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Questa Rock-pile Weathering Study: Geotechnical Characterization

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Abstract

The Questa Weathering and Stability Study that was commissioned by Molycorp, Inc. (now Chevron Mining Inc., CMI) included extensive geotechnical characterization of the rock pile and analog materials. For the most part the Questa rock piles are matrix supported. This paper provides a summary of the geotechnical characterization results obtained during the research project. It provides summary level information and compares the summary statistics, especially the coefficients of variation, obtained for the results with those from previous studies as compiled in the literature. The results show that the variability as expressed by the coefficients of variation obtained for the Questa study is similar to those in the literature. These consistent results show that the geotechnical characteristics of the Questa materials do not contain significant "outliers". Furthermore, the characteristics are consistent between rock piles so that all the data can be combined into one set of data for evaluation. It is expected that the friction angle will not reduce significantly with time as the rock piles age because geochemical evaluations concluded that new clay minerals will not form in the rock piles in the 100 to 1000 year timeframe. While weathering products may result in the deposition of cementation in the matrix it is not expected that this will result in measurable effects on the c-parameter.

Introduction

The Questa Weathering and Stability Study that was commissioned by Molycorp, Inc. (now Chevron Mining Inc., CMI) included extensive geotechnical characterization of the rock pile and analog materials. For the most part the Questa rock pile materials are matrix supported. The purpose of the Weathering and Stability Study was to determine the technical basis for how and to what extent, considering geological, geochemical, mineralogical, hydrological, and geotechnical processes and rates, weathering would affect the gravitational stability of the Questa mine-rock piles in 100 and 1000 years.

This paper provides a summary of the geotechnical characterization methods and results of the rock pile and analog materials. A brief summary of the rock pile construction, focusing on the "front rock piles", i.e. those next to NM Highway 38, is provided next. This is followed by summaries of the geotechnical characterization activities and results. Finally, a short discussion on the time-dependent geotechnical change of the rock pile is presented.

This summary report provides a broad view of the geotechnical characteristics focusing on the ranges and statistics of the parameters; it does not set out to provide an interpretation of the results in its present form. The tables and figures were mostly taken from the graduate theses and internal reports. A summary of the geology, hydrology and geochemistry of the Questa rock piles is provided by Logsdon (2011). It is recommended that the paper by Logsdon (2011) be reviewed to obtain a better perspective on the overall conclusion provided in the present paper.

Rock Pile Construction and Local Natural Analogs

The open pit mine at the Questa mine operated from 1964 to 1979. During this period a number of rock piles were constructed as shown on Figure 1. End tipping and dozing were used to construct these angle of repose rock piles in one or more lifts on steep slopes. The "front rock piles" designated as Sugar Shack South, Middle and Sulphur Gulch South, were constructed between 1974 and 1979. The original terrain was very steep, almost similar to the 36 degrees of the angle of repose slope of the rock piles. The mined rock in these piles therefore forms a thin layer along the original surface.

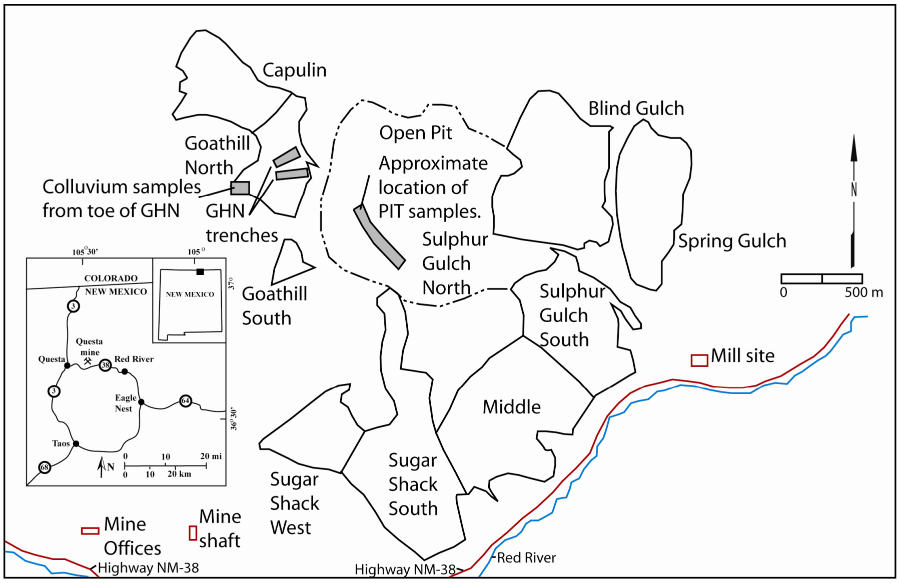

Figure 1: Questa rock piles and other mine features

There are no records relating the material characteristics in the mine pit to their relative location on the rock piles. Therefore, at the beginning of the Weathering and Stability Study no specific information was available on the geologic formations or other characteristics of the materials in individual rock piles.

During the Weathering and Stability Study a number of geologic features in the vicinity of the Questa mine, but distinct from the rock piles themselves, were identified as natural analogs, i.e. mineralogical and physical proxies to long-term weathering of the rock piles. These analogs are the alteration scars, debris flows, weathered bedrock and slope colluvium. While they are useful geologic analogs, there were extensive discussions about their insitu characteristics and depositional conditions that are different from those of the sub aerially deposited rock piles. Extensive geochemical testing of the alteration scars was very useful in obtaining long term weathering information indicating no new clay formation over periods of up to 1 million years. Geotechnical testing of these local natural analogs was also included as part of the Weathering and Stability Study.

Geotechnical Characterization Activities and Results

Introduction

The overall geotechnical characterization included a number of prior field sampling and laboratory testing campaigns (also referred to as "legacy testing") by consultants before the initiation of the Weathering and Stability Study as well as the work during the project. Legacy testing considered by the new study included the following:

- Robertson GeoConsultants (RGC) as summarized by URS Corporation (2003)
- NorWest Corporation (2004)

The original work plan was to focus significantly on the Roadside Rock Piles (Dawson and Horton, 2011). However, about the time of initiating the Weathering and Stability Study the Goathill North (GHN) rock pile had a stability failure through the shallow foundation layers. To stabilize the pile, material was removed from the top of the pile and placed as a buttress near the toe. The GHN program refocused the Weathering and Stability Study to a detailed study of GHN as an example of a generalized rock pile, consistent with treating the Weathering and Stability Study as a body of scientific research, not as an engineering analysis of specific rock piles for which stability concerns already existed. The excavation process allowed an extensive sampling and mapping activity of the upper reaches of the GHN pile from specially excavated trenches, and this provided a very large inventory of materials for geotechnical and geochemical evaluation. This was followed by supplementary sampling and testing of materials from the other rock piles. These samples were all tested in the laboratories of the New Mexico Institute of Mining and Technology, Socorro, NM (NMT) using the standard operating procedures (SOP's) developed for the project. The SOP's for geotechnical testing were identical to the ASTM test methods.

A number of specific and focused geotechnical testing campaigns were also carried out, these included:

- Selected site-wide sampling and laboratory testing of rock materials in the UBC laboratory (Azam and Wilson, 2006).
- Collection of five megasamples for laboratory testing at the Golder Associates laboratory in Burnaby, BC; testing included index tests plus large and small scale direct shear, triaxial shear, hydraulic conductivity, and soil water characteristics curves (Nunoo, 2009).
- In situ direct shear tests of 300 X 300 mm and 600 x 600 mm samples at low normal stress. A large number of tests conducted were distributed across the rock piles and natural analogs (Boakye, 2008).

The sections below provide brief descriptions of the tests as well as summaries of the results. As part of the Weathering and Stability Study a statistical analysis was performed to evaluate whether the data sets for the individual rock piles can be considered statistically similar to each other. It was found that there was no statistical difference between the various data sets and that it would therefore be acceptable to combine all the data into one large data set. This is an important outcome as it allows the use of a large database for most parameters.

Index Properties

In situ density

In situ density of the rock pile and local natural analogs was measured using sand cone and sand replacement methods. Table 1 summarizes the in situ density results. Previous studies indicate that the coefficient of variation for in situ dry density is 5 to 10 percent (Baecher and Christian, 2003). The values of the rock piles and alteration scars reported in Table 1 are of this magnitude. It must be noted that this research program did not include any relative density measurements.

Table 1: In situ dry density for rock piles and natural analogs

Test Location	# of Tests	Range (kg/m^3)	Mean (kg/m^3)	Standard Deviation (kg/m^3)	Coefficient of Variation (%)
Rock Piles	153	1400 to 2400	1,800	140	7.8
Alteration scars	13	1500 to 2300	1,900	210	11.1
Debris flow	10	1300 to 2200	1,900	340	17.9
Colluvium/Weathered rock	1	-	2,200	-	-

In situ water content

Samples were taken in sealed cans for oven dry water content measurements. Table 2 summarizes the in situ water content results. Previous studies indicate that the coefficient of variation for in situ water content is 6 to 63 percent (Baecher and Christian, 2003). All values reported in Table 2 fall within this large range. The insitu water content of the rock pile materials has a higher coefficient of variation than that of the the other materials. This may be due to a larger range of particles sizes for the various samples with finer samples resulting in higher water contents.

Table 2: In situ water content for rock piles and natural analogs

Test Location	# of Tests	Range (percent)	Mean (percent)	Standard Deviation (percent)	Coefficient of Variation (%)
Rock Piles	390	1 to 24	10	4	40
Alteration scars	48	1 to 20	9	4	22.5
Debris flow	36	1 to 29	5	4	12.5
Colluvium/Weathered rock	13	9 to 26	14	3	21.4

Particle size distribution

Particle size analyses were done using sieves and hydrometer analyses. The maximum sieve size used for the laboratory testing was a 3-inch sieve and larger particle sizes were not determined through measurement, weighing, etc. Initially all particle size analyses for the Weathering and Stability Study were done using dry sieving. Comparing the results with legacy test results done using wet sieving showed that the wet sieving results had higher percentages of fines. An investigation was then made of the differences in percentage fines between wet and dry sieving of a series of rock pile samples (Nunoo, 2009). Table 3 provides a summary of the wet and dry sieving done by NMT for selected samples.

Figure 2 provides the ranges of particle size distributions for the Goathill North rock pile as well as those obtained from a broad literature review for worldwide rock piles.

Particle Shape

An investigation of particle shape of rock pile and natural analogs was made using the approach proposed by Powers (1982) to obtain measures of sphericity and roundness by visual methods. In order to limit errors four individuals, including two geologists and two mining engineers, described the particle shapes using this chart. A rigorous, semi-quantitative method involved selecting five sieve sizes (2 inch, 1 inch, ½ inch, No. 4 and No. 10 sieves) to separate the particles or rock fragments into different size fractions. A summary of the results for all samples is presented in Figure 3. The results of this analysis indicate that rock fragments at the Questa mine are mainly subangular, and subdiscoidal and subprismoidal. Note that the sphericity and angularity of the rock fragments of the younger rock piles are relatively similar to those of the older analogs (sample locations are shown in Figure 5; the QPS sample is for an alteration scar material). This suggests that long-term weathering (>100 years) does not noticeably affect the particle shapes at the test locations (Nunoo, 2009).

Table 3: Summary table of particle size results conducted at New Mexico Tech. Note that two separate samples were collected from Sugar Shack West rock pile

Sample Id	Description	Particle Size, Dry Sieving			Particle Size, Wet Sieving		
		% Gravel	% Sand	% Fine	% Gravel	% Sand	% Fine
MIN-SAN-0001	Debris Flow	52.4	45.7	1.9	53.2	34.3	12.6
QPS-SAN-0001	Alteration Scar	64.9	33.1	2.0	62.0	29.1	9.0
SSW-SAN-0005	Sugar Shack West	56.7	40.2	3.1	49.8	32.2	18.1
SPR-SAN-0001	Spring Gulch	71.4	25.9	2.7	66.4	22.6	11.0
SSW-SAN-0001	Sugar Shack West	46.4	52.3	1.4	33.2	44.7	22.1

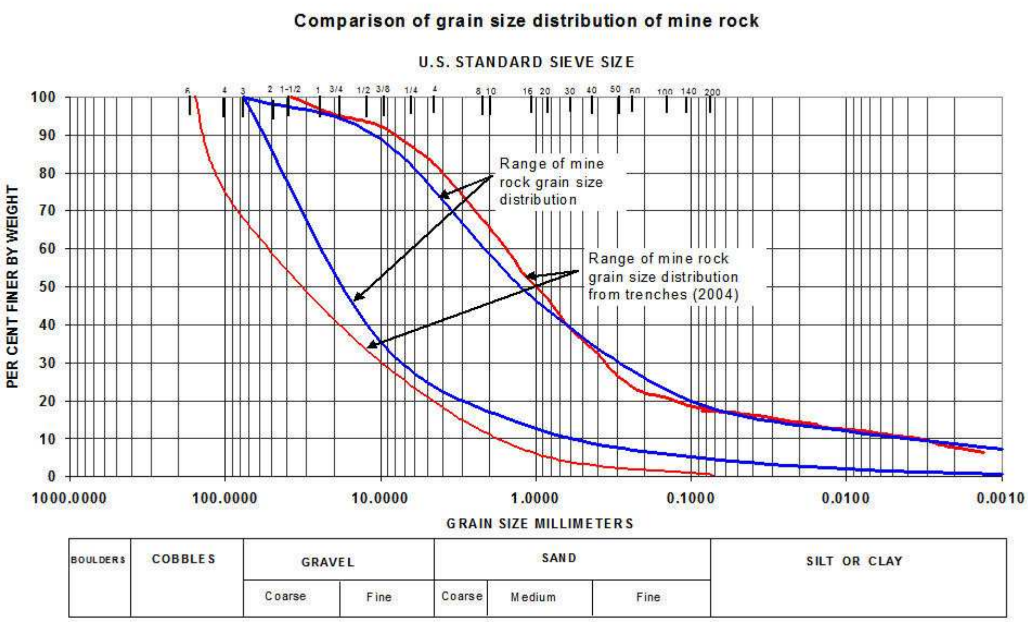

Figure 2: Particle size distributions of rock piles world-wide and GHN rock pile, Questa (referred to as

Specific Gravity

The specific gravity of the materials was determined on the minus no. 4 sieve (4.75 mm) fragments using the pycnometer method (ASTM 854-02) and for particles larger than 4.75 mm using the Method for Coarse Aggregates (ASTM C127-04). The average value obtained from these two methods is reported. Table 4 summarizes the specific gravity results for the Goathill North pile. Previous studies indicate that the coefficient of variation for specific gravity is 1 to 10 percent (Baecher and Christian, 2003). All values reported in Table 4 fall within this large range.

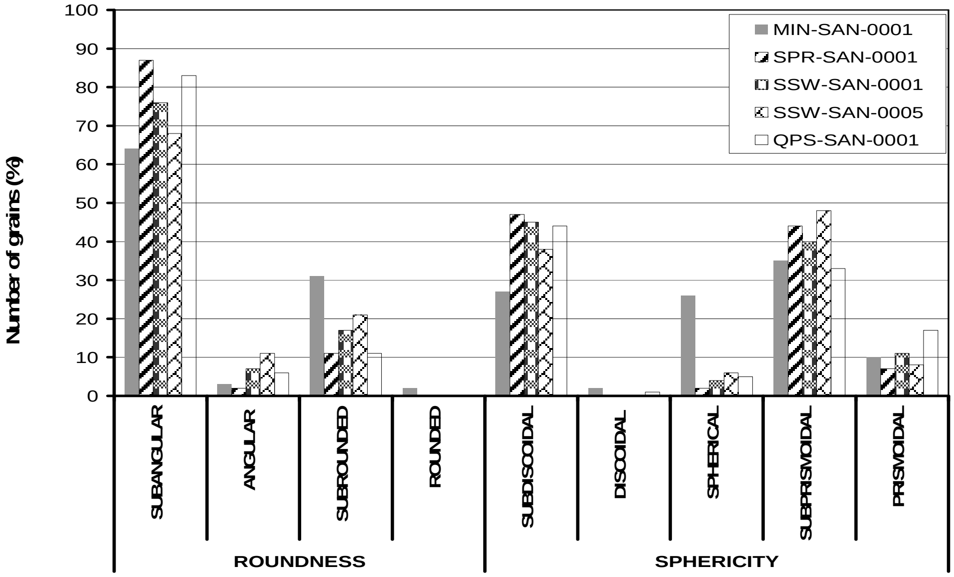

Figure 3: Overall distribution of sphericity and roundness class for all five samples

Table 4: Specific gravity for rock piles and natural analogs

Test Location	# of Tests	Range	Mean	Standard Deviation	Coef of Var (%)
GHN Rock Pile	47	2.60 to 3.00	2.74	0.08	3

Atterberg Limits

Atterberg limit tests were performed on the minus no. 40 sieve (425 μm) fraction. Table 5 summarizes the Atterberg limits results. Previous studies indicate that the coefficient of variation for liquid and plastic limits is 3 to 20 percent (Baecher and Christian, 2003). All values reported for liquid limit and plastic limit fall within these ranges.

Table 5: Atterberg limit for GHN rock pile (80 samples)

Parameter	Range	Average	Std Dev	Coef of Var (%)
Liquid Limit	25 to 50.5	34	4.5	13
Plastic Limit	14.5 to 30.8	21	3.1	15
Plasticity Index	3.9 to 24.8	12.9	4.3	33

Shear Strength

Shear strength data for the Questa rock piles and natural analogs are available from a number of sources as summarized below. Two failure criteria were used to obtain the shear strength parameters: the Mohr-Coulomb failure criterion to obtain the angle of internal friction and c-parameter values and a curved failure envelope using the expression $\tau = A\sigma_n^b$. Best fit regression lines were adopted in analyzing the test results for both failure criteria to obtain the shear strength parameters listed below. This approach was taken to obtain consistent data that is not subject to engineering judgment.

Legacy Data

Robertson GeoConsultants collected a series of samples for direct shear tests on 2.4 inch (61mm) diameter and 12 inch (300mm) square specimens. The testing was performed by Advanced Terra Testing of Lakewood, CO and AMEC in their Phoenix, AZ laboratory. Also, URS Corporation (2003) assigned a series of triaxial tests that were completed by Thurber Consultants, Victoria, BC.

NMT direct shear testing

NMT performed a large number of small scale (2.4 inch, 61mm square) direct shear tests on air dried samples scalped to the minus #6 sieve. Tables 6 and 7 provide summaries of peak and large deformation friction angles for the various rock pile samples. Note that the terminology of “large deformation” is used here instead of “critical state” as it was not clear that the latter was reached in the large deformations used in the testing. The maximum deformation in these tests was 10 to 13mm.

The Mohr-Coulomb parameters were determined using regression analysis of the normal and shear stresses obtained during the test. This was done to make sure that no biases are introduced due to individual interpretations of the results. Reference is therefore not made to critical friction angle ($\square_c$).

Table 6: Peak friction angle (degrees) of all rock piles (normal stress of 160-750 kPa)

Location	No of Samples Tested	Min (degrees)	Max (degrees)	Range (degrees)	Mean (degrees)	Standard Deviation (degrees)	Coefficient of Variation (%)
All Rock Pile samples	99	35.3	49.3	14.0	42.2	2.9	6.9
GHN	57	37.8	47.8	10.0	42.7	2.2	5.2
Middle Rock Pile	4	37.8	44.5	6.7	40.7	3.3	8.1
Spring Gulch	11	35.9	49.3	13.4	39.7	3.8	9.6
Sugar Shack South	8	38.9	48.0	9.1	43.8	3.0	6.9
Sugar Shack West	19	35.3	47.9	12.6	41.8	3.4	8.2

Table 7: Large deformation friction angle (degrees) of all rock piles (normal stress of 160-750 kPa).

Location	No of Samples Tested	Min (degrees)	Max (degrees)	Range (degrees)	Mean (degrees)	Standard Deviation (degrees)	Coefficient of Variation (%)
All Rock Pile samples	99	32.8	44.4	11.6	38.5	2.4	6.2
GHN	57	33.7	44.3	10.6	38.8	2.4	6.2
Middle Rock Pile	4	36.7	38.1	1.4	37.4	0.7	1.9
Spring Gulch	11	32.8	39.9	7.1	36.6	2.3	6.3
Sugar Shack South	8	35.9	41.9	6	39.0	2.2	5.6
Sugar Shack West	19	35.5	44.4	8.9	38.7	2.4	6.2

NMT in situ direct shear testing

NMT also had an extensive field testing campaign whereby 52 in situ direct shear test. The single box equipment was 12-inch (300mm) and 24-inch (600mm) square and 12 inches (300mm) deep (Fakhimi, et al, 2008). Tests were performed in rock pile and analog materials at low normal stresses ranging from 15 to 75 kPa. A total of 52 tests were performed at 13 locations shown on Figure 4. Because of the presence of large particles (larger than 20 percent of the side dimension of the shear box) in the shear zones at some test locations only 24 test results were considered valid. The range of in situ dry densities at 42 of the tests was 1,410 to 2,680 kg/m^3, with a mean of 1,925 kg/m^3, a standard deviation of 267 kg/m^3 (coefficient of variation of 14 percent) (Boakye, 2008).

The c-parameter values were calculated by drawing a line equal to the laboratory friction angle through the normal and shear stresses at failure. A total of 20 tests from the Questa rock piles resulted in a range of c-parameter values of 0 to 25.9 kPa with mean value of 9.6 kPa and a standard deviation of 7.2 kPa. This represents a high coefficient of variation. The two tests in the alteration scars had c-parameter values of 12.1 and 23.9 kPa and those in the debris flows had values of 31.4 and 46.1 kPa.

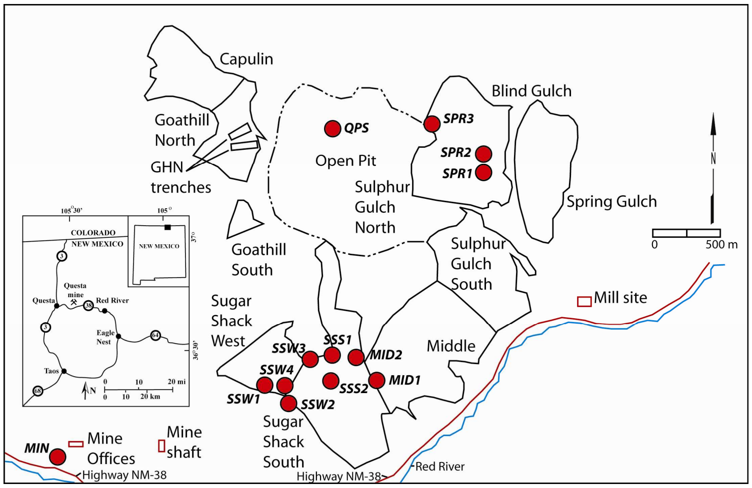

Figure 4: Location of in-situ samples (red circles)

Direct shear and triaxial test program by Golder Associates, Burnaby, BC.

This test program was designed to obtain further insights in the role of laboratory equipment type and size (and therefore particle size) and moisture content on the effects of the shear strength parameters. The test series included the following:

- 12 inch (square) direct shear on minus 1 inch material prepared at three water contents: air dried, moist and saturated
- 2.5 inch (round) direct shear on minus No. 6 sieve material prepared at three water contents: air dried, moist and saturated
- 2.5 inch (square – one sample) direct shear on minus No. 6 sieve material prepared at three water contents: air dried, moist and saturated
- CU TX testing on 4-inch diameter samples

Test samples were obtained from the 5 locations shown on Figure 5 and were sieved to minus 1 inch in the field before shipping the samples to Golder Associates. Further screening was done in the laboratory to prepare samples of the minus No. 6 sieve material. The test specifications were to compact the small direct shear specimens at 1,700 kg/m^3 and the large specimens at 1,800 kg/m^3. These values were selected because the lowest average in situ dry density was 1,800 kg/m^3. As the in situ materials contains particles of larger diameter than one inch (refer to Figure 2) this value was considered a good estimate of the average in situ dry density for the minus one inch material, while the lower value of 1,700 kg/m^3 was considered a good estimate for the finer materials (minus No. 6 sieve).

Tables 9 and 10 provide summaries of the peak friction angle direct shear test results obtained by Golder Associates for the 12 inch and 2.4 inch specimens respectively. Figure 6 provides a summary of the peak friction angle results in graphical form.

Table 11 summarizes the shear strength parameters for the saturated direct shear tests and the 4-inch diameter triaxial tests.

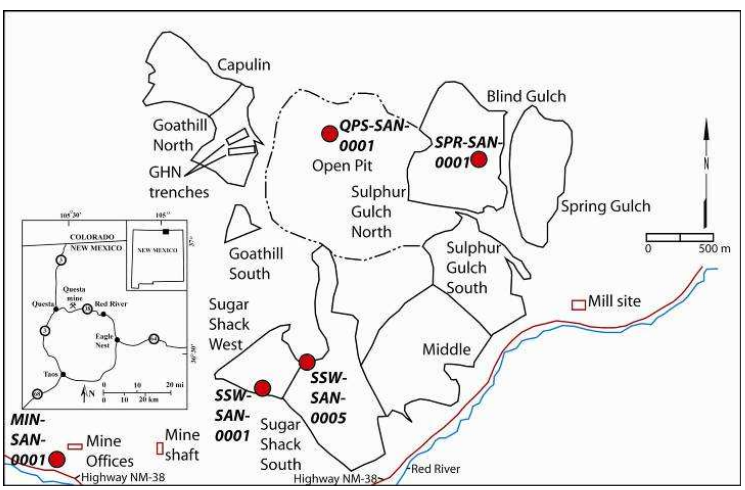

Figure 5: Sample locations for Golder Associates shear testing program

Table 9: Peak shear strength parameters from direct shear tests using the 0.3-m (12-inch) shear box. The normal stresses used for the shear tests were 50, 150, 250, and 400 kPa.

Sample ID	Description	Condition	Water Content (%)	c (kPa)	Φ‘(degrees)	A (kPa**(1-b))	B
MIN-SAN-0002	Debris Flow	Air dried	0.15	45.8	45.7	3.98	0.79
QPS-SAN-0002	Alteration Scar		0.50	18.4	48.3	1.98	0.91
SSW-SAN-0006	Sugar Shack West		0.40	12.0	48.1	2.40	0.87
SPR-SAN-0002	Spring Gulch		1.78	11.5	52.1	2.24	0.91
SSW-SAN-0002	Sugar Shack West		0.15	29.4	47.0	3.48	0.81
MIN-SAN-0002	Debris Flow	Moist	9.65	33.3	45.6	2.57	0.86
QPS-SAN-0002	Alteration Scar		9.50	35.5	44.9	3.36	0.81
SSW-SAN-0006	Sugar Shack West		11.35	41.3	36.8	3.54	0.76
SPR-SAN-0002	Spring Gulch		9.45	21.8	48.4	2.03	0.91
SSW-SAN-0002	Sugar Shack West		9.80	37.1	43.5	4.40	0.75
MIN-SAN-0002	Debris Flow	Saturated	13.13	12.9	40.2	1.95	0.86
QPS-SAN-0002	Alteration Scar		13.10	20.8	41.7	1.67	0.91
SSW-SAN-0006	Sugar Shack West		13.60	18.0	34.2	1.25	0.91
SPR-SAN-0002	Spring Gulch		11.75	43.6	41.3	3.43	0.79
SSW-SAN-0002	Sugar Shack West		13.68	13.7	42.6	2.36	0.84

Table 10: Peak shear strength parameters from direct shear tests using the 0.06-m (2.4-inch) shear box. The normal stresses used for the shear tests were 50, 150, 400, and 700 kPa.

Sample ID	Description	Condition	Water Content (%)	c (kPa)	Φ'(degrees)	A (kPa**(1-b))	B
MIN-SAN-0002	Debris Flow	Air dried	1.55	32.2	39.3	2.85	0.81
QPS-SAN-0002	Alteration Scar		2.57	54.4	38.5	6.14	0.69
SSW-SAN-0006	Sugar Shack West		2.97	30.3	39.2	2.32	0.84
SPR-SAN-0002	Spring Gulch		2.59	33.9	38.4	2.96	0.80
SSW-SAN-0002	Sugar Shack West		2.55	64.4	35.8	4.75	0.73
MIN-SAN-0002	Debris Flow	Moist	10.37	29.3	38.4	1.70	0.89
QPS-SAN-0002	Alteration Scar		14.23	39.1	35.3	3.54	0.76
SSW-SAN-0006	Sugar Shack West		12.00	47.7	34.0	3.68	0.75
SPR-SAN-0002	Spring Gulch		8.91	26.8	38.9	1.80	0.88
SSW-SAN-0002	Sugar Shack West		11.27	38.8	35.8	2.47	0.82
MIN-SAN-0002	Debris Flow	Saturated	16.49	20.2	35.9	1.66	0.88
QPS-SAN-0002	Alteration Scar		18.29	24.0	34.4	1.65	0.87
SSW-SAN-0006	Sugar Shack West		18.22	22.9	30.7	1.32	0.89
SPR-SAN-0002	Spring Gulch		16.05	31.0	33.2	1.57	0.88
SSW-SAN-0002	Sugar Shack West		16.69	26.1	35.6	1.68	0.88

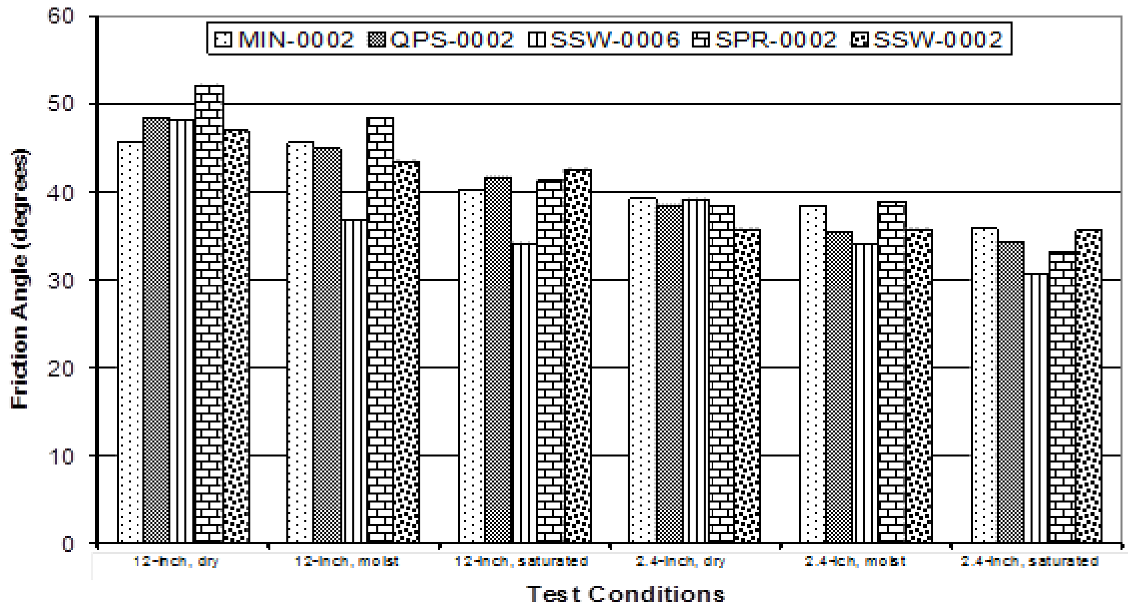

Figure 5: Summary of Peak Friction Angle Results for Golder Associates Direct Shear Tests

Table 11: Summary of peak shear strength parameters from direct shear and triaxial tests by Golder Associates

Sample ID	Description	2-inch Direct Shear		2.4-inch Direct Shear		Triaxial	
		c' (kPa)	Φ'(degrees)	c' (kPa)	Φ'(degrees)	c' (kPa)	Φ'(degrees)
MIN-SAN-0002	Debris Flow	12.9	40.2	20.2	35.9	3.4	39.3
QPS-SAN-0002	Alteration Scar	20.8	41.7	24.0	34.4	7.9	40.4
SSW-SAN-0006	Sugar Shack West	18.0	34.2	22.9	30.7	10.8	39.4
SPR-SAN-0002	Spring Gulch	43.6	41.3	31.0	33.2	5.8	43.2
SSW-SAN-0002	Sugar Shack West	13.7	42.6	26.1	35.6	5.3	41.5

Time Dependent Geotechnical Change of Rock Pile

To recap, Table 12 presents a summary of the friction angle values obtained by a range of academic and commercial laboratories for various test conditions.

The geochemical and geological evaluations show that while there are indications that jarosite and other weathering products have been developing and will continue to do so, their contributions to "cementation" and therefore more pronounced development of measurable shear strength at zero normal stress is expected to be negligible for a considerable period into the future. Similarly, matric suction is not expected to have any significant contribution to a measurable c-parameter.

Considering the physical behavior of the angular particles in the rock piles the following model is proposed for the measured low insitu c-parameter values at low normal stresses: at the time of deposition the rock piles consisted of angular particles that were deposited at low density and demonstrated very little interlocking, etc. As the rock piles aged the structure deformed as the particle interlocking increased. Such interlocking results in non-linear shear strength behavior at low normal stress which also was interpreted as an “equivalent c-parameter” at this low normal stress.

In general, Questa rock fragments presented high durability and strength even after undergoing hydrothermal alteration, blasting, deposition, and exposure to weathering. These results and other studies suggest that changes in physical properties (i.e. particle size, texture and fabric) have a larger effect on the friction angle than do mineralogic and chemical changes. Collectively, these results suggest that future weathering will not substantially decrease the friction angle of the rock piles with time.

Conclusions

This paper presents a summary of the geotechnical characterization results of the Questa Rock Piles as obtained by a number of laboratories over time. The following conclusions can be drawn from these results:

- Collectively the data are consistent in values. This is the case for data from the various rock piles as well as data obtained by a wide range of laboratories.
- The variability observed for the geotechnical characteristics in the rock piles as expressed by the coefficient of variation is similar to that of other geotechnical materials as compiled in the literature. This shows that there are no clear “outliers” in the data.
- The shear strength values obtained by the various testing campaigns indicate that:
    - The friction angles for the peak and large deformation test results range from the high 30’s to high 40’s
    - The peak friction angles decrease slightly with an increase in moisture content
    - The peak friction angle of samples containing larger diameter particles is higher than that for samples containing smaller particles
- Future weathering will not substantially decrease the friction angle of the rock piles with time as the geochemical studies concluded that new clay minerals will not form in the next 100 to 1000 years. This is related to the geochemistry of the materials and is not influenced by climatic conditions.

Table 12: Summary of friction angle values obtained from different test conditions

Company	Conditions	Number of samples	Box size	Friction Angle (degree)
NMT high	Dry	17	2-inch	33.4-54.3 Mean 42.1 Std Dev. 3.3
NMT Low	Dry	57	2-inch	38-56.1 Mean 48 Std Dev. 4
NMT high	Dry	2	4-inch	43.5-45.6 Mean 44.6
NMT In situ		2		48.7-49.6 Mean 49.2
Golder	Dry	5	2.4-inch	35.8-39.3 Mean 38.2 Std Dev. 1.4
	Moist	5	2.4-inch	34.0-38.9 Mean 36.5 Std Dev.2.1
	Saturated	6	2.4-inch	34.0-38.9 Mean 36.5 Std Dev.2.1
	Dry	5	12-inch	45.7-52.1 Mean 48.3 Std Dev. 2.4
	Moist	5	12-inch	36.8-48.4 Mean 43.8 Std Dev.4.3
	Saturated	5	12-inch	34.2-42.6 Mean 40.0 Std Dev.3.3
UBC	Dry	20	2-inch	28.8-41.9 Mean 36.0 Std Dev.3.9
RGC	Saturated	18	12-inch	26.6-59.0 Mean 43.5 Std Dev.7.3
		18	2.4-inch	28.9-41.5 Mean 35.2 Std Dev.4.0
Norwest	Dry	7		19.7-30.0 Mean 26.1 Std Dev.4

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All the published papers and theses which were prepared as part of the Weathering and Stability Project from NMT authors can be accessed at:

http://geoinfo.nmt.edu/staff/mclemore/Environmental.html

References

Azam, S. and Wilson, G.W., 2006. Geotechnical characterization of shear strength and hydraulic properties of waste rock samples from Questa Mine: Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, British Columbia, Canada.

Baecher, G.B. and Christian, J.T., 2003. Reliability and Statistics in Geotechnical Engineering, JohnWiley and Sons.

Boakye, K., 2008. Large In Situ Direct Shear Tests on Rock Piles At the Questa Mine, Taos County, New Mexico: M.S. Thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

Dawson, R. and Horton, J. 2011. Roadside Piles Long-Term Stability, Proc. Tailings and Mine Waste 2011.

Fakhimi, A., Boakye, K., Sperling, D.J. and McLemore, V.T. 2008. Development of a modified in situ diect shear test technique to determine shear strength parameters of mine rock piles, Geotechnical Testing Journal, Vol. 31, No. 3, ASTM. 1 – 5.

Logsdon, M. 2011. Questa Rock-Pile Weathering Study: Geology, Hydrology and Geochemistry, Proc. Tailings and Mine Waste 2011.

Nunoo, S., 2009. Geotechnical Evaluation of Questa Mine Material, Taos County, New Mexico: M.S. Thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

Norwest Corporation, 2004. Goathill North Slide Investigation, Evaluation and Mitigation Report: unpublished report to Molycorp Inc., 3 vol.

Powers, M.C., 1982. Comparison chart for estimating roundness and sphericity: AGI (American Geological Institute), Alexandria, Va., data sheet 18.1.

URS Corporation, 2003. Mine rock pile erosion and stability evaluations, Questa mine: unpublished Report to Molycorp, Inc., 4 volumes.