Geotechnical characterization of mine waste rock
Charactérisation géotechnique de débris rocheux miniers

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ABSTRACT
The determination of geotechnical charactertiscs of waste rock is essential for addressing issues of in situ hydrology and the stability of steep and high-standing dumps. Based on laboratory investigations and numerical modeling, this paper gives the geotechnical properties of a selected waste rock under saturated and unsaturated conditions. Results indicated that the engineering behavior of the investigated waste rock is similar to granular soils and governed by the "well-graded" and "very angular" nature of the materials. The samples exhibited low air entry values (0.2 and 0.8 kPa) and low water storage (0.44) along with a high saturated hydraulic conductivity (1 x 10^{-5} m/s). The hydraulic conductivity dropped sharpely beyond the air entry value by up to eight orders of magnitude at 200 kPa. The shear strength was identical to loose coarse materials and was primarily derived from the angle of internal friction that measured 37^{o} to 39^{o}, similar to the angle of repose. Additional strength can be availabe in the form of effective cohesion due to clays and cementation and apparent cohesion due to matric suction.

RÉSUMÉ
La détermination des charactéristiques géotechniques des débris rocheux est nécessaire pour résoudre les problèmes du lessivage de dans située hydrologie et la stabilité des dépotoirs miniers. Cet article, basé sur des recherches de laboratoires et modèles numériques, présente les propriétés géotechniques de débris rocheux conservés sous des conditions saturées et insaturées. Selon les résultats obtenu, le comportement des débris rocheux étudiés est le même que pour les sols granulaires; le comportement est déterminé par la nature des matériaux de grosseur similaire et très anguleux. Les échantillons ont présenté des valeurs basses pour l'entrée d'air (0.2 et 0.8 kPa) et pour le stockage d'eau (0.44), et une valeur élevée pour la conductivité hydraulique saturée (1 x 10^{-5} m/s). À une pression de 200 kPa, la conductivité hydraulique diminue rapidement au-delà de la valeur d'entrée d'air, jusqu'à un ordre de magnétude de huit. La force de rupture géologique était identique à celle des matériaux granuleux lâches et venait principalement de l'angle interne de friction qui mesurait entre 37^{o} et 39^{o}, ce qui est semblable à l'angle de repos. Une force supplémentaire est disponible sous la forme d'une cohésion efficace de l'argile et cémentation, ainsi que la cohésion apparente d'une matrice suceuse.

Keywords: waste rock, geotechnical index properties, soil water characterisitic curve, hydraulic conductivity, shear strength

1 INTRODUCTION

The determination of geotechnical charactertiscs of mine waste rock is essential for developing sustainable (cost effective, environmentally friendly, socially viable) waste management methods. The main challenge associated with this class of materials is their heterogeneity that, in turn, arises from parent geology (material properties and mineral composition), mining operation (blasting and sequencing), construction practice (transportation and dumping), and climatic conditions (temperature and precipitation). The engineering properties of the waste rock affect the overall stability of steep and high-standing (400 to 800 m) slopes and the *in situ* hydrologic behavior of the mine waste dumps (Valenzuela et al. 2008).

Material heterogeneity is particularly important for large-scale mining operations. Huge quantities (2 x 10^{5} to 4 x 10^{5} tons per day) of waste rock with no economic value are generated as a by-product over a number of years. The waste rock comprises of low-grade and barren materials that have to be excavated to access the underlying metal-rich ore body. During active mining, intact rocks from different geological facies are broken down to various degrees by blasting and sequentially deposited along a hillside where the material develops an angle of repose (38^{o}) slope face. The conventional dump construction method, known as *end dumping*, results in material segregation as the coarse chunks travel longer distances than the fine particles (Nichol et al. 2000). As the face advances, the heterogeneity within the dump gradually increases owing to repetitive trafficking of heavy machinery. The internal structure of the deposit also evolves due to complex weathering phenomena. Azam et al. (2007) divided these phenomena into physical processes (abrasion, particle crushing, growth of mineral and ice crystals or slaking due to volume changes in clay minerals) and chemical processes (dissolution, oxidation, hydrolysis, diffusion and precipitation). The corresponding grain size breakdown and the development of clays takes place over time and the rate of this evolution depends on the climate.

Climatic conditions at a mine site govern compositional transformations and geotechnical behavior of the deposited material in the man-made earth structure. Most mining projects are located in the arid and semi-arid regions of the globe where evapotranspiration exceeds precipitation. Waste rock dumps in such areas undergo alternate wetting and desiccation cycles owing to seasonal climatic variations. A clear understanding of material properties during saturation and desaturation is key to a sustainable design of the waste containment facilities.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-3421

The main objective of this paper was to determine the geotechnical properties of waste rock materials under saturated and unsaturated conditions. Representative samples were retrieved from a typical waste rock dump face at a base metal mine in a semi-arid area. Initially, the geotechnical index properties were determined to classify the materials. Next, the soil water characteristics curves (SWCC) were obtained using the index properties along with the grain size data. Thirdly, the hydraulic conductivity functions were estimated from knowledge of the measured saturated hydraulic conductivity and the previously determined SWCC. Finally, the shear strength properties were directly determined using the direct shear test.

2 RESEARCH METHODOLOGY

2.1 *Geotechnical Index Properties*

The geotechnical index properties were determined to classify the investigated materials and for use in the determination of unsaturated soil behavior. First, the specific gravity (Gs) was determined according to the ASTM Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer (D 854-06). Next, the grain size distribution analyses were performed according to the ASTM Standard Test Method for Particle-Size Analysis of Soils (D 422-63(2007)). For sieve analysis, material coarser than 19.1 mm was removed and approximately 2000 g of the remainder waste rock sample was allowed to pass through a series of sieves. The hydrometer analysis was conducted using 50 g of material finer than 0.075 mm. Finally, the consistency limits were determined according to the ASTM Standard Test Method For Liquid Limit, Plastic Limit and Plasticity Index of Soils (D 4318-05).

2.2 *Soil Water Characteristics Curves*

The soil water characteristics curves were determined using the geotechnical index properties (w, Gs, and γ_d) along with the best fit of the measured grain size distribution data (Fredlund et al. 2002). The water content and dry unit weight pertained to the saturated hydraulic conductivity tests, described below. The measured grain size distribution data were fitted according to the unimodal equation given by Fredlund et al. (2000). The computer software of SoilVision Systems Inc. was used for SWCC estimation. Based on a physico-empirical approach, the software divided the GSD into uniform particle sizes, each size assigned an individual SWCC from the database of measured SWCC, and all summed to develop the entire curve.

2.3 *Hydraulic Conductivity Functions*

The unsaturated hydraulic conductivity functions were determined according to the method described by Fredlund et al. (1994) using the computer software of SoilVision Systems Inc. This method requires various parameters obtained from the SWCC and k_{sat} data as input. For this purpose, the SWCC was re-estimated through the continuous mathematical function developed by Fredlund and Xing (1994). Further, the saturated hydraulic conductivity was measured in a stainless steel permeameter (105 mm high and 145 mm internal diameter) using the falling head method. The mold was filled with the thoroughly mixed waste rock materials weighing approximately 1350 g. The top and base plates were sealed using rubber 'O' rings and the former plate was connected to a 100 mL calibrated burette (700 mm high and 15 mm diameter). The air bubbles were removed from both the permeameter and the graduated burette. A control valve regulated downward water flow from the graduated burette through the specimen under a hydraulic gradient of 1 ± 0.5.

2.4 *Shear Strength Properties*

The shear strength properties were obtained according to the ASTM Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions (D3080-04) using a 100 mm x 100 mm x 45 mm shear box. To minimize the effect of mold size, material finer than 4.75 mm was discarded. The remainder was placed between two saturated porous stones up to a thickness of about 30 mm. Each specimen was saturated with distilled water and allowed to drain under a vertical seating stress of 10 kPa. The tests were performed under normal stresses (22, 44, and 88 kPa) corresponding to those at dump faces and using a strain rate of 0.05 mm/min. The test data were collected using an automated data acquisition system.

3 RESULTS AND DISCUSSION

3.1 *Geotechnical Index Properties*

Table 1 gives the geotechnical index properties of the waste rock samples. The specific gravity measured 2.8 ± 0.05 thereby indicating the possible presence of clays and heavier than sand-like materials in the investigated waste rock. This is supported by the consistency limits that indicated the existence of some water adsorbing capacity in the materials. In particular, the liquid limit and plasticity index data for TP 1.3 was found to be about twice that of the other two samples.

Table 1. Summary of geotechnical index properties

Property	TP 1.1	TP 1.3	TP 2.1
Gs	2.80	2.83	2.78
Liquid Limit (%)	23	40	23
Plastic Limit (%)	18	30	17
Plasticity Index (%)	5	10	6
– 4.750 mm (%)	60.8	48.7	70.9
– 0.074 mm (%)	13.7	12.3	11.0
– 0.002 mm (%)	6.6	4.6	4.9
D_{10} (mm)	0.02	0.03	0.09
D_{30} (mm)	0.94	2.1	0.92
D_{60} (mm)	4.0	6.6	3.2
Cc *	11.0	22.2	2.9
Cu †	200	220	36
USCS Symbol ‡	SM–SC	GM	SW–SC

* Coefficient of Curvature, $Cc = (D_{30})^2/(D_{10})(D_{60})$
† Coefficient of Uniformity, $Cu = D_{60}/D_{10}$
‡ Unified Soil Classification System

Figure 1 gives the grain size distribution of the investigated waste rock. All of the samples were found to be well-graded containing variable quantities of the following grain sizes: fine gravel (19 mm – 4.75 mm); coarse sand (4.75 mm – 2.0 mm); medium sand (2.0 mm – 0.425 mm); fine sand (0.425 mm – 0.075 mm); silt (0.075 mm – 0.002 mm); and clay (finer than 0.002 mm). The well-graded nature of the investigated materials is confirmed by the D_{10}, D_{30}, and D_{60} values and the corresponding Cc and Cu values reported in Table 1. The various samples were classified as follows: TP 1.1, SM–SC (mixture of sand, silt, and clay); TP 1.3, GM (mixture of gravel, sand, and silt); and TP 2.1, SW-SC (well-graded mixture of gravel, sand and clay). Further, the clay size fraction in the samples, that measured 5.5 ± 1%, generally correlated well with the consistency limits data given above.

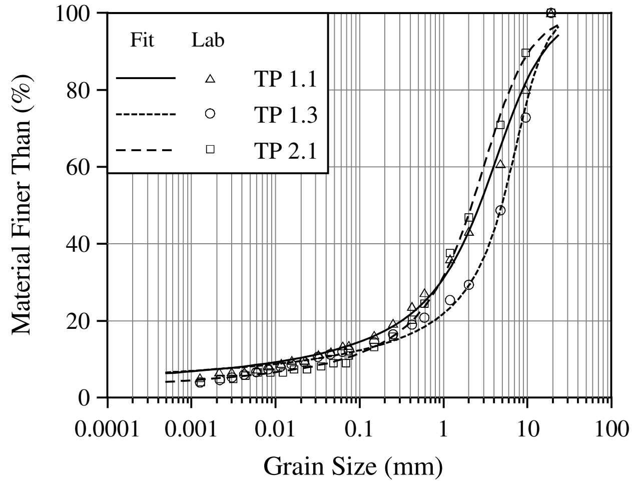
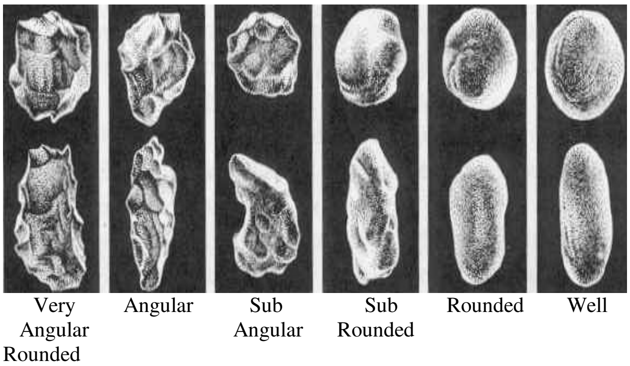


Figure 1. Grain size distibution

Figure 2 provides a comparison of the properties of particles usually encountered in soils with that found in the investigated waste rock. The granular shapes of waste rock materials coarser than 4.75 mm are shown in Figure 2 (b). The waste rock particles are distinctly characterized as “Angular” to “Very Angular”. The high angularity along with the high Cu (Table 1) is expected to govern the shear strength behavior of the investigated waste rock.



(a) Typical particle shapes in granular soils

(b) Material coarser than 4.75 mm in the investigated waste rock

Figure 2. Comparison of granular properties of soils and waste rock

3.2 *Soil Water Characteristics Curves*

Figure 3 gives the SWCC for the investigated waste rock samples. The estimated SWCC data is summarized in Table 2. All of the samples exhibited a saturated volumetric water content (θs) equal to 0.44 and an air entry value (ψa) between 0.2 kPa and 0.8 kPa. Likewise, the residual water content (θr) values were found to fall between 0.26 to 0.30 with the corresponding residual matric suction (ψr) of 1.5 ± 1 kPa for all but one sample. The high ψr for the TP 1.1 sample (that was found to be 60 kPa = 0.6 m of water) is attributed to the presence of slightly higher clay content in this sample (Table 1). Despite small variations, the SWCC data clearly indicated that the hydrological behavior of the investigated waste rock materials is similar to that of sandy soils usually encountered in geotechnical engineering practice. Such soils are characterized by low air entry and water storage values due to the low capillarity resulting from the large pore spaces in the material (Fredlund and Rahardjo 1993). Further, the estimated SWCC data for the investigated waste rock closely match the laboratory measured SWCC data for similar materials such as waste rock samples from an arid zone mine (Azam et al. 2007) and coarse-grained materials in residual soils (Indrawan et al. 2006).

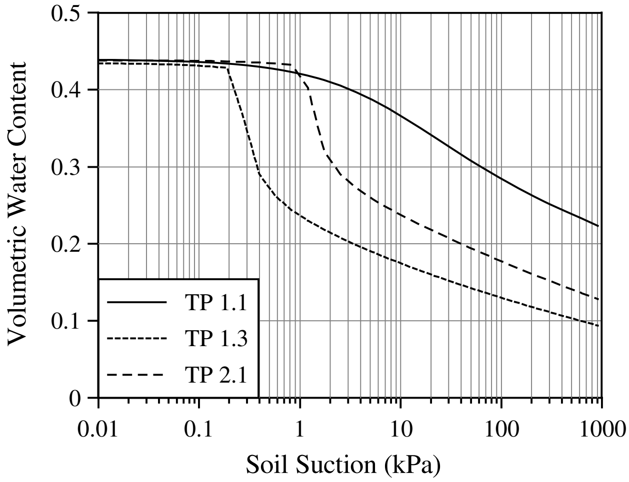


Figure 3. Soil water characteristics curves

Table 2. Summary of soil water characteristics curves

Property	TP1.1	TP1.3	TP 2.1
Saturated Water Content, θ_s	0.44	0.43	0.44
Air Entry Value, ψ_a (kPa)	0.8	0.2	0.8
Residual Water Content, θ_r	0.3	0.26	0.28
Residual Matric Suction, ψ_r (kPa)	60	0.5	2.5

3.3 *Hydraulic Conductivity Functions*

Table 3 gives the measured hydraulic conductivity and Figure 4 plots the hyraulic conductivity function. As expected, the measured saturated hydraulic conductivities were typical of granular materials. The samples generally kept the saurated hydraulic conductivity up to the air entry values beyond which the former dropped sharpely with increasing suction. For example at 200 kPa suction, the hydraulic conductivity reached 10^{-11} m/s (for TP 1.1 and TP 1.3 samples) and 10^{-13} for the TP 2.1 sample. Again, these data compare quite well with published data on similar materials.

Table 3. Summary of hydraulic conductivity tests

Property	TP1.1	TP1.3	TP 2.1
Dry Unit Weight, γ_d (kg/m^3)	1570	1562	1608
Saturated hydraulic conductivity, (m/s) x 10^{-5}	1.1	1.1	1.3

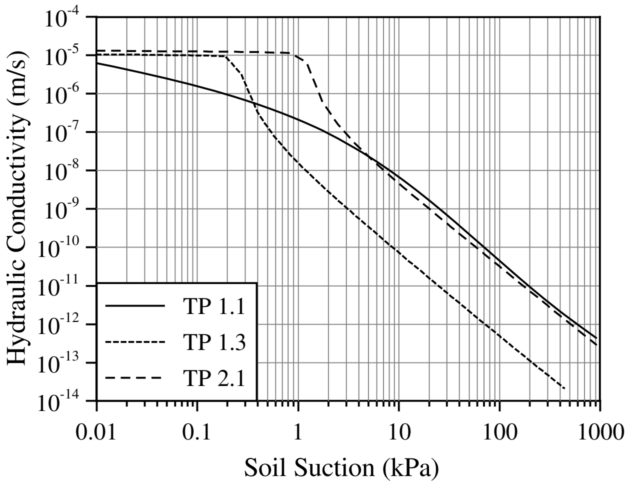


Figure 4. Hydraulic conductivity functions

3.4 *Shear Strength Properties*

Figure 5 plots the results of direct shear tests in the form of shear stress versus horizontal displacement. Likewise, Table 4 gives a summary of the test results. All of the samples were found to behave like loose materials, that is, the principal stress difference gradually increased to a maximum or ultimate value. Concurrently, continuous deformations were observed with negligible change in the principal stress difference. According to Holtz and Kovacs (1981), the void ratio of loose samples decreases from an initial state to a critical value beyond which no further decrease is possible during shearing. The friction angle (ϕ^o) measured 37^o to 39^o that closely matched with the angle of repose of waste rock materials at the face of dumps (Linero et al. 2007). The slightly higher friction angle of TP1.3 is attributed to the low initial void ratio and the high Cu of the sample. All samples exhibited a small amount of cohesion (c) due to the presence of 4 to 7% clay size fraction including clay minerals and precipitation of secondary minerals causing grain-to-grain cementation. Overall, the shear strength of the investigated waste rock is primarily derived from the friction angle between the angular particles.

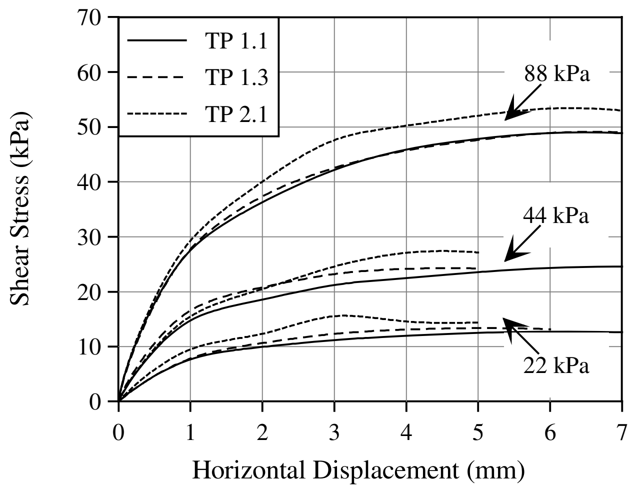


Figure 5. Results of direct shear tests

Table 4. Summary of shear strength tests

Property	TP1.1	TP1.3	TP 2.1
Initial Void Ratio, e	0.78	0.76	0.78
Friction Angle, ϕ^o	37.1	38.9	37.0
Cohesion, c (kPa)	0.7	2.9	1.4

3.5 *Scope of Results*

The geotechnical properties of the investigated materials pertain to the dump face. Waste rock dumps possess several other zones with distinct engineering characteristics. The physical model developed by Azam et al. (2007) consists of alternating fine-grained (water retaining) and coarse-grained (free draining) layers and a basal rubble zone. This model explains dump stability as any pore pressure increase in the fine layers is offset by the coarse layers during precipitation events. The basal rubble zone that serves as a toe drain can be quite effective in relieving pore pressure in seismic events. Further, apparent cohesion can provide additional shear strength to the waste rock dump under unsaturated conditions. Theoretically, the material structure can be partly held intact by the web-like meniscus of water called the contractile skin that is intertwined throughout the particles. The surface tension of the water draws the particles together, increasing the inter-particle forces at the granular contact (Fredlund et al. 1996).

4 CONCLUSIONS

- The overall geotechnical behavior of waste rock is governed by the granular characteristics, namely: the grain size distribution and the grain shapes. The investigated samples were found to be well-graded materials containing gravel, sand, silt, and clay. All of the samples were characterized as “Angular” to “Very Angular”.
- The hydrological behavior of waste rock is similar to that of sandy soils usually encountered in engineering practice. The investigated materials exhibited low air entry values (0.2 and 0.8 kPa) and low water storage (0.44) due to the low capillarity resulting from the large pore spaces in the material.
- The saturated hydraulic conductivity measured 1 x 10^{-5} m/s that is typical for granular materials. All of the samples generally kept the saurated hydraulic conductivity up to the air entry values. Thereafter, the hydraulic conductivity dropped sharpely with increasing suction: a drop of six to eight orders of magnitude was found at 200 kPa suction.
- The shear strength of waste rock is identical to loose coarse materials and is primarily derived from the angle of internal friction that measured 37^o to 39^o, similar to the angle of repose. Additional strength can be availabe in the form of effective cohesion due to clays and cementation and apparent cohesion due to matric suction.

ACKNOWLEDGEMENTS

The authors acknowledge the laboratory space and computing facilities provided by the University of British Columbia and the University of Regina, respectively. Thanks to Dr. Fernando Junqueira and Mr. Kazi Mohiuddin for their help during laboratory investigations and manuscript write-up.

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