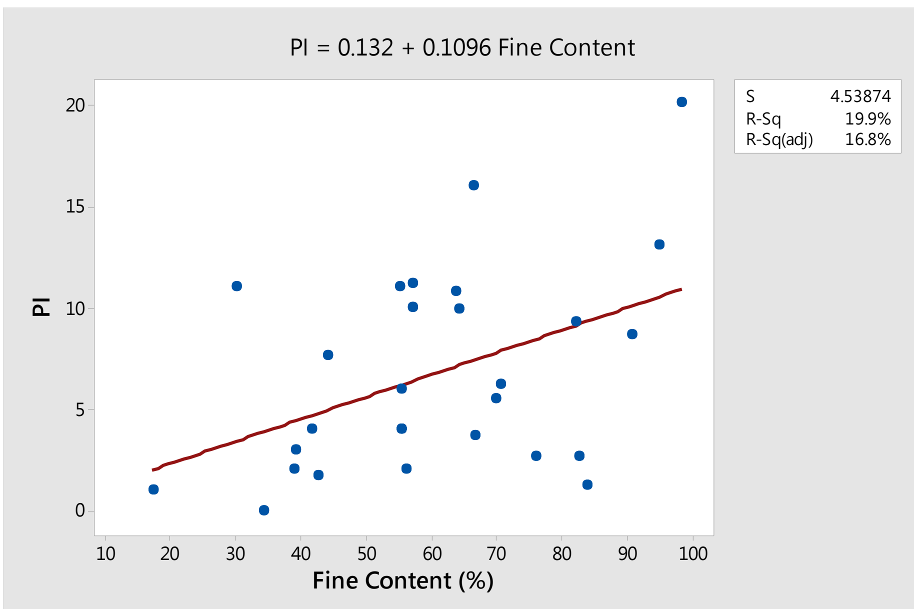


Figure 3-13 Relationship between fines content and plastic index (*PI*) of fine coal tailings

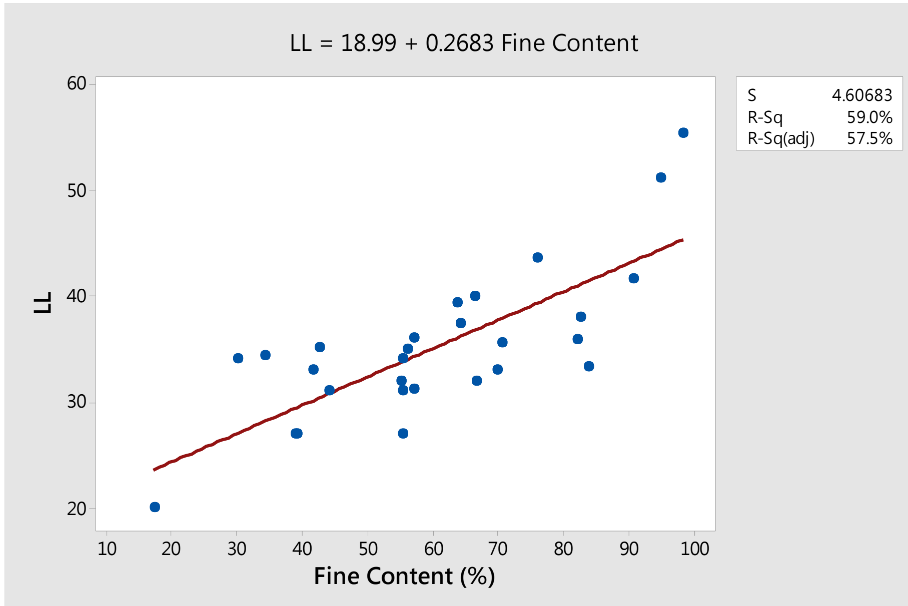


Figure 3-14 Relationship between fines content and liquid limit (*LL*) of fine coal tailings

Figure 3-15 and Figure 3-16 presented the correlation between the percentage of clay size particles and *PI* and *LL* of fine coal tailings. The R^2 value of the regression relationship between *PI* and fines content is 0.199, and the R^2 value of the regression relationship between *PI* and percentage of clay size particles is 0.307. This shows the percentage of clay size particle has higher impact on *PI*. For the *LL*, the R^2 value of the regression relationship is 0.59 with fines content and 0.548 with percentage of clay size particles. For the LL, fines content and the percentage of clay size particle have similar impact.

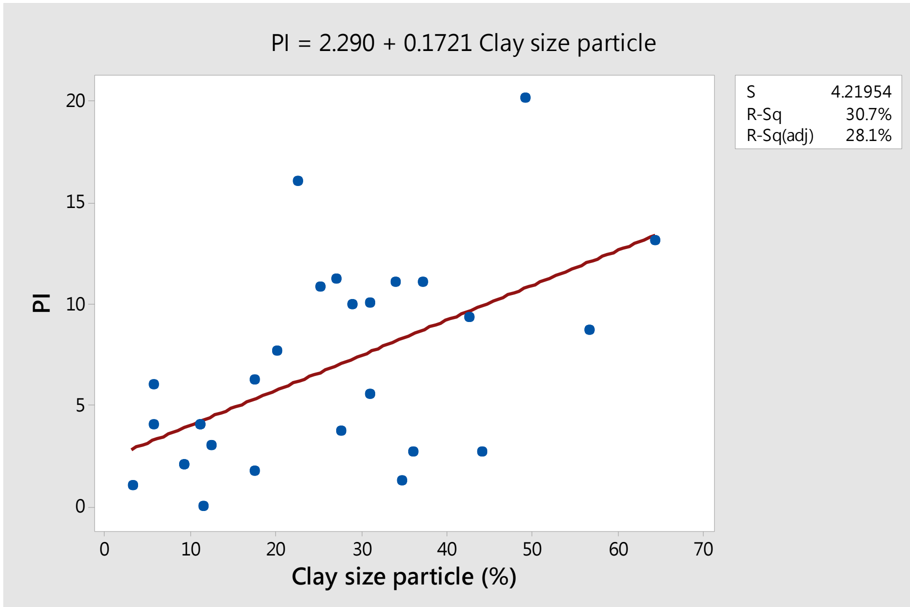


Figure 3-15 Relationship between clay size particles and plastic index (*PI*) of fine coal tailings

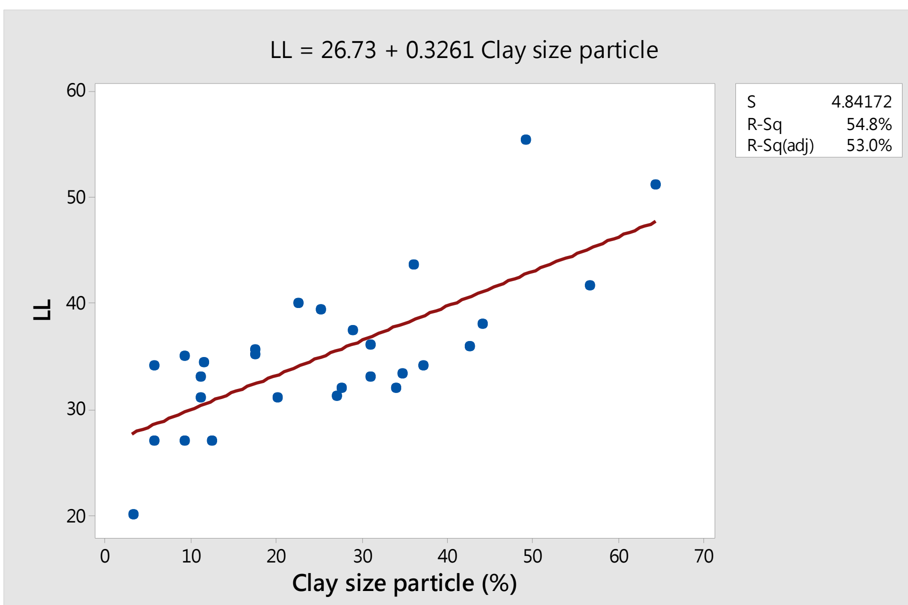


Figure 3-16 Relationship between clay size particle and liquid limit (*LL*) of fine coal tailings

In order to check the conclusion of previous paragraph, ANOVA tests were conducted on all four relationships. Figure 3-17 and 3-18 shows the results of ANOVA tests for plastic index. Both ANOVA tests were conducted with the null hypothesis that there is no relationship between *PI* and factor with significance level of 0.05. Figure 3-17 shows a P-value 0.049, which is smaller than 0.05, gives the conclusion that *PI* has a relationship with fines content. Figure 3-18 gives a P-value 0.02, which is also less than 0.05. We reject the null hypothesis meaning that the percentage of clay size particle do have impact on *PI*.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Fine Content	25	665.733	26.629	19.97	0.049
Error	2	2.667	1.333		
Total	27	668.399			

Figure 3-17 Results of ANOVA test between *PI* and fines content

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Clay size particle	23	656.41	28.540	9.52	0.020
Error	4	11.99	2.998		
Total	27	668.40			

Figure 3-18 Results of ANOVA test between PI and percentage of clay size particle

Figure 3-19 shows that coefficient of consolidation of the fine coal tailings has a linear negative relation with the percentage of fines content. As the percentage of fine content increases, the rate of consolidation of fine coal tailings decreases. The regression equation is

$$\mathrm{Cv} = 151.8 - 1.627x$$

where x is the percentage of fines content and C_v is the coefficient of consolidation (m^2/yr). This equation only includes the coal samples from PSU research team that were classified as SM or ML. To confirm whether this equation can be applied to different mine tailings, this study uses three different samples from Qiu and Sego (2001), fine coal tailing classified as CL, gold tailing classified as ML, and copper tailing classified as ML. The C_v given from Qiu and Sego (2001) is a range, so we used the fines content of the samples and see whether the responding y will fall into the range of it. For fine coal tailing, the factor x is 66.4 and the corresponding C_v is 43.76, which is much higher than the upper bond of the range it provided (17.26). For gold tailings, the fines content percentage is 81.3 (%) and the corresponding C_v is 19.52, which fell into the provided range (13.58 to 80.07 (m^2/yr). For copper tailing, the fines content percentage is 31.3 (%) and the corresponding C_v is 100.87 (m^2/yr), which also fell into the provided range of 22.32~104.23 (m^2/yr). The summary of these properties is showed in Table 3-16. It is noted that this equation can only be applied for mine tailings classified as SM and ML. Application of this equation to the mine tailings classified as CL or SW-SM needs further investigation.

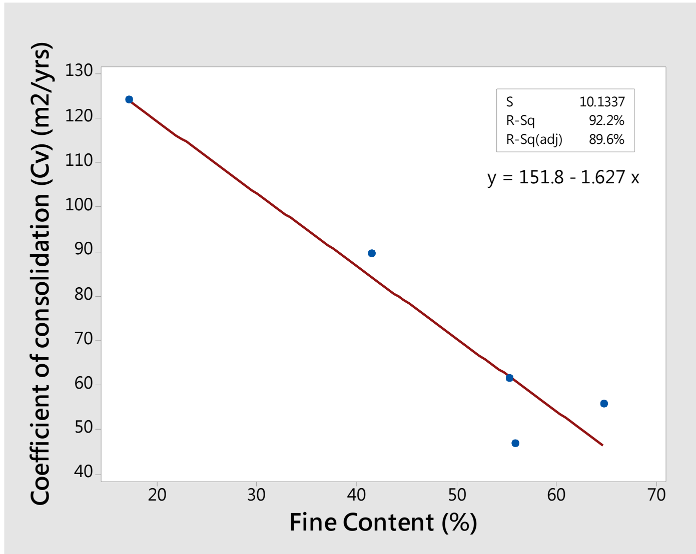


Figure 3-19 Relationship between fines content (%) and C_v of fine coal tailings from PSU research team

Table 3-16 Summary of USCS, fines content, and C_v from Qiu and Sego (2001)

	USCS	Fines content (%)	C_v (given) (m^2/yrs)	C_v (predict) (m^2/yrs)
Fine Coal	CL	66.4	1.48~17.26	43.76
Gold	ML	81.3	13.58~80.07	19.52
Copper	ML	31.3	22.32~104.23	100.87

CHAPTER 4 SUMMARY AND CONCLUSIONS

This study collected the properties of mineral tailings that were presented in the previous publications and from the results of laboratory tests from PSU research team. The compiled database includes the properties of tailings of gold, copper, zinc, nickel, iron, fine coal, and coarse coal. The properties that are presented in the database include basic properties (i.e. specific gravity, Atterberg limits, grain size distribution), void ratio, compression index, hydraulic conductivity, and geo-mechanic properties.

The comparisons of properties between different mineral tailings were carried out in this study. The results indicate that fine and coarse coal tailings tend to have lower specific gravity than other minerals. The specific gravity of mixed tailings is either between the value of single mineral tailings (i.e. copper-gold) or higher than single mineral tailings (i.e. copper-zinc, copper-gold-zinc). The reason of the variability of specific gravity of mixed and single mineral tailings is that mother rock plays a vital role in specific gravity of mineral tailings. In order to get a more precise data, the mother rock of mine tailings need to be considered.

For the USCS classification, most of the mine tailings are classified as CL to ML since mine tailings are the mineral waste generated from the segregation of pure mineral, the particles size of mine tailing tends to be fine particles. The void ratio and compression index (Cc) of mineral tailings are also presented in this study. For the hydraulic conductivity, after removing outlier, the results of fine coal tailings from Qiu and Sego (2001) and PSU research team (2018) have similar values. Copper tailings generally have higher hydraulic conductivity than gold tailings. Compared with other mineral tailings, fine coal tailings have the lowest hydraulic conductivity.

The correlation between fines content and plasticity of fine coal tailings was carried out in this study. The analysis indicates a positive correlation between fines content and plastic index. The R^2 value of regression relationship between fines content and *PI* is 0.199. The R^2 value of regression relationship between fines content and *LL* is 0.59. The correlation between the percentage of clay size particle and plasticity was carried out. The R^2 value of regression relationship between fines content and *PI* is 0.307. The R^2 value of regression relationship between fines content and *LL* is 0.548. Based on the results, the percentage of clay size particle has more impacts on *PI*. For *LL*, fines content and the percentage of clay size particle have similar impact.

An equation of the relationship between percentage of fines content and coefficient of consolidation (C_v) was carried out in this thesis; this equation is applicable for fine coal, gold, and copper tailings that are classified as SM and ML.

The collected database showed that most of the mineral tailings still lack information in both basic properties (i.e. liquid limit and plastic index) and advanced laboratory testing. Even the existing data showed high variability.

References

Al-Tarhouni, M., Simms, P., andSivathayalan, S. (2011).“Cyclic behaviour of reconstituted and desiccated–rewet thickened gold tailings in simple shear.” *Canadian Geotechnical Journal*, 48(7), 1044–1060.

ASTM. “Standard practice for wet preparation of soil samples for particle-size analysis and determination of soil constants.” ASTM D2217-85, West Conshohocken, PA.

ASTM. “Standard test method for consolidated-undrained triaxial compression test for cohesive soils.” ASTM D4767-11, West Conshohocken, PA.

ASTM. “Standard test method for particle-size analysis of soils.” ASTM D422-63, West Conshohocken, PA.

ASTM. “Standard test method for unconsolidated-undrained triaxial compression test on cohesive soils.” ASTM D2850-15, West Conshohocken, PA.

ASTM. “Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass.” ASTM D2216, West Conshohocken, PA.

ASTM. “Standard test methods for liquid limit, plastic limit, and plasticity index of soils.” ASTM D4318-17, West Conshohocken, PA.

ASTM. “Standard test methods for modulus and damping of soils by fixed-base resonant column devices.” ASTM D4015-15, West Conshohocken, PA.

ASTM. “Standard test methods for one-dimensional consolidation properties of soils using incremental loading.” ASTM D2435/D2435M-11, West Conshohocken, PA.

Azam, S., and Li, Q. (2010). Tailings dam failures: a review of the last one hundred years. *Geotechnical News*, 28(4), 50-54.

Baoshan, Z., and Chopin, L. (1983).“SHEAR WAVE VELOCITY AND GEOTECHNICAL PROPERTIES OF TAILINGS DEPOSITS.” *Bolletin of the International Association of Engineering Geology*.

Bartholomeeusen, G., Sills, G. C., Znidarčić, D., VanKesteren, W., Merckelbach, L. M., Pyke, R., Carrier, W. D., Lin, H., Penumadu, D., Winterwerp, H., Masala, S., andChan, D. (2002).“Sidere: numerical prediction of large-strain consolidation.” *Géotechnique*, 52(9), 639–648.

Braja M. Das (2011) Principles of foundation engineering.

Bonin, M. D., Nuth, M., Dagenais, A.-M., andCabral, A. R. (2014).“Experimental Study and Numerical Reproduction of Self-Weight Consolidation Behavior of Thickened Tailings.” *Journal of Geotechnical and Geoenvironmental Engineering*, 140(12), 04014068.

Busch, B. R. A., Backer, R. R., Atkins, L. A., Kealy, C. D., Hathaway, S. K., and Carlson, J. W. (1975).*Physical Property Data on Fine Coal Refuse*. U.S. Bureau of Mines. Spokane, Wash.

FEMA. (2011).*Dam Safety in the United States*. Federal Emergency Manageme

Geremew, A. M., andYanful, E. K. (2013).“Dynamic Properties and Influence of Clay Mineralogy Types on the Cyclic Strength of Mine Tailings.” *International Journal of Geomechanics*, 13(4), 441–453.

Hegazy, Y. A., Cushing, A. G., andLewis, C. J. (2004).*Physical, mechanical, and hydraulic properties of coal refuse for slurry impoundment design*. Monroeville, PA.

Hu, L., Wu, H., Zhang, L., Zhang, P., andWen, Q. (2017).“Geotechnical Properties of Mine Tailings.” *Journal of Materials in Civil Engineering*, 29(2), 04016220.

International Commission on Large Dams (ICOLD). (2001). *Tailings dams - risk of dangerous occurrences, lessons learnt from practical experiences (Bulletin 121).*

James, M., Aubertin, M., Wijewickreme, D., and Wilson, G. W. (2011).“A laboratory investigation of the dynamic properties of tailings.” *Canadian Geotechnical Journal*, 48(11), 1587–1600.

Kossoff, D., Dubbin, W.E., Alfredsson, M., Edwards, S.J., Macklin, M.G., and Hudson-Edwards, K.A. (2014). Mine tailings dams: characteristics, failure, environmental impacts, and remediation. *Applied Geochemistry*, 51, 229-45.

National Research Council. (2002). Coal waste impoundments: risks, responses, and alternatives. sashington, D.C.: National Academies Press

de Oliveira-Filho, W. L., and van Zyl, D. (2006).“Modeling discharge of interstitial water from tailings following deposition. Part 2: Application.” *Solos Rochas*, 29(2), 211–221.

Qiu, Y. (Jason), and Sego, D. C. (2001).“Laboratory properties of mine tailings.” *Canadian Geotechnical Journal*, 38(1), 183–190.

Quille, M. E. (2010).“Geotechnical properties of zinc/lead mine tailings from Tara Mines, Ireland.” *The Accounting Review*, 86(4).

Rico, M., Benito, G., Salgueiro, A.R., Díez-Herrero, A., and Pereira, H.G. (2008). Reported tailings dam failures: a review of the European incidents in the worldwide context. *Journal of Hazardous Materials*, 152(2), 846-852.

R. Lyman Ott and Michael Longnecker (7th edition) *An Introduction to Statistical Methods and Data Analysis*.

Salam, S., Xiao, M., Khosravifar, A., Liew, M., Liu, S., andRostami, J. (2019).“Characterizations of Static and Dynamic Geotechnical Properties and Behaviors of Fine Coal Refuse.” *Canadian Geotechnical Journal*, cgj-2018-0630.

Saxena, S. K., Lourie, D. E., andRao, J. S. (1984).“Compaction Criteria for Eastern Coal Waste Embankments.” *Journal of Geotechnical Engineering*, 110(2), 262–284.

Ullrich, C. R., Thacker, B. K., andRoberts, N. R. (1991).“Dynamic Properties of Fine-Grained Coal Refuse.” *International Conferences of Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, 13.

USGS. (2016).*Mineral Commodity Summaries*. Reston, Virginia

Wijewickreme, D., Sanin, M.V, andGreenaway, G. R. (2005).“Cyclic shear response of fine-grained mine tailings.” *Canadian Geotechnical Journal*, 42(5), 1408–1421.

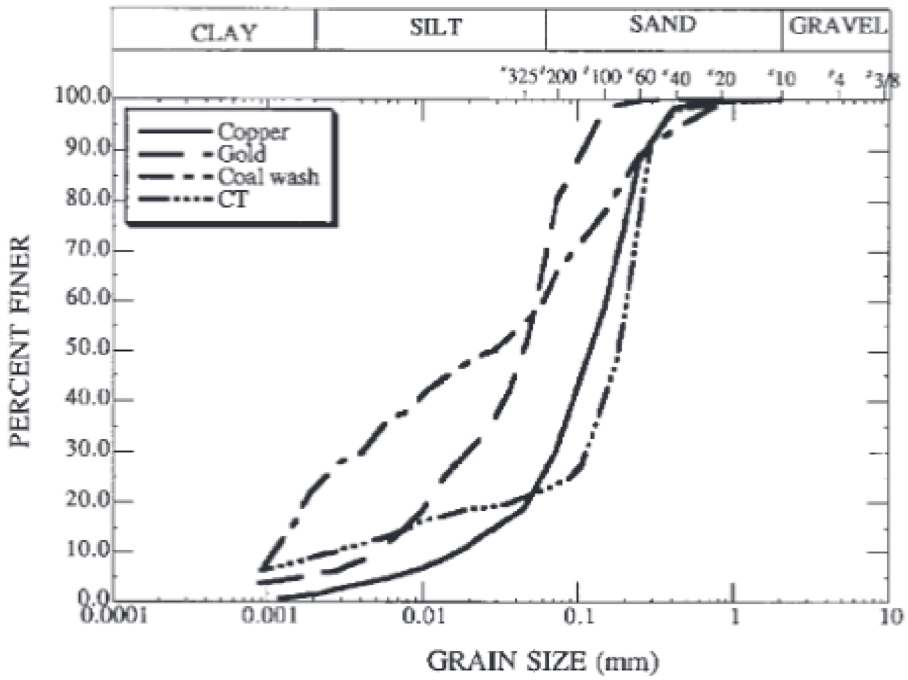
Wong, R. C., Mills, B. N., andLiu, Y. B. (2008).“Mechanistic Model for One-Dimensional Consolidation Behavior of Nonsegregating Oil Sands Tailings.” *Journal of Geotechnical and Geoenvironmental Engineering*, 134(2), 195–202

Xiao, M. (2015). Geotechnical engineering design. John Wiley & Sons.

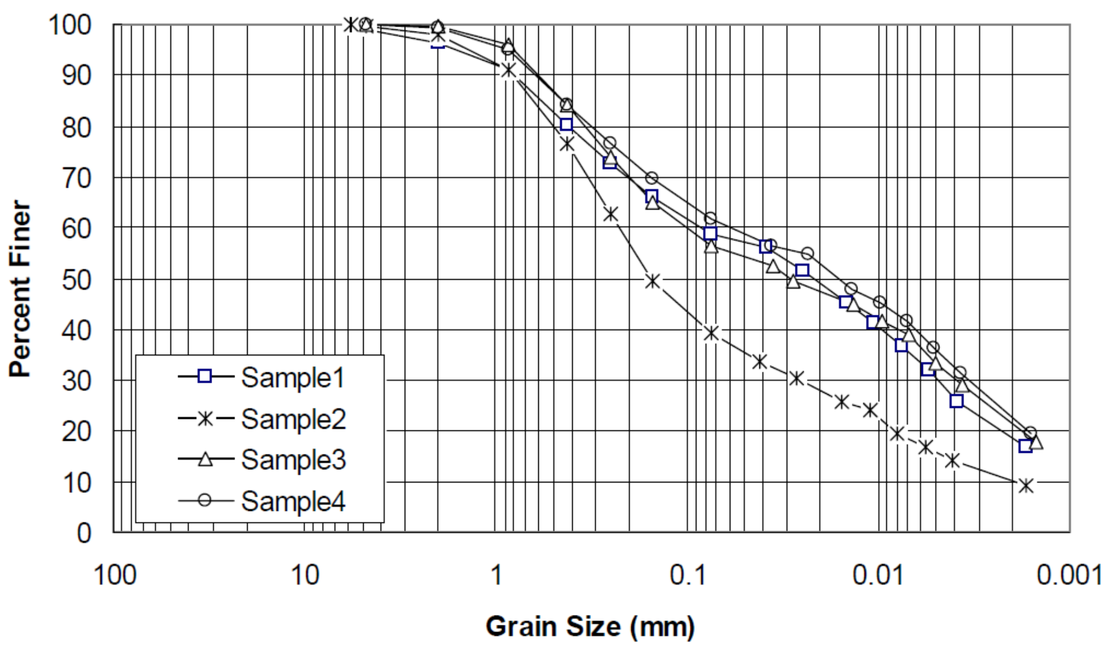
Zeng, X., Goble, J. A., andFu, L. (2008).“Dynamic Properties of Coal Waste Refuse in a Tailings Dam.” *Geotechnical Earthquake and Engineering and Soil Dynamics IV Congress*.

Zhao, J.Bin, Ji, Y. C., Liu, X., andLi, D. (2014).“Experimental Study on Dynamic Characteristics of Tailings.” *Applied Mechanics and Materials*, 580–583, 455–459.

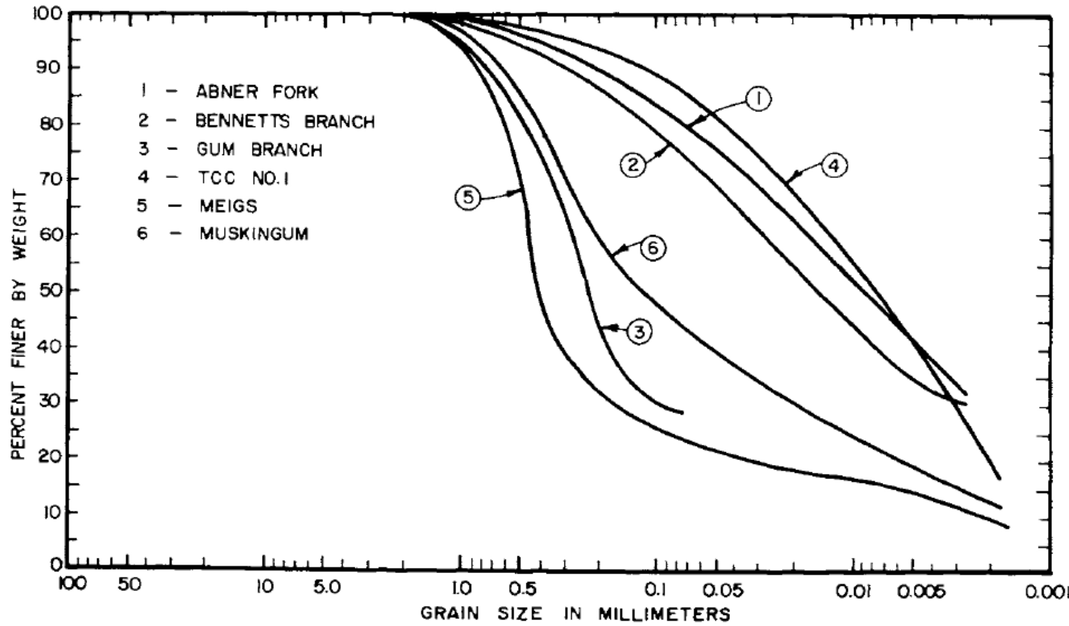
APPENDIX A: Grain Size Distributions of Fine Coal Tailings



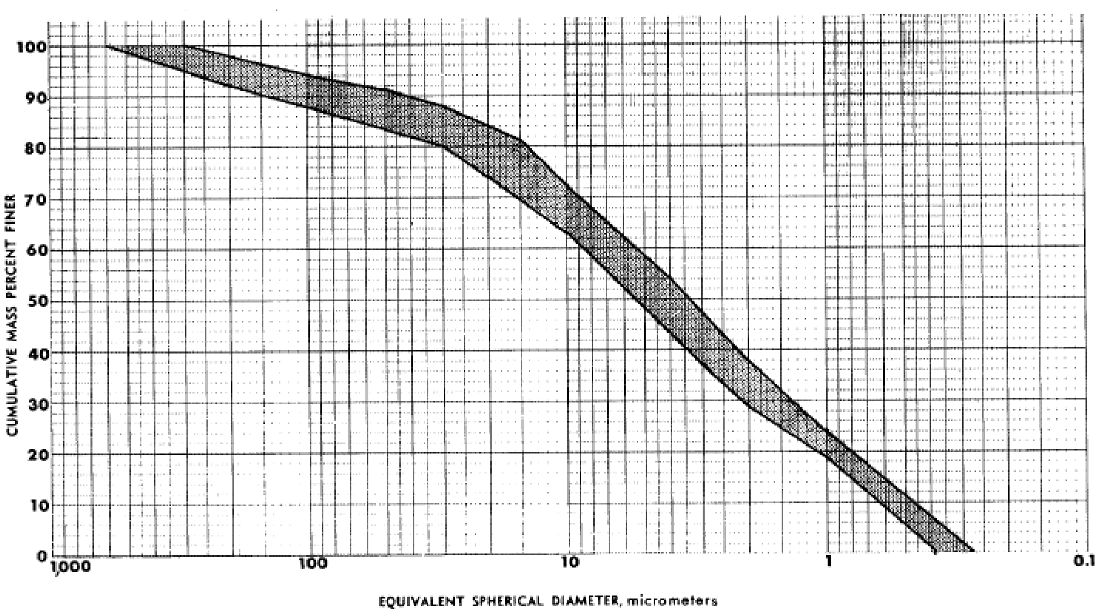
GSD 1-1 Qiu and Sego (2001)



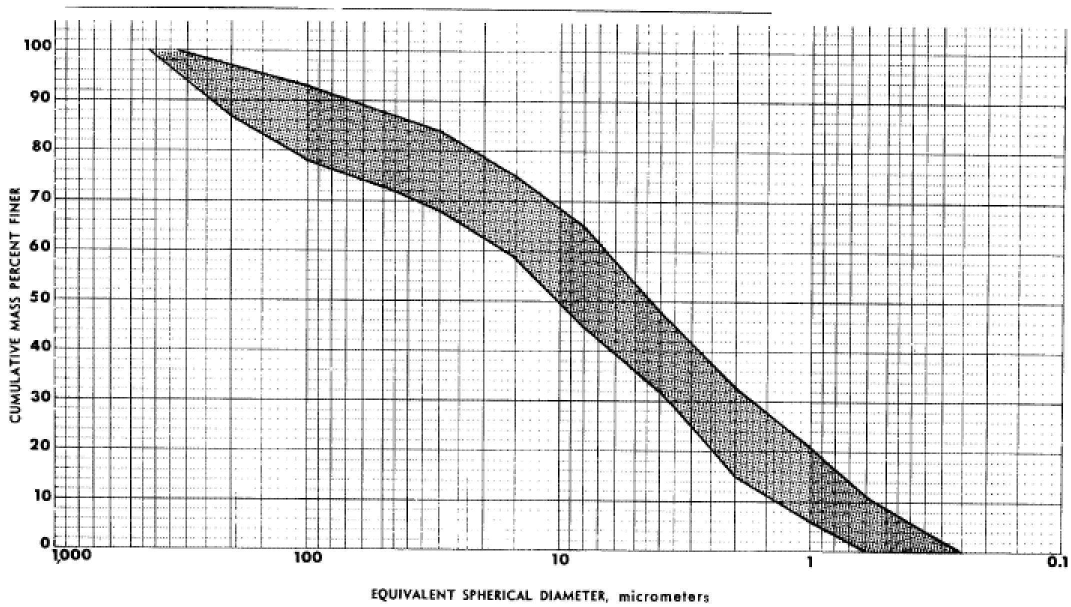
GSD 1-2 Zeng et al. (2008)



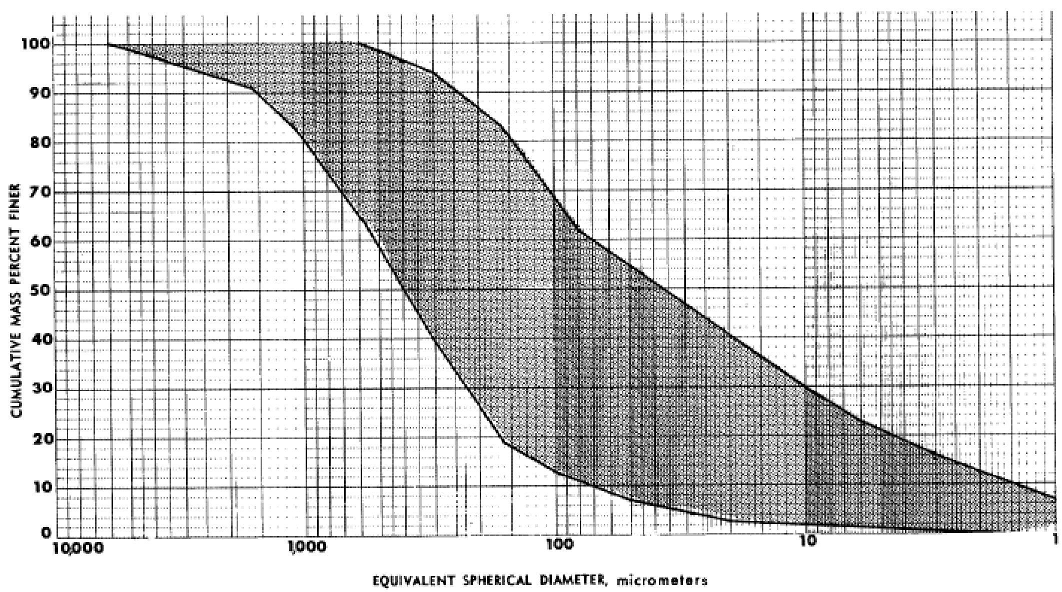
GSD 1-3 Ullrich et al. (1991)



GSD 1-4 Busch et al. (1975), WDH-1



GSD 1-5 Busch et al. (1975), WDH-2



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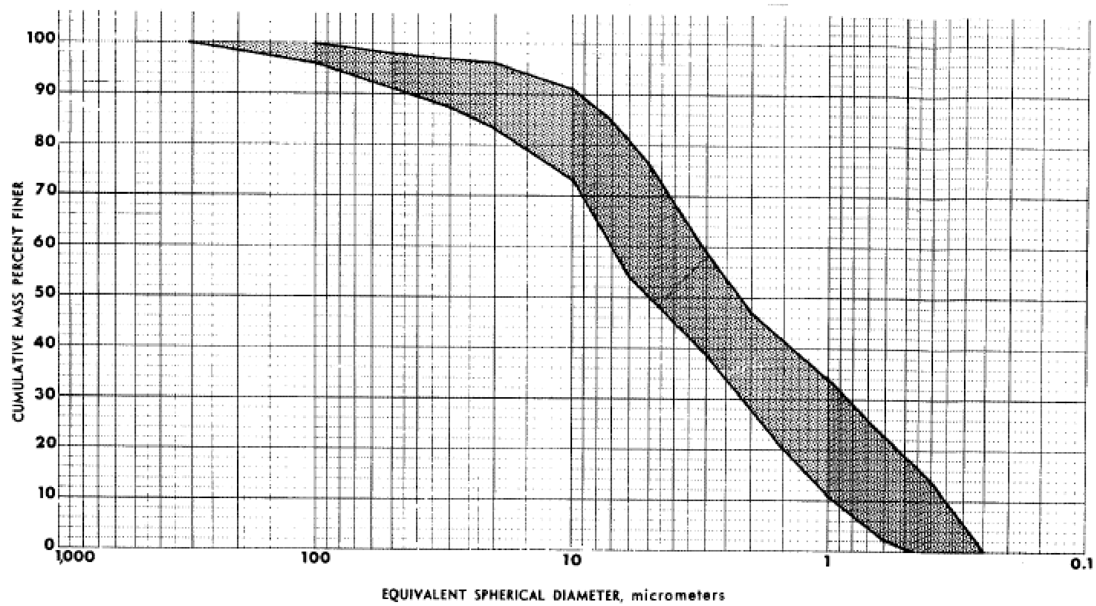
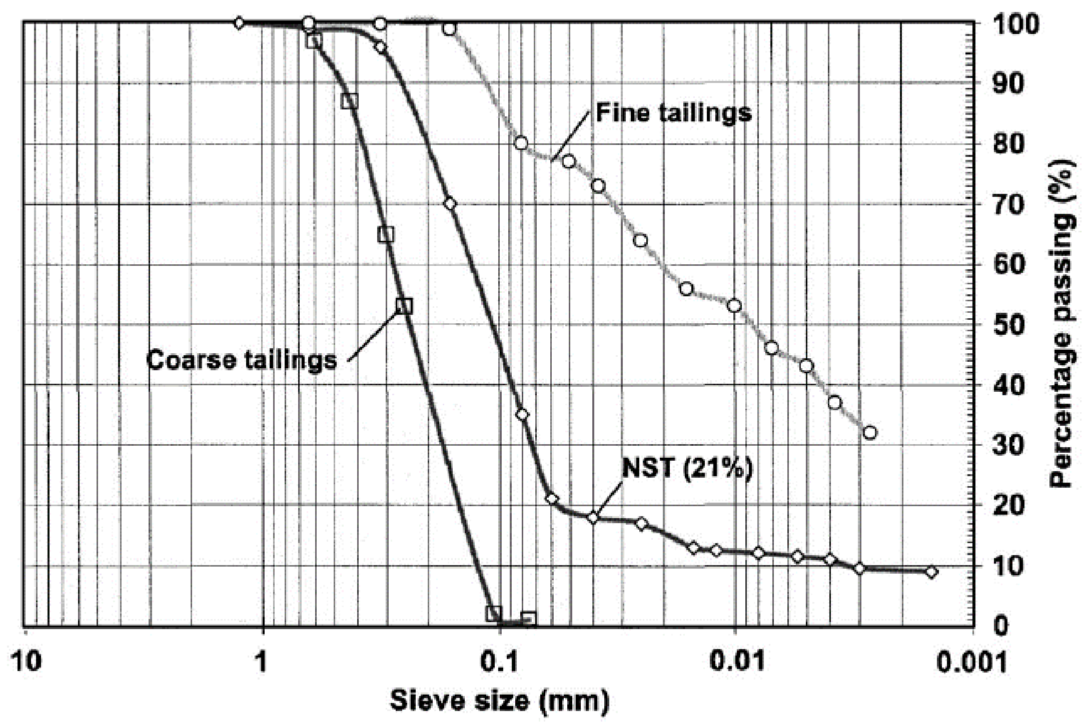
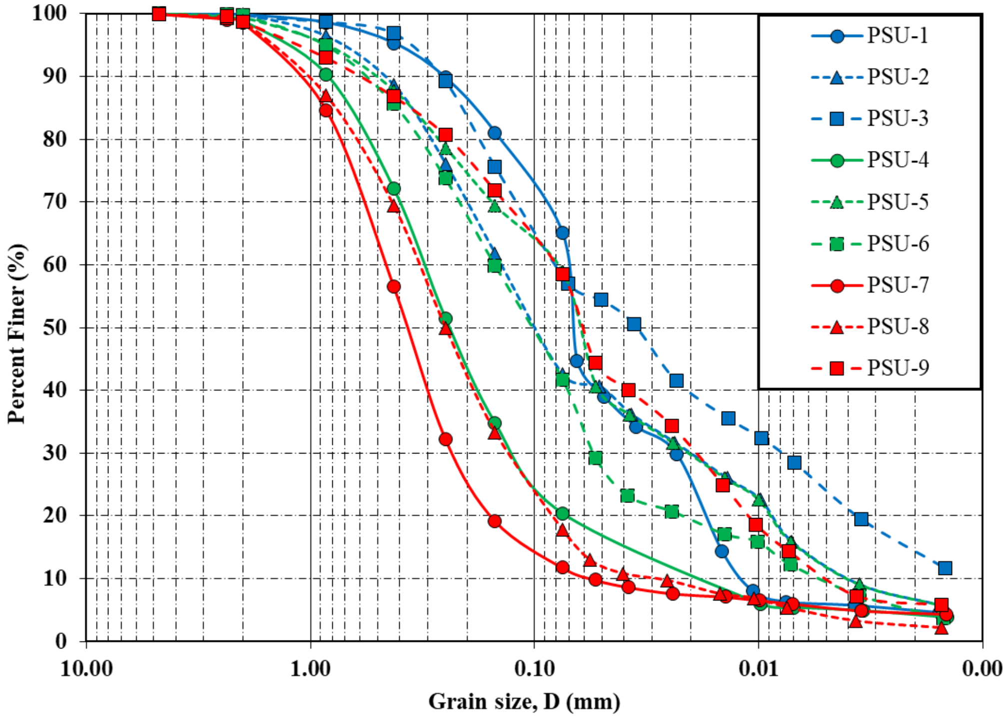


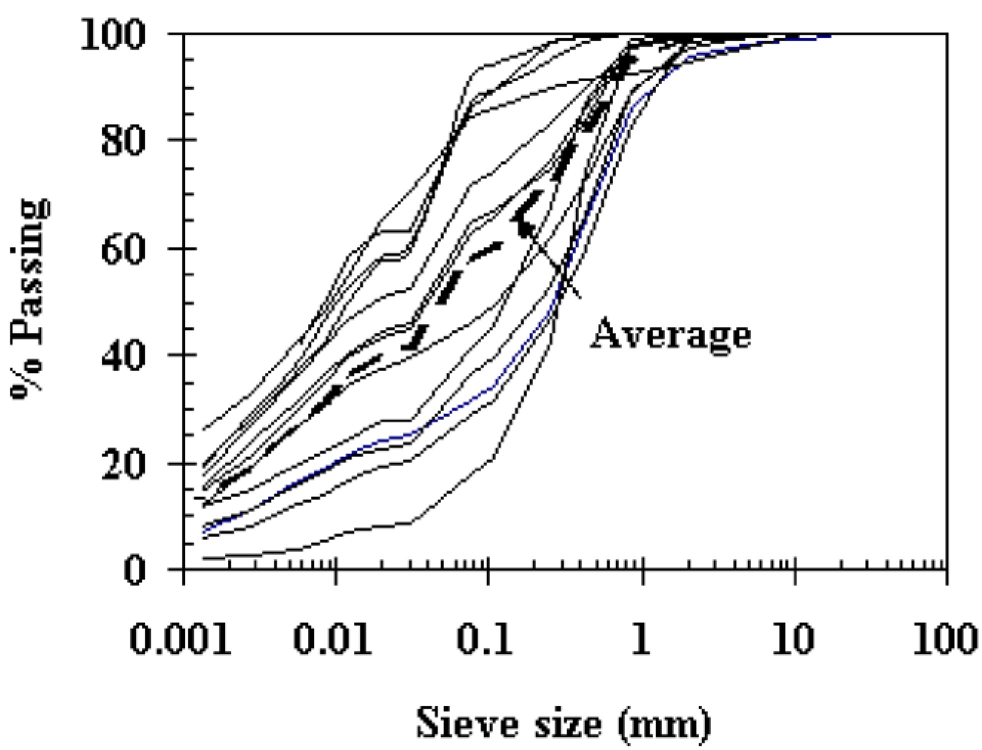
GSD 1-7 Busch et al. (1975), BDH-2



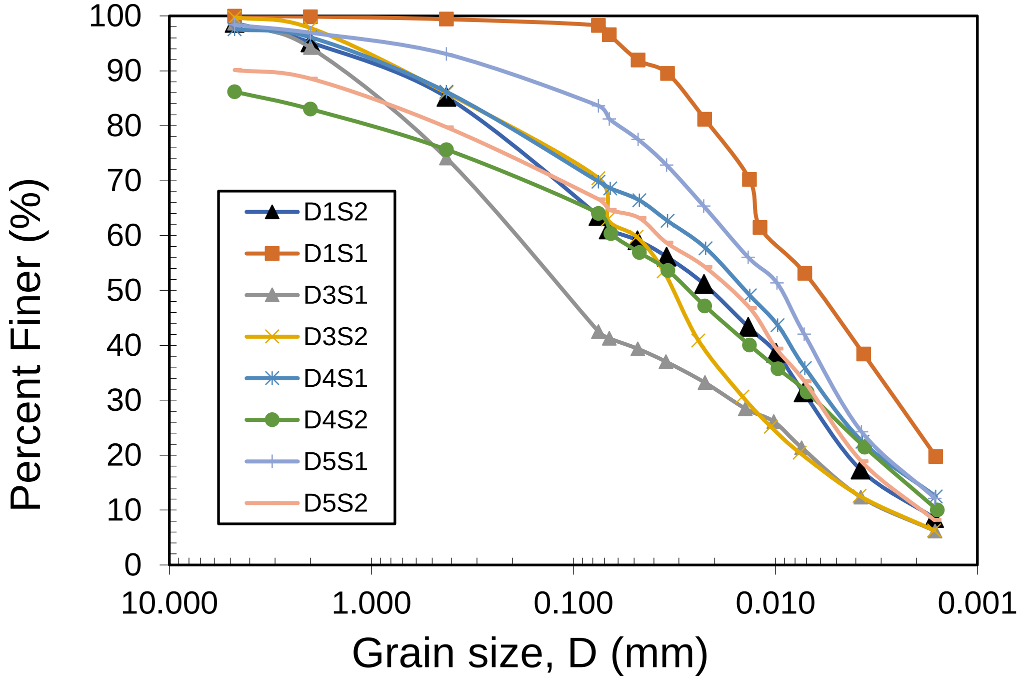
GSD 1-8 Wong et al. (2008)



GSD 1-9 PSU (2018)

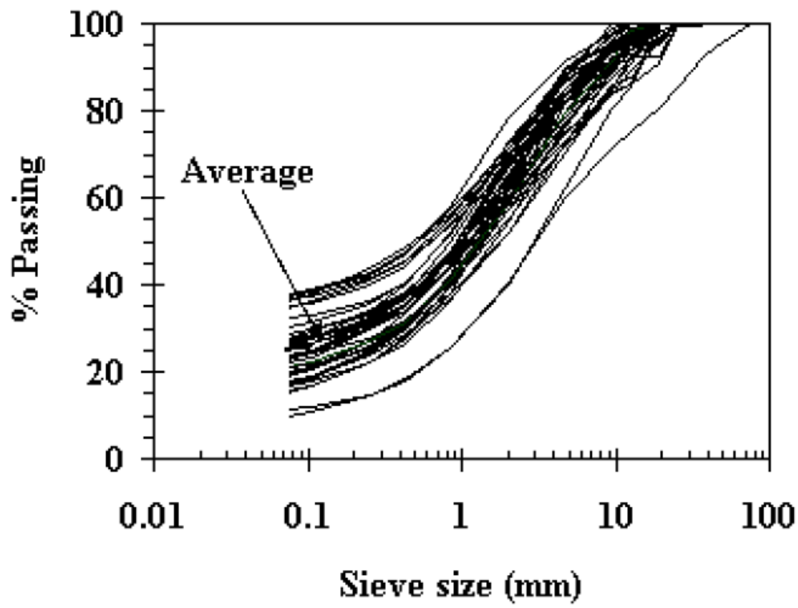


GSD 1-10 Hegazy et al. (2004)

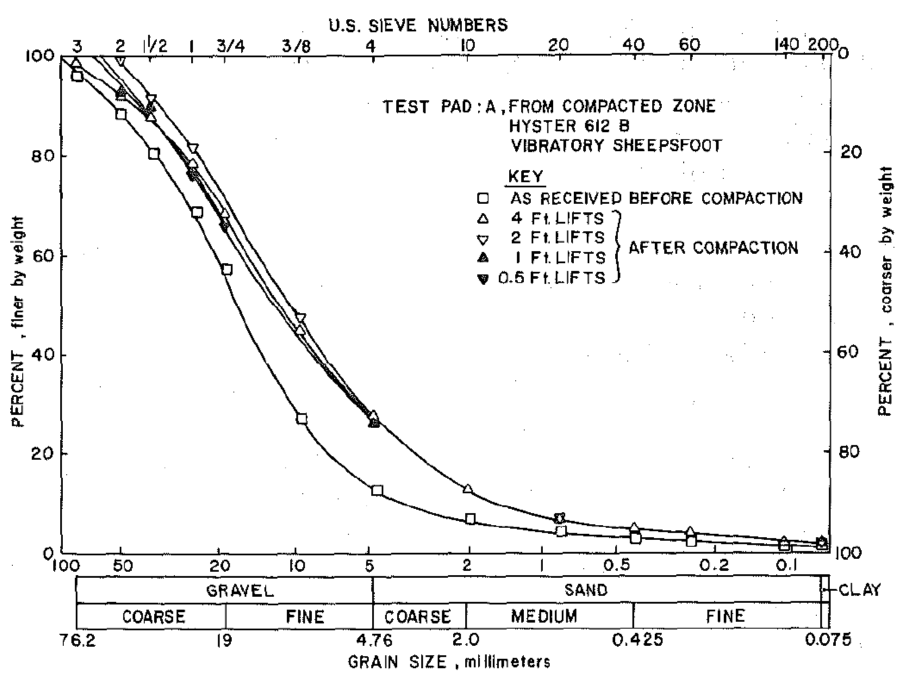


GSD 1-11 PSU (2019)

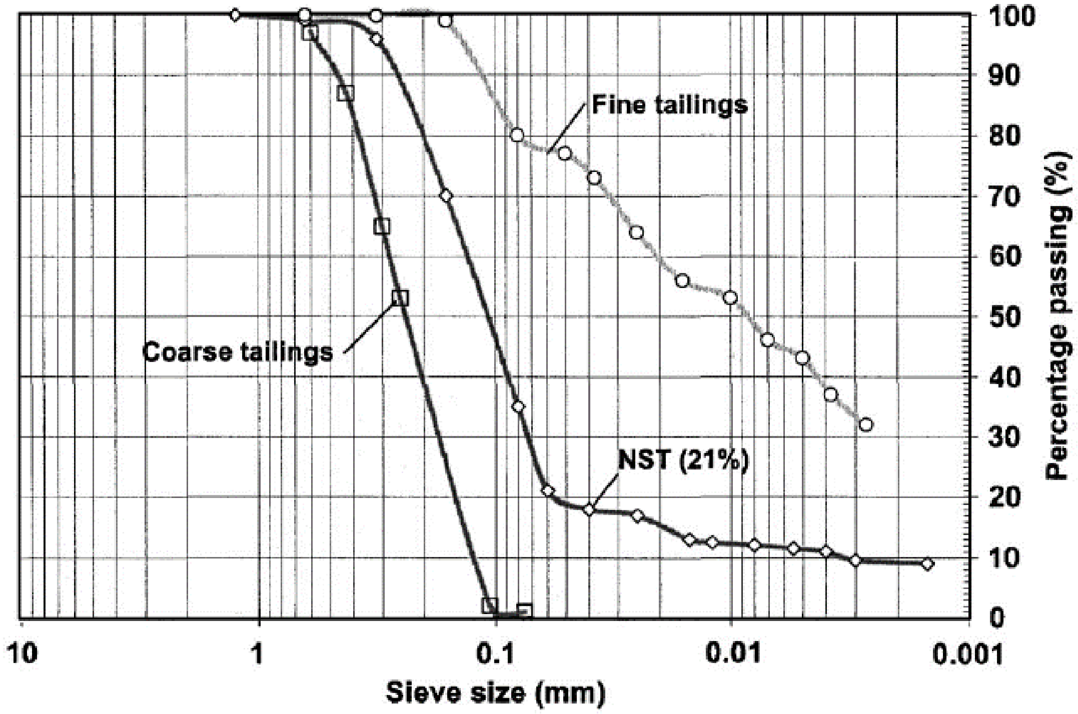
APPENDIX B: Grain Size Distributions of Coarse Coal Tailings



GSD 2-1 Hegazy et al. (2004)

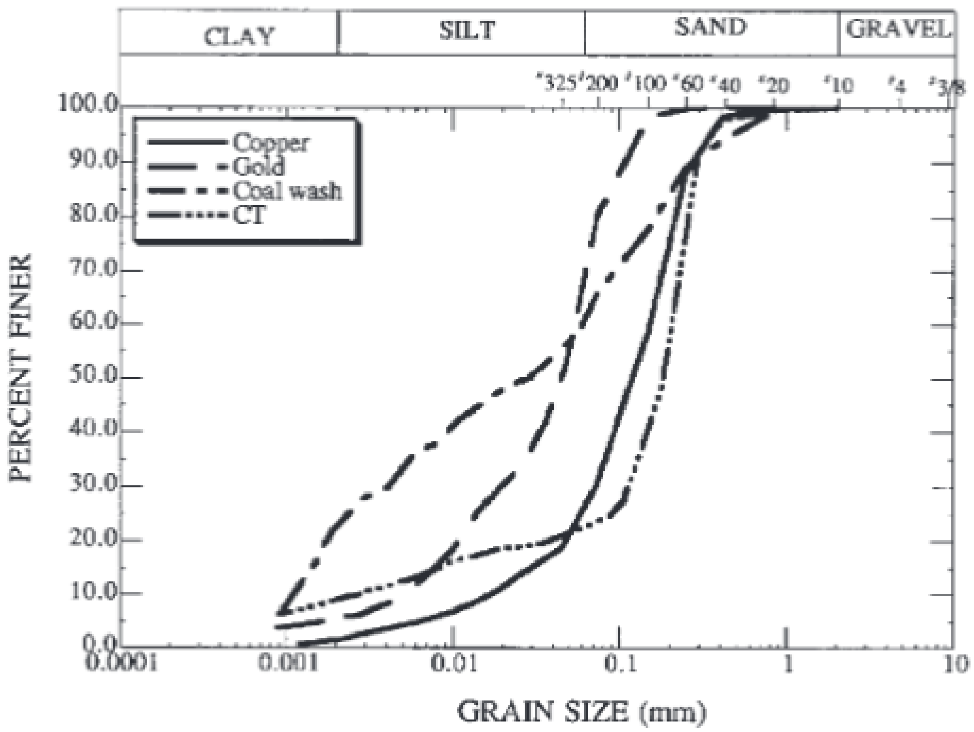


GSD 2-2 Saxena et al. (1984)

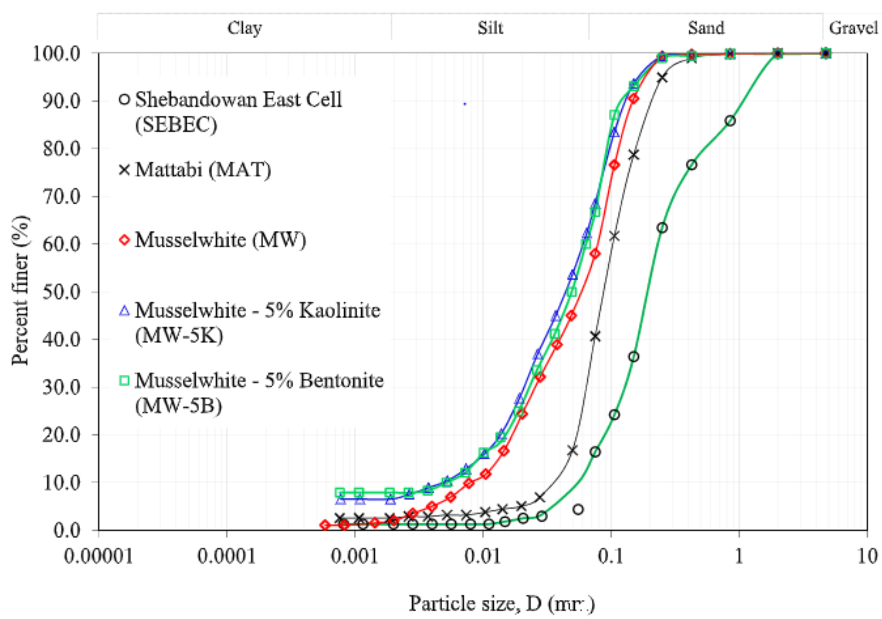


GSD 2-3 Wong et al. (2008)

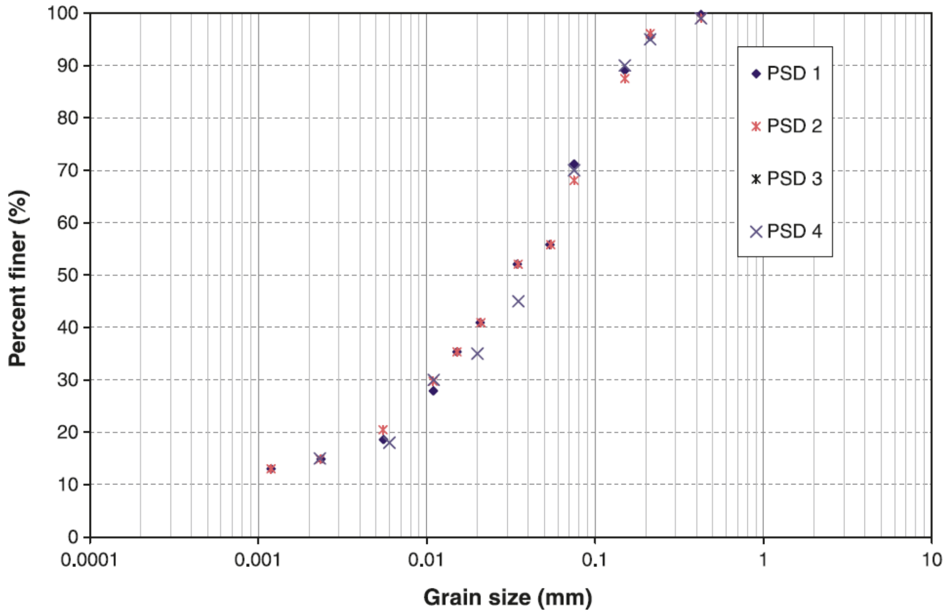
APPENDIX C: Grain Size Distributions of Gold Tailings



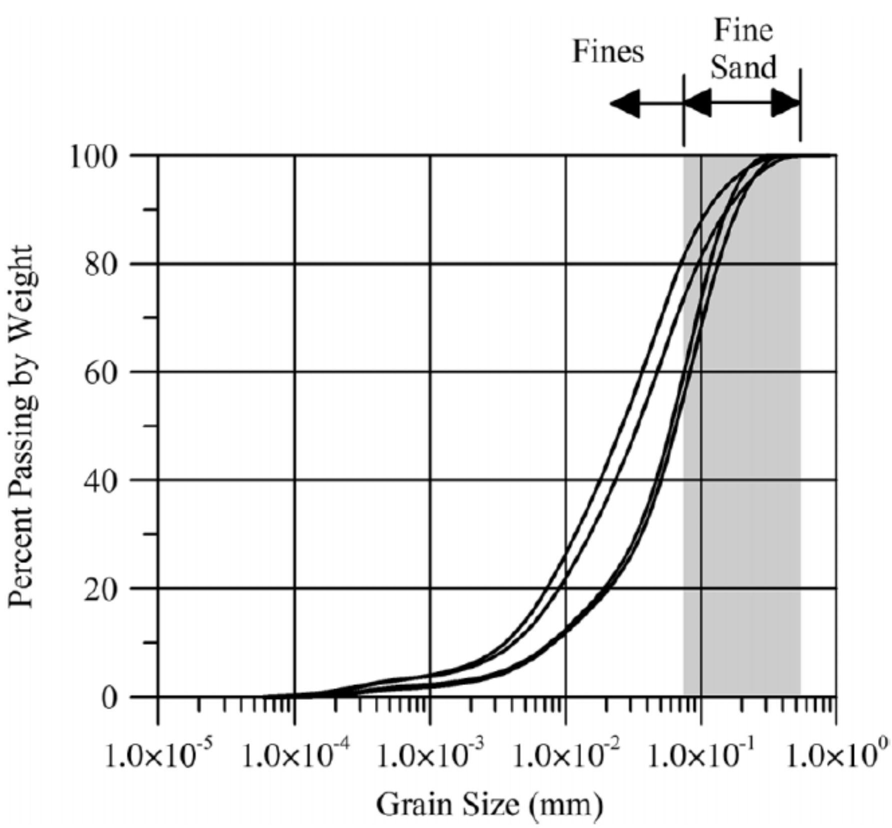
GSD 3-1 Qiu and Sego (2001)



GSD 3-2 Geremew and Yanful (2013)

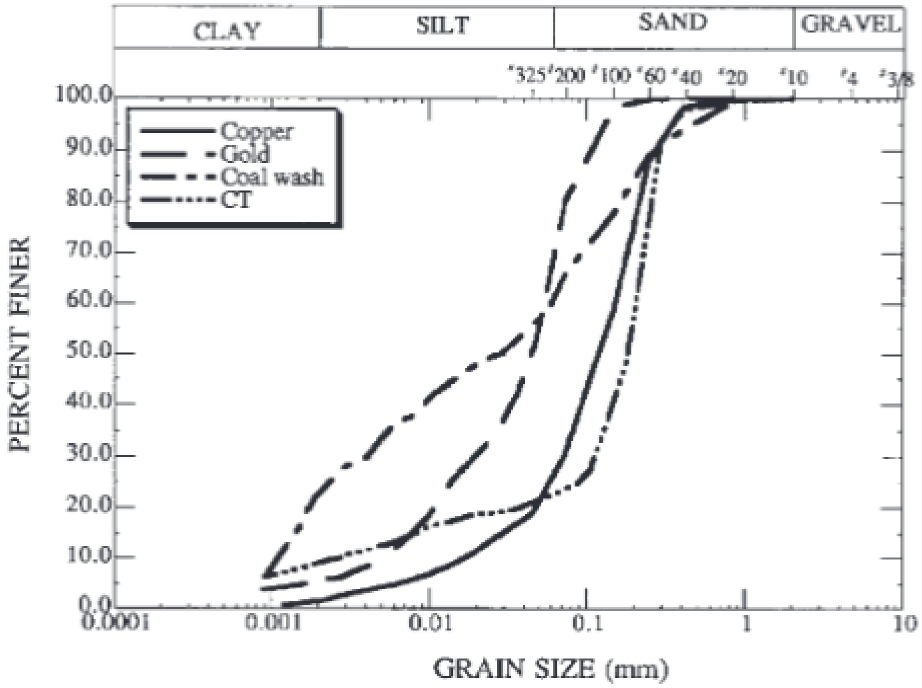


GSD 3-3 Al-Tarhouni et al. (2011)

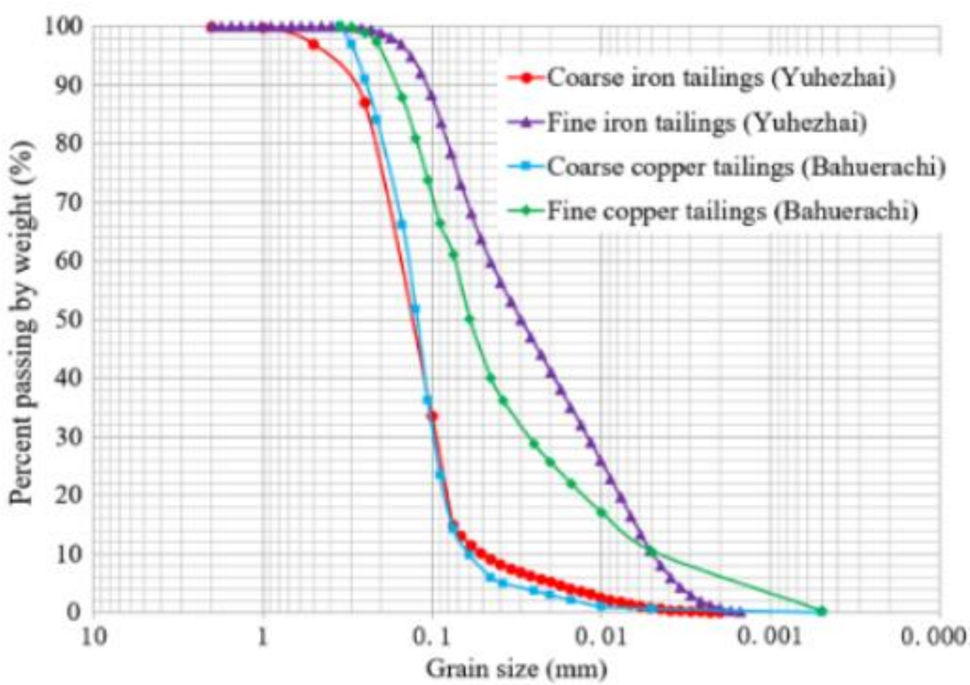


GSD 3-4 James et al. (2011)

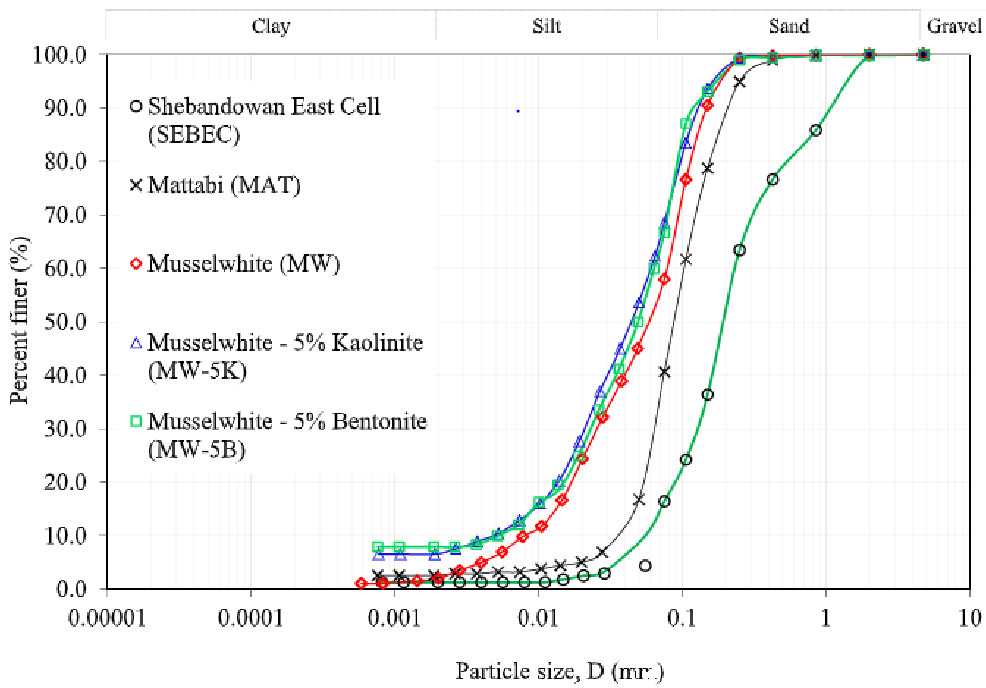
APPENDIX D: Grain Size Distributions of Copper, Iron, Nickel, and Zinc Tailings



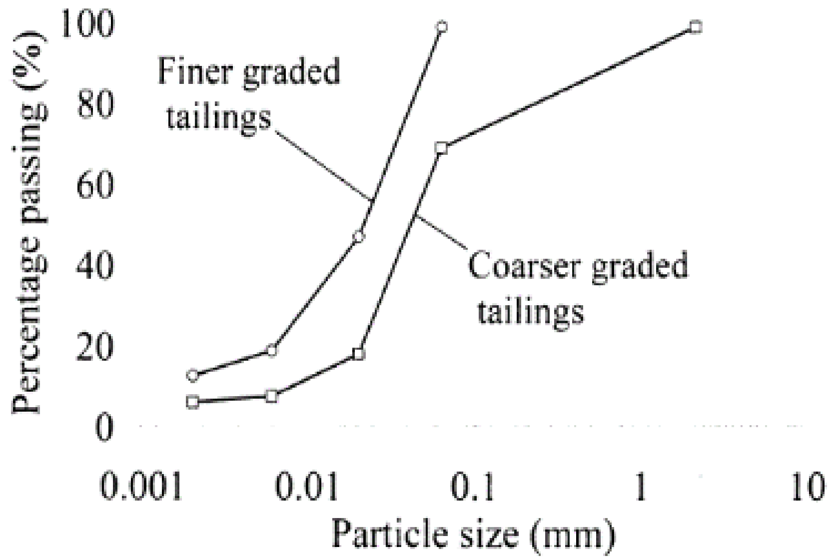
GSD 4-1 Qiu and Sego (2001)



GSD 4-2 Hu et al. (2017)



GSD 4-3 Geremew and Yanful (2013)



GSD 4-4 ME Quille (2010)