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EFFECTS OF CHEMISTRY, MINERALOGY, PETROGRAPHY AND ALTERATION ON ROCK ENGINEERING PROPERTIES OF THE GOATHILL NORTH ROCK PILE AT THE MOLYCORP QUESTA MINE, NEW MEXICO

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Abstract

In order to evaluate the relationships between weathering and durability and strength of rock samples from the Goathill North rock pile at the Molycorp Questa mine, NM, we conducted slake durability and point load tests. Slake durability index (ID_2) values ranged from 84 to 98%. Point load strength index (Is_{50}) averaged for all rock units ranged from 1.1 to 5.7 MPa. Results show a slight positive trend between ID_2 and paste pH. Two populations of data are distinguishable when ID_2 is plotted versus the percentages of chlorite, illite and internal friction angle. In general, Is_{50} values increase toward the interior of the rock pile. Preliminary conclusions indicate that the durability and strength of the rock pile material generally increase toward the interior of the rock pile. Pre-rock pile alteration and post-rock pile weathering history have affected the durability of the GHN rock pile samples.

Introduction

Slake durability and point load tests were conducted to estimate durability and strength of rock samples from the Goathill North (GHN) rock pile at the Molycorp, Inc. Questa molybdenum mine, Taos County, New Mexico. Durability and strength of rocks are important properties of rock masses and rock materials used in studying and avoiding slope failure. Studies of, and solutions to, ground movement problems require a site-specific understanding of the geology, hydrogeology, hydrology, and especially the geotechnical properties. In some cases, slope instability can be related to the degree of weathering in the rock material (Kitagawa, 1999; Maharaj, 1999). Between 1995 and 2001, it was reported that 15% of all accidents that have occurred in U.S. surface mines were slope failures. Rock falls can cause serious fatalities to miners as well as damage to machinery (McHugh and Girard, 2002).

Molycorp, Inc. began to examine the effects of weathering on the stability of rock piles at their Questa molybdenum mine in 2002 to assess present and future weathering effects on the stability of the rock piles (Molycorp Inc., 2002. Rock piles, the preferred term by many in the metal mining industry today, refer to the man-made structures consisting of piles of non-ore material removed in order to extract ore. This material, referred to in older literature as mine waste, mine soils, overburden, subore, or proto-ore, does not include the tailings material that consists of non-ore material remaining after milling.

A large multi-disciplinary field team was established to identify and assess conditions and processes occurring in the rock piles, especially related to the physical and chemical weathering of rock-pile materials at the Questa mine. A key component of this weathering study is to examine the mineralogical, chemical, and physical changes in these materials, if any that have occurred since construction of the rock piles. If this can be accomplished, it should be possible to determine the effect of weathering on the geotechnical behavior of the rock piles as a function of time and degree of weathering. The current approach is to test the geotechnical behavior of samples across a range of weathering states that are characterized by petrology, mineralogy, and chemistry for samples that are collected from the existing rock piles and elsewhere in the Questa-Red River area. Many changes could take place in the rock- pile materials due to chemical or physical weathering, but the rate at which the changes will occur depends on many factors, some of which are addressed in this paper.

Weathering is a complex interaction of physical, chemical, and biological processes that can change the physical characteristics and chemical composition of rocks. *Weathering* is the disintegration of rock by physical, chemical, and/or biological processes at or near the surface that results in the reductions of grain size, changes in mineralogical composition, and possibly changes in cohesion or cementation. For the purpose of this study, weathering refers to the changes in the rock-pile material characteristics after deposition. The physical properties of unweathered rock differ widely among rock types as well as within the same rock type. Weathered rocks exhibit textures and chemical changes that are characteristic of the conditions to which they have been exposed after placement.

Different hydrothermal alteration and weathering mineral assemblages can occur in the same sample producing various mineral compositions, texture, degrees of hardness, and pore/capillary structure. These variations are due to different degrees of weathering, pre-mining hydrothermal alteration, or both, and can result in the minerals breaking down, dissolving, or being replaced. Weathering processes are grouped as physical or chemical (Price, 1995). Hydrothermal alteration also can be accompanied by intense microfracturing and large-scale fracturing of the host rock (Molling, 1989; Meyer, 1991). Both chemical and physical weathering can affect the durability and strength of rocks (Giani, 1988). One result of weathering, for example, could be cementation of the rock pile as a result of precipitation of new minerals.

The purpose of this paper is to investigate how durability and strength of rocks are affected by chemistry, mineralogy and petrography, which together reflect pre-mining alteration and short- and long-term weathering of the materials in the rock piles Slake durability and point load tests were selected in this research due to the nature of the GHN samples and for test simplicity and reliability.

Background

Questa Mine

The Questa molybdenum mine is located on the western slope of the Taos Range of the Sangre de Cristo Mountains, Taos County, in northern New Mexico (Fig. 1). During the period of open pit mining (1969-1981), approximately 328 million short tons of overburden rock was stripped and deposited onto mountain slopes and into tributary valleys forming nine rock piles around the area of the open pit (URS Corporation, 2000).

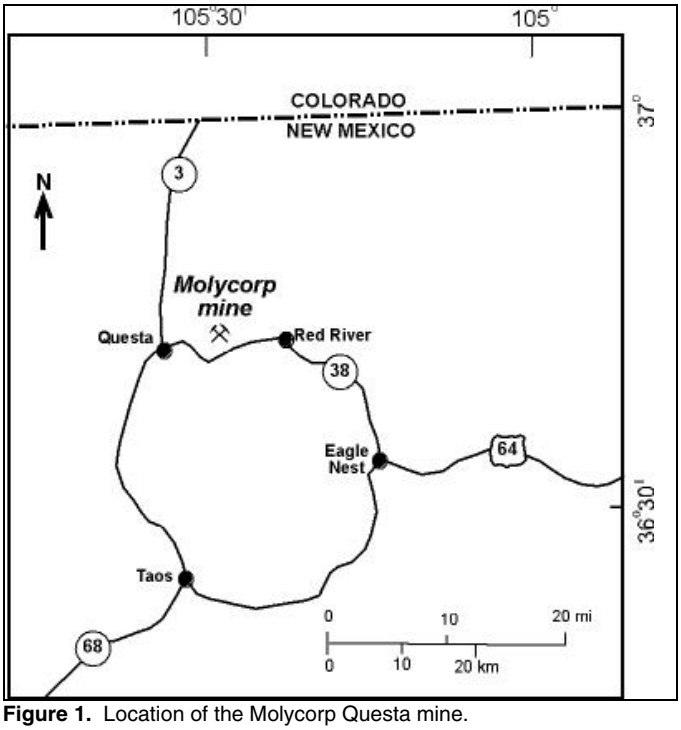


Figure 1. Location of the Molycorp Questa mine.

Goathill North (GHN) rock pile

The GHN rock pile is one of nine Questa rock piles. It contains approximately 5.5 million yds^3 (16 million short tons) of overburden material and has slopes similar to the original topography. GHN rock pile was approximately 630 ft high and 200 ft thick (URS Corporation, 2000; Norwest Corporation, 2003) before it was regraded in 2004-2005. GHN rock pile was constructed during 1969-1974 when material was end-dumped in an alteration scar area, which is a natural, actively eroding landslide area caused by acidic weathering (Meyer and Leonardson, 1990; Norwest Corporation, 2003). GHN is situated in the headwater areas of the Goat Hill drainages and it is located approximately 2 miles upstream from Red River valley. The GHN rock pile was divided into two areas: a stable area and an unstable area. The colluvium beneath part of the GHN rock pile was unstable and resulted in some material moving down slope. The samples for this study came from the stable portion of GHN. The unstable portion of the rock pile was an active landslide area, involving 2.5 million yds^3 of material (Norwest Corporation, 2003). Evidence of slope instability and actual sliding of the unstable portion of the GHN rock pile was observed in the 1974, 1976, 1977, 1991, and 1997 aerial photographs (Norwest Corporation, 2003). The colluvial foundation at GHN first failed between 1969 and 1973 (Norwest Corporation, 2003). Molycorp stabilized GHN by removing material off the top portion of both areas and relocating it to the bottom of the pile (Norwest Corporation, 2003). This regrading process has decreased the slope, reduced the load, and created a buttress to prevent movement of the rock pile.

Characterization of the GHN rock pile

The regrading process of GHN rock pile offered a rare opportunity to study and characterize the structure, composition, and material properties of rock-pile units in trenches through different parts of the rock pile. Each trench was surveyed using a differential global positioning system. For every trench, geologic maps, longitudinal sections, and logs of each bench were created to describe the different subsurface material units. Descriptions included unit thickness, dip, stratigraphic position, texture, and spatial extent of the geologic units. Subsurface geologic units were defined on the basis of grain size, color, stratigraphic position, texture, and other physical properties that could be determined in the field. Geologic units were correlated within each trench, and most geologic units were correlated down slope through a series of five successively excavated trenches. Eighteen units were differentiated, described and sampled (Tachie-Menson, 2006; McLemore et al., 2005, 2006a, b). A series of representative samples of the rock pile was examined and collected from a traverse along a single bench within a trench in GHN. A typical longitudinal section of the geologic units in bench 9, from trench LFG-006, is shown in Figure 2.

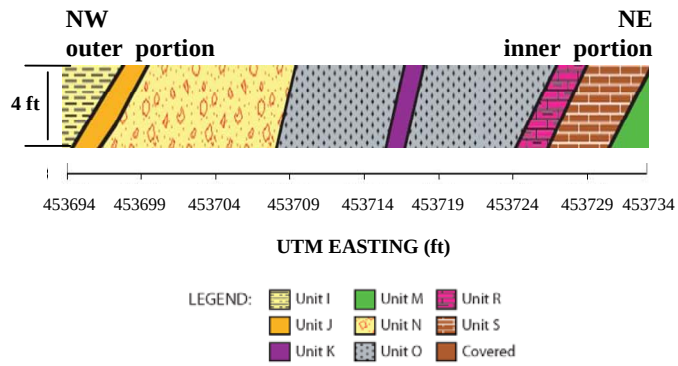


Figure 2. Geologic cross section of bench 9, trench LFG-006. Samples were obtained at approximately 5 ft intervals along benches. Refer to this figure for subsequent plots. Note the vertical exaggeration (1 horizontal ≈ 4 vertical).

Test Samples and Engineering Test Procedures

Description of the Test Samples

The lithologies mined from the open-pit deposit are grouped into five major rock types: rhyolite (Amalia Tuff), andesite breccia, andesite (including latite and quartz latite), granitic porphyry, and aplite, all of which have been hydrothermally altered to varying degrees. Field and laboratory analyses indicate that the GHN rock pile consists primarily of rock fragments of hydrothermally-altered andesite and rhyolite (Amalia Tuff) in a sand to clay matrix (McLemore et al., 2005, 2006a, b). The slake durability and point load tests were performed on samples of these rock fragments.

Slake Durability Test

Franklin and Chandra (1972) developed the slake durability test to evaluate the influence of alteration on rock by measuring its resistance to deterioration and breakdown when subjected to wetting and drying cycles. The durability of rocks can be described as their resistance to breakdown under weathering conditions over time. Slaking occurs from the swelling of rocks containing clay minerals when in contact with water. The slake durability index (ID_2) provides a measure of durability. It gives quantitative information on the mechanical behavior of rocks according to the amount of clay and other secondary minerals produced in them due to exposure to weathering (Fookes, et. al., 1972).

The slake test apparatus is shown in Figure 3. For each slake durability test, a representative sample is selected containing 10 rock pieces, each weighing between 40 and 60 g, providing a total sample weight ranging from 450 to 550 g. The sample is placed in a screen drum and both the drum and the sample are oven-dried at a temperature of 110° ± 5° C to a constant weight. After the sample cools to room temperature, the drum is coupled to a motor and rotated immersed in distilled water at a speed of 20 rpm for 10 min. The sample is again oven-dried at a temperature of 110° ± 5° C to a constant weight. The sample is submitted to a second wetting and drying cycle.

The slake durability index is calculated after the second cycle, using this formula:

$$ID_2 = \frac{W_F - C}{B - C} \times 100 \qquad (1)$$

where:
ID_2 = slake durability index (second cycle), (%)
B = mass of drum plus oven-dried sample before the first cycle, (g)

W_F = mass of drum plus oven-dried sample retained after the second cycle, (g)
C = mass of drum, (g).

Figure 3. Photograph of the slake durability apparatus consisting of the motor and test drums.

A visual and an index classification are established according to the appearance of the remaining rock pieces and the range of the ID_2 as shown in Tables 1 and 2.

Table 1. Visual description of the rock samples retained in the test drum after the second cycle (after Franklin and Chandra. 1972).

Type	Description
I	Pieces remain virtually unchanged
II	Consist of large and small pieces
III	Exclusively small fragments

Table 2. Slake durability index classification (after Franklin and Chandra. 1972).

ID_2 (%)	Durability classification
0 – 25	Very Low
26 – 50	Low
51 – 75	Medium
76 - 90	High
91 – 95	Very High
96 - 100	Extremely High

Point Load Strength Test

The point load test is a simple test used to estimate rock strength. The equipment used consists of a loading frame that measures the force required to break the sample and a system for measuring the distance between the two plate contact points, as shown in Figure 4.

One of many advantages of the point load test is that rock samples fail at much lower applied loads compared with compression test. Therefore, equipment with a lower load capacity is required (Fookes, et. al., 1972). In addition, the point load test can be performed on samples with different shapes, either core or irregular shaped samples (Broch and Franklin, 1972). Since the GHN samples are irregularly shaped fragments and not drill cores, the point load test was a suitable choice for this project. The point load index (Is_{50}), obtained with the point load test is adequate as a standard to classify rock strength (Broch and Franklin, 1972).

The point load strength index is calculated using this formula:

$$Is_{50} = \frac{P}{D_e^2} \times F \qquad (2)$$

where:
Is_{50} = point load strength index, (MPa)
P = load, (kN)
$D_e = 4A/\pi$, equivalent core diameter for an irregular rock lump, (m^2)
A = WD, minimal cross sectional area of the plane through the platen contact points, (m^2)
W = minimal cross sectional width of the plane through the platen contact points, (m)
D = minimal cross sectional distance of the plane through the platen contact points, (m)
F = Size Correction Factor = $(D_e/50)^{0.45}$

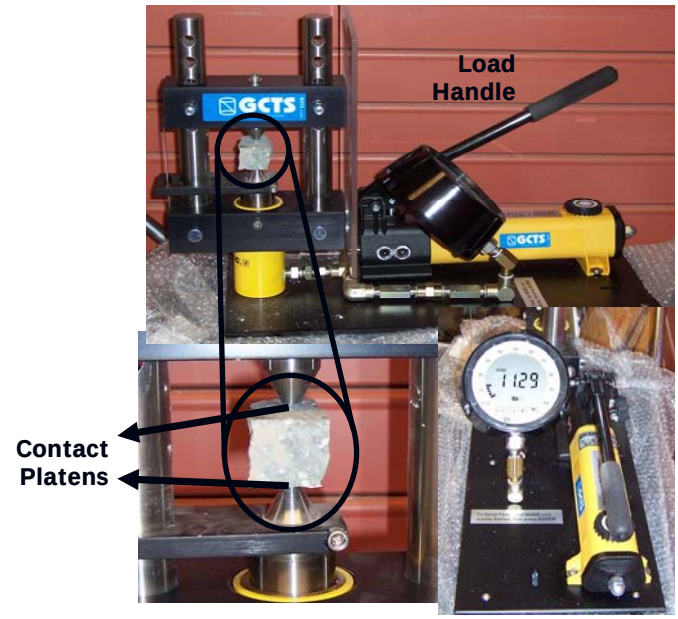


Figure 4. Photograph of the point load strength equipment, consisting of loading and measuring systems.

Tests Reproducibility

In order to validate the slake durability and point load results, these tests were performed in duplicate and triplicate for a few samples. The reproducibility results are shown in Table 3.

Table 3. Slake durability (rows 1-4) and point load (last row) index values for duplicate or triplicate samples.

Sample Identification	1	2	3	Average ± standard deviation
GHN-KMD-0013 (%)	96.36	97.18		96.77 ± 0.58
GHN-KMD-0017 (%)	84.14	86.70		85.42 ± 1.81
GHN-KMD-0014 (%)	98.25	99.03	98.05	98.44 ± 0.52
GHN-KMD-0063 (%)	99.10	97.79	98.73	98.54 ± 0.67
GHN-KMD-0016 (MPa)	3.37	3.42		3.40 ± 0.04

Description of the GHN Rock Pile Material

Chemical, mineralogical, and petrographical analyses, as well as descriptions of rock fragments, including their pre-mining hydrothermal-alteration mineralogy were performed on rock fragments from the GHN rock-pile material (McLemore et al., 2005, 2006a, b; Donahue et al., 2007). These analyses and descriptions were completed by researchers at the New Mexico Institute of Mining and Technology and at the New Mexico Bureau of Geology and Mineral Resources.

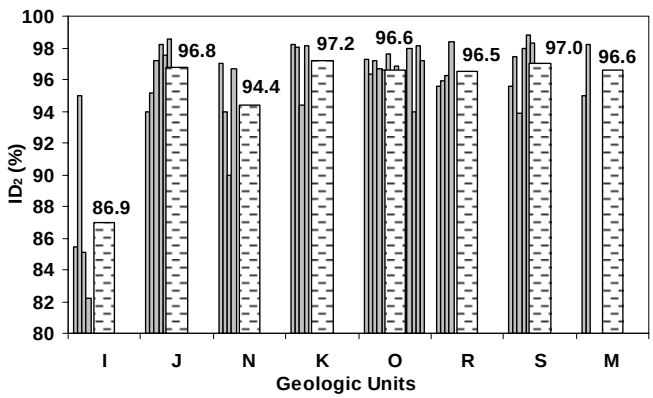
The GHN rock-pile material consists of mixtures of two lithologies, andesite and rhyolite (Amalia Tuff). Little, if any, fresh, unaltered primary igneous material was deposited in the GHN rock pile. Most of the material was hydrothermally altered prior to mining (i.e., prior to placement in GHN rock pile; Donahue et al., 2007). The outer unit I and inner unit M contained significant amounts of hydrothermally QSP (Quartz-Sericite-Pyrite)-altered rhyolite, whereas the other units contained mostly hydrothermally-altered andesite (Fig. 2). Typically, paste pH increased with distance from the outer, oxidized zone (west) towards the interior units (east) of the GHN rock pile. The outer zone was oxidized (weathered) based upon the white and yellow coloration, low paste pH, presence of jarosite and authigenic gypsum, and absence of calcite (McLemore et al., 2006a, b).

Results and Discussion

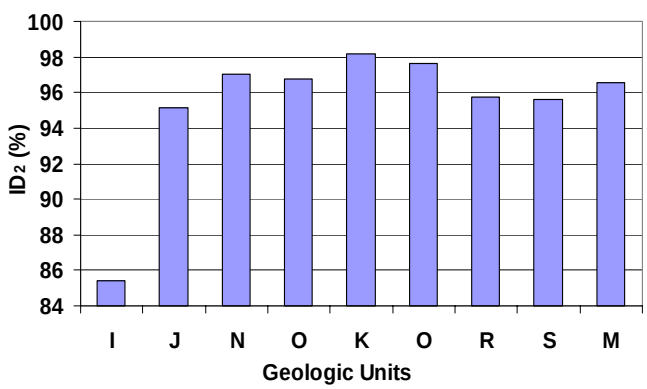
Slake Durability Test

A total of 78 samples were used for slake durability tests. The averaged ID_2 values ranged from 84 to 98%, with all of the samples classified as being high to extremely high durable (Table 1). From this total, 4 samples consisted of large and small fragments and were classified with high durability; 15 samples were classified with very high durability, with 3 of the 15 were virtually unchanged and 12 consisted of large and small fragments; 57 samples were classified with extremely high durability, with 15 of the 57 remained virtually unchanged, 40 consisted of large and small fragments, and 2 consisted of exclusively small fragments (Table 1).

Results from all samples from the same geological unit were averaged to obtain the slake durability for that unit (Fig. 5a). The averaged durability values for samples from the most oxidized portion of the pile, corresponding to unit I, are dramatically lower than the averaged durability values of samples from the inner geologic units of the rock pile. An increase in slake durability index towards the interior of the rock pile is observed for bench 9, trench LFG 006 (Fig. 5b).



5a



5b

Figure 5. Columns graphs of slake durability index (ID_2). Graph 5a shows averaged ID_2 values per geologic unit. Graph 5b shows ID_2 values from samples across bench 9, trench LFG-006. Unit I is closest to the outermost margin of the pile and Unit M is the most interior sample. The oxidized sample (unit I) shows the lowest ID_2. See Figure 2 for geologic cross section.

Results show that the slake durability index of rock samples correlate with the weathering intensity, petrography, chemistry, lithology, hydrothermal alteration and geotechnical properties. Paste pH and internal friction angle exhibit two populations when plotted versus slake durability index (Fig. 6a, 7). Samples with lower slake durability indices correspond to lower paste pH values in the outer zone of the GHN rock pile, but not all low paste pH samples correspond to low ID_2. Samples with lower slake durability indices correspond to lower internal friction angle values in the outer zone of the GHN rock pile, but not all low internal friction angle values correspond to low ID_2. Internal friction angle values were obtained by conducting direct shear tests on fine-grained matrix material (Gutierrez, 2006; McLemore et al., 2006a, b). Paste pH values are lower toward the outer portion of the pile due to increased post-mining oxidation and differences in lithology and hydrothermal-QSP alteration (Fig. 4b; McLemore et al., 2005, 2006a, b). Paste pH values were obtained by conducting laboratory testing on crushed rock and fine-grained matrix samples (Tachie-Menson, 2006; McLemore et al., 2006a, b).

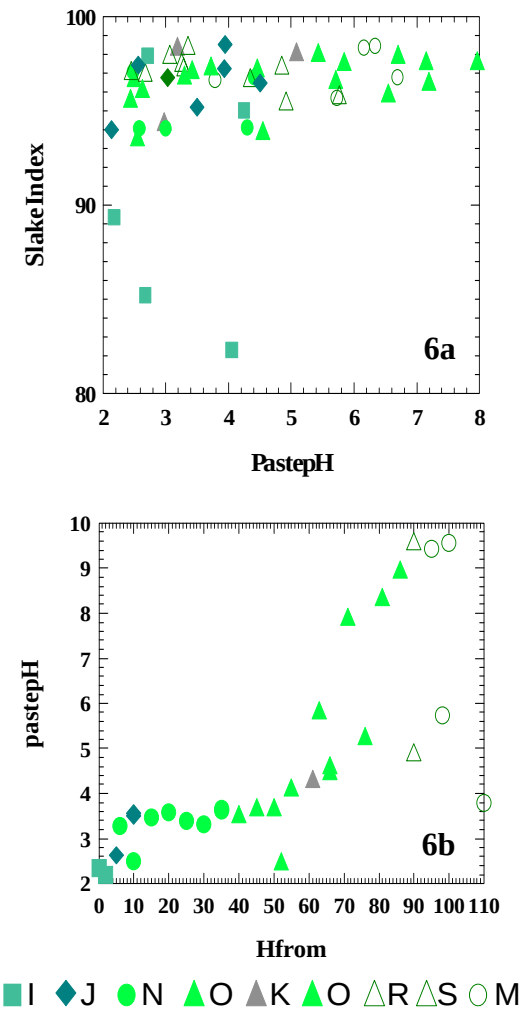


Figure 6. Scatter plots of ID_2 versus paste pH. Graph 6a includes all samples from GHN by geologic units and shows two populations. Samples with lower slake durability indices correspond to lower paste pH values in the outer zone of the GHN rock pile, but not all low paste pH samples correspond to low ID_2. Graph 6b shows paste pH along the pile from the northwest edge of the pile towards the interior for bench 9, showing lower paste pH in the outer oxidized portion of the pile (McLemore et al., 2006a, b). Hfrom is the horizontal distance from the outer edge of GHN in feet. Refer to Figure 2 for geologic section. SlakeIndex is expressed in percentage.

Two populations of data are observed in the plot of slake durability index values versus the percentage of chlorite (Fig. 8a) and illite (Fig. 9a). The percentage of chlorite increased towards the interior of the rock pile. This suggests that the material in the interior of the rock pile had experienced greater pre-mining propyllitic alteration, since chlorite is a predominant mineral in the propyllitic- alteration

mineral assemblage (Fig. 9b; Molling, 1989; McLemore et al., 2006b). Presence of illite is indicative of the material in the outer portion of the pile having experienced more intense pre-mining QSP alteration (Fig. 9b).

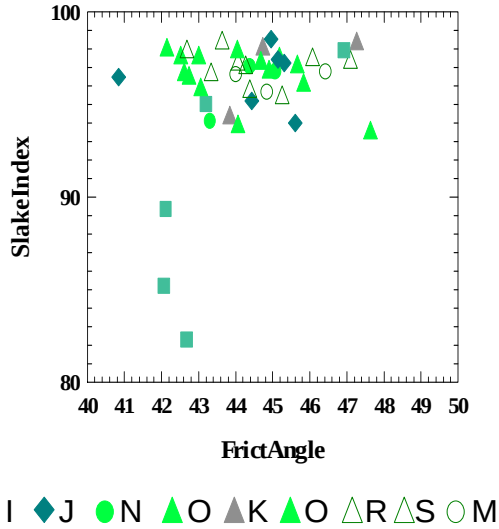


Figure 7. Scatter plot of ID_2 versus internal friction angle. The graph includes all samples from GHN by geologic units and shows two populations. Samples with lower slake durability indices correspond to lower internal friction angle values in the outer zone of the GHN rock pile, but not all low internal friction angle values correspond to low ID_2. Refer to Figure 2 for geologic section. SlakeIndex is expressed in percentage. Hfrom is the horizontal distance from the outer edge of GHN in feet.

Point Load Strength Test

Preliminary point load tests were performed on a total of 25 samples. Samples are from benches 7, 8 and 9 in trench LFG-006, benches 12 and 14 in trench LFG-007, and bench 18 from trench LFG-008. Point load strength index values (Is_{50}) of samples from the same geologic unit were averaged (Fig. 10a). The Is_{50} averaged values ranged from 1.1 to 5.7 MPa. All samples were classified with medium to very high strength according to Broch and Franklin (1972). Preliminary results show that Is_{50} generally increased towards the inside of the GHN rock pile (Fig. 10a, 10b).

Results show that the point load strength index of rock samples correlates with geotechnical properties. Point load strength index increases with increase in internal friction angle and also with increase in slake durability index (Fig, 11, 12). The most oxidized sample (unit I) shows lower point load strength and slake durability indices, as well as lower internal friction angle. Consequently, these properties can be used as a measure of strength.

Preliminary Conclusions

Durability and strength values generally increased towards the interior of the GHN rock pile. Durability and strength values of samples from the most oxidized portion of the pile, unit I, are lower than values of samples from the inner units of the rock pile. These differences correlate with lithology, including pre-mining hydrothermal alteration and post-mining weathering effects.

Slake durability index of samples from the GHN rock pile ranged from 84 to 98%, with all of the samples classified as high to extremely high durable. Point load strength for samples from GHN rock pile ranged from 1.1 to 5.7 MPa; these samples were classified as medium to very high strength. Such values compare well with values from other rock piles in Nevada where Quine (1993) measured slake durability indices of 93 to 99% with a single value of 6% (highly weathered sample). These values show that the rock fragments are quite strong even though blasted rock fragments within the GHN rock pile were highly fractured and altered before deposition in the rock pile and subsequent weathering.

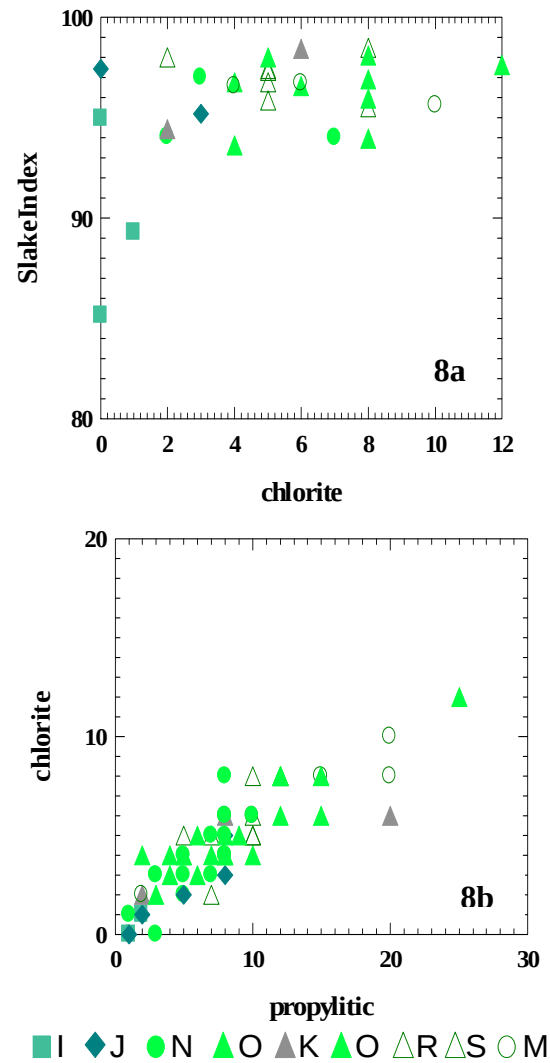


Figure 8. Scatter plots of ID_2 versus percentages of chlorite. Graph 8a includes all samples from GHN by geologic units. Graph 8b shows that samples with high percentages of chlorite correspond to more intense propyllitic alteration, and these samples are more abundant in the interior portion of the pile. Refer to Figure 2 for geologic section. Chlorite and propyllitic are expressed in percentage of the entire sample (rock fragments and fine-grained matrix).

Samples with lower slake durability indices correspond to lower paste pH values in the outer zone of the GHN rock pile, but not all low paste pH samples correspond to low ID_2. McLemore et al. (2006a, b) showed that paste pH typically increased with distance from the outer, oxidized zone (west) towards the interior units (east) of the GHN rock pile. The outer zone consisted predominantly of hydrothermally-QSP altered rhyolite (Amalia Tuff) that was weathered (oxidized) based upon the white and yellow coloration, low paste pH, presence of jarosite and authigenic gypsum, absence of calcite, and increased LOI (loss on ignition; McLemore et al., 2006a, b). The low slake durability index values can be attributed, in part, to increased post-rock-pile oxidation of samples that are located at the outer margin of the pile (Unit I).

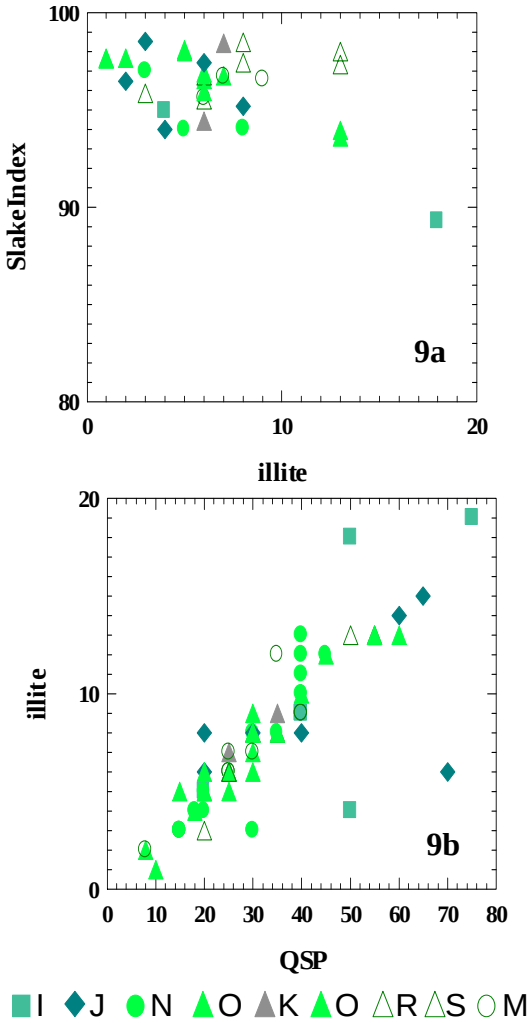


Figure 9. Scatter plots of ID_2 versus percentage of illite. Graph 9a includes all illite samples from GHN by geologic units Graph 9b shows that high percentages of illite corresponds to more intense QSP alteration, and these samples are located in the outer portion of the rock pile. Refer to Figure 2 for geologic section. Illite and QSP are expressed in percentage.

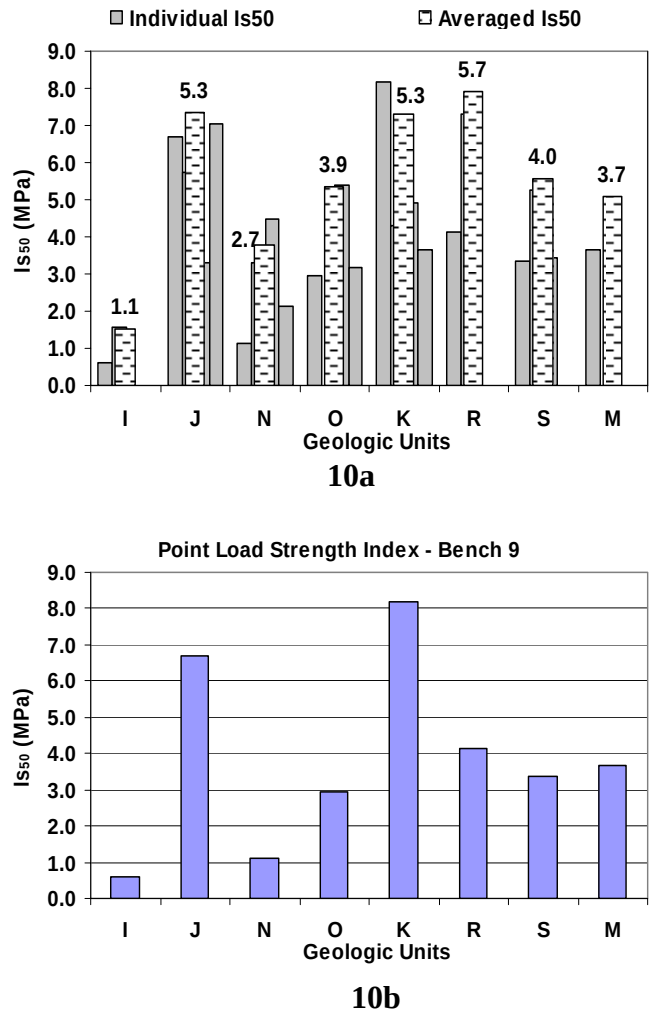


Figure 10. Column plots of averaged point load strength index (Is_{50}) per geologic unit. Graph 10a shows averaged Is_{50} values per geologic unit. Graph 10b shows Is_{50} values from samples across bench 9, trench LFG-006. The most oxidized sample (unit I) shows lower point load strength index values than samples from the inner portion of the rock pile.

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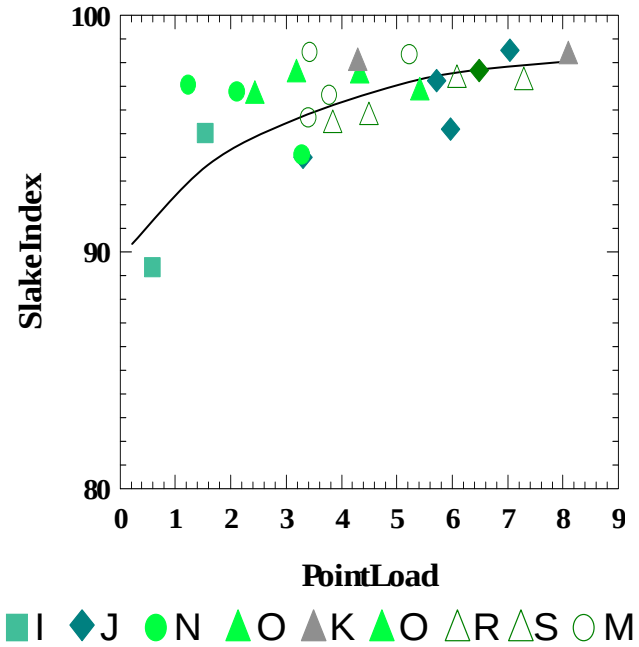

Figure 11. Scatter plot of ID_2 versus Is_{50}. The graph includes all samples from GHN by geologic units tested for point load strength test. Lower durability and strength are observed on the most oxidized samples (Unit I). R^2 of the regression line is 0.45. Refer to Figure 2 for geologic section. PointLoad is expressed in MPa and SlakeIndex in percentage.

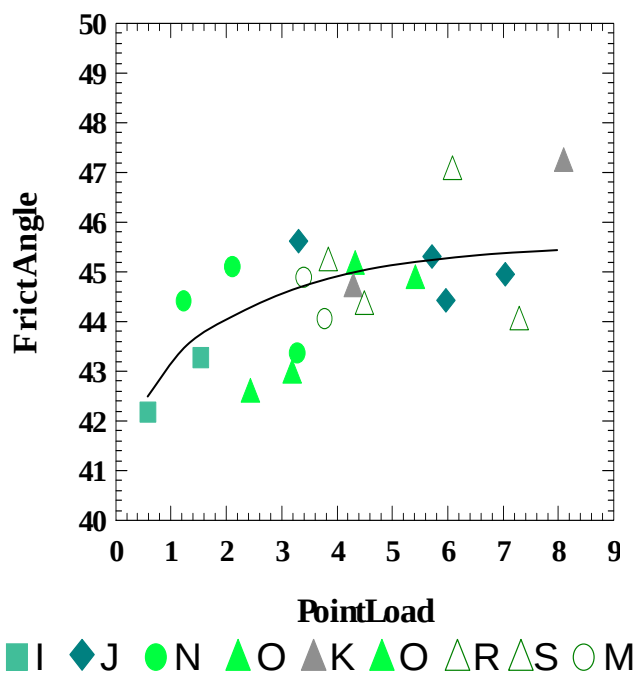

Figure 12. Scatter plot of internal friction angle of fine-grained matrix samples versus Is_{50} of rock samples. The graph includes all samples from GHN by geologic units tested for point load strength test. Lower internal friction angle of fine-grained matrix samples and lower strength of rock samples are observed in the most oxidized samples (Unit I). R^2 of the regression line is 0.4. Refer to Figure 2 for geologic section. PointLoad is expressed in MPa.

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