Characterization and Selection of Waste Rock Borrow Material for Use as Rock Armor to Reduce Tailing Impoundment Side-slope Erosion

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Abstract

A waste rock characterization effort was designed and implemented to identify favorable waste rock borrow material for use as rock armor on a tailing impoundment side-slope reclamation project. The following criteria were applied: 1) sufficient volumes of material; 2) particle size distributions with greater than 50% of the material larger than 12.5-mm particle diameter; 3) acid-base accounting showing positive net neutralization potential; and 4) sufficient nutrient levels and minimal potentially phytotoxic elements to facilitate revegetation. In addition, a field-scale erosion test designed to simulate a 100-year, 24-hour storm event was conducted to determine the efficacy of the selected rock material and of selected ripping treatments in controlling erosion. Two generally non-acid generating and erosion resistant mine-waste rock types were found: argillite and arkose material. Within the potential source areas, evidence of oxidation (yellowish-red staining) was a good predictor of net acid -generating material and used as exclusion criteria. Argillite was used as rock armor on short slopes and the coarser arkose material for slope-lengths greater than 90-meters.

Introduction

Erosion rates are controlled by soil type, precipitation intensity, slope angle and length, vegetation cover and the amount of surface armor from rock fragments that serve to dissipate raindrop energy and retard runoff velocities. Side-slope reclamation in the southwestern USA has frequently suffered from extensive channel degradation, rilling and gullying that requires extensive maintenance. Several factors contribute to poor performance:

- Side-slope terracing, gradient changes and irregular topography result in pooling, ponding, overtopping and downcutting.
- Channel designs are unstable due to excessive flow concentration and channel incision or over-topping.
- Steep side-slopes capped with fine-grained cover material cannot be maintained because the rock fragment content and vegetative cover success on the side-slopes is insufficient to reduce erosion.

- Erosion control methods (i.e. straw waddles, diversion channels) are improperly installed.

In semi-arid regions, erosion is strongly controlled by the amount of rock fragments on the surface; for example, a 50% rock fragment cover has been observed to reduce erosion by 80% to 95% on 10 (H):1 (V) side-slopes (Simanton et al., 1984; Poesen and Lavee, 1994). Other studies on natural slopes in southeastern Arizona showed that the percent of surface rock fragment correlates strongly with slope angle; 5:1 and 2.5:1 side-slopes averaged 48% and 60% rock fragments respectively (Simanton et al., 1994). In addition, 5:1 slope lengths were typically 90-meters (m) compared to 45 m to 60 m for the 2.5:1 slopes. These authors also noted that rock fragments less than 7.5 mm in diameter were transported off-slope, suggesting the 3/8-inch sieve is an appropriate cut-off for considering rock fragment percentages. Highly developed micro-topography was also observed on the natural desert study slopes, serving to reduce runoff velocities.

Nonetheless, even with relatively high rock fragment content, reclaimed side-slopes are initially highly erosive because the emplaced cover material is loose (reduced soil cohesion) and the rock fragments are generally below the surface rather than above it. Initial rilling and gullying can lead to long-term erosion even after vegetative growth because of increased flow velocities in the rills/gullies, necessitating the need to repair observed rilling and gullying even if surface conditions appear otherwise stable. The stability of initial slope conditions, therefore, is also a design concern.

On the portion of the Asarco Mission Mine located on the San Xavier District of the Tohono O'Odham Nation (SXD), available mine waste cover material (alluvium) generally grades from a sandy-loam to a coarse sand material with less than 2% gravel-size or greater material. Previous reclamation at this site performed in the 1970s and 1980s with these borrow material show highly eroded side-slopes. Asarco and SXD decided during the final reclamation planning to use alluvium as cover material on generally flat surfaces and rock-armor on the tailing impoundment side-slopes to adequately control long-term erosion. Waste rock stored on-site provided the cheapest and most accessible rock armor source; nonetheless, the uniformity of physical and geochemical properties of the waste rock material was unknown. In addition, surface water routing to minimize erosion and control gullying needed to be evaluated. This paper describes the characterization and evaluation process for selecting rock armor sourced from Mission Mine waste rock material.

Site conditions

The Asarco Mission Mine is located in southeastern Arizona, USA in the Sonoran Desert. Soils at the site are generally deep and well drained. Vegetation is primarily upper Sonoran Desert shrub, which is dominated by trees and shrubs with minor amounts of perennial grasses. Average annual precipitation at the site is 338 mm; the maximum 24-hour predicted precipitation ranges from 51 mm to 108 mm for the 2-year and 100-year return period events, respectively.

Mine waste facilities on the SXD portion of the mine are located at elevations approximately 820 to 1000-meters above mean sea level. There are three contiguous, upstream constructed, tailing impoundments; two of the impoundments were merged into one impoundment (Figure 1). Previous environmental studies indicated that the tailings would remain circum-neutral after closure. The total tailing reclamation surface area is approximately 465-hectares with 140-hectares of side-slopes. The impoundments were constructed in approximately 6-meter high increments with 2.5:1 slopes using setbacks that result in an average 3:1 slope. Overall slope lengths ranged from approximately 60 m near the rear of the impoundment and over 180 m at the front dam. *(moved to final design section)*

Rock Armor Selection Methods

The primary considerations for classification of favorable rock armor material were 1) sufficient volumes of material; 2) particle size distribution (PSD) showing greater than 50 percent of the material larger than 12.5 mm particle diameter; 3) acid-base accounting showing positive net neutralization potential (NNP); and 4) sufficient nutrient levels and absence of elements at phytotoxic concentrations. Asarco and SXD did not plan an active slope revegetation program; however, various options were considered for a modest revegetation effort if selected slope armoring materials were suitable for plant growth. Rock armor source investigations consisted of the following steps:

1. Review of geochemical data from previous environmental investigations on the tailing impoundments and waste rock facilities and waste rock dumping records to identify potential rock armor borrow areas.
2. Field investigations of rock types: Test pits and trenches were implemented in all potential borrow areas with sample collecction for PSD, pH, and acid-base accounting (ABA) to determine erosion resistance and the potential for acid generation.
3. Evaluation of revegetation potential for tailings slope armor: Physical and geochemical characteristics of potential borrow material and borrow material mixed with alluvium were reviewed to determine soil texture, macro- and micro-nutrient levels, and potential phytotoxicity.

After the selection of potential waste rock material sources that met the rock armor selection criteria, field scale erosion tests were performed to validate erosion modeling and material placement assumptions. Final rock armor source selection was based on source areas, erosion resistance, and haulage and placement costs.

Investigation Approach

Existing laboratory geochemical data from 31 tailing and 51 waste rock samples provided the following chemical property characteristics: percent total moisture, saturated paste pH, ABA, and Synthetic Precipitation Leaching Procedure (SPLP) (EPA 1312) for metals. Data analysis consisted of the following calculations by dump and rock type: the Net Neutralization Potential (NNP) means and standard deviations, the Acid Neutralizing Potential (ANP) and Acid Generation Potential (ANP/AGP) ratio using ANP and AGP results for pyritic sulfur. The SPLP metals concentration means and standard deviations were calculated by rock type and the results (multiplied by 20 to account for dilution in the SPLP test method) were compared with threshold values for potential phytotoxic effects identified in the literature (Barth, 1986; Schafer, 1979).

The predominant rock types located at the mine waste rock storage facilities are argillite, quartz monzonite, arkose, siltstone, volcanics, and alluvium. Based on the existing geochemical data, quartz monzonite and siltstone appeared to be predominately negative NNP, whereas argillite and arkose material showed primarily postive NNP values. Six different potential rock armor borrow sources were identified on the Mission North Dump (MND North and West argillite areas), Waste Rock 3 Dump (WR3 argillite and volcanic areas), South Oxide Dump (SOD), San Xavier North Dump (SXND arkose area), and an in-pit argillite source to be mined (in-pit argillite). Figure 1 presents an overview map of the areas chosen for investigation and their locations relative to the tailings impoundment.

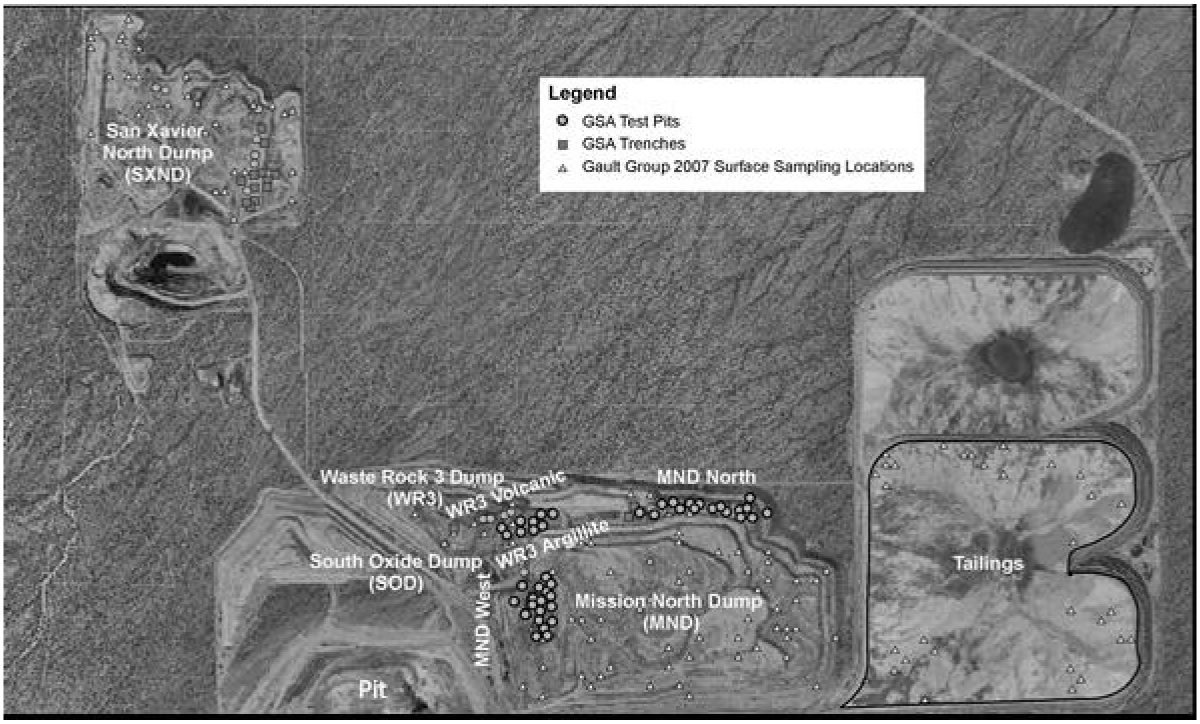

Figure 1. Potential mine waste rock armor sources and test pits, trenches and other sample locations

Of note, alluvium was not considered to be a rock armor source due to its high erosivity; however, it was evaluated as a subgrade material that could be used to reduce the amount of rock armor needed, neutralize potential acid generation from the waste rock and also provide an acceptable plant growth media.

Field Sampling and Characterization

A field characterization program consisting of several intervals of backhoe/trackhoe test pitting and dozer trenching was conducted within each potential borrow source areas to evaluate material lateral continuity and depth, particle size distribution (PSD), ABA, pH, and AGP. In general, exploratory backhoe test pits were followed with deeper trackhoe and bulldozer trenching in more favorable areas. Material from excavated pits was geologically logged in approximately 60 cm deep intervals for rock type, color, the degree of pyrite oxidation as determined from visible staining (i.e. jarosite, goethite), and PSD; trenches were geologically logged at 6 m lateral intervals.

Excavated material from each test-pit and trench (one to four locations per trench) was analyzed for PSD using digital imaging. For this method, a reference object (either a scaling ball or object of known size) is placed on the pile of excavated material, and a digital photo is taken perpendicular to the slope of the pile (Figure 2). Depending on material size, a series of one to three images, at different scales are taken. Images were submitted to Split Engineering (Tucson, AZ) and processed using Split-Desktop (ver. 3.0, 2010), which generates PSD curves for the material shown in the images. These data are especially useful in determining the percentage of large rock material (i.e. > 2-inch diameter) that is highly resistant to erosion, as traditional laboratory PSD methods may not fully represent the fraction of larger particles since practical sample sizes for collection are limited to 5 gallon buckets. PSDs were not determined where finer-grained materials (i.e. alluvium) were encountered within waste rock areas.

Figure 2. Comparison of coarse (left) and fine-grained (right) argillite and Split-Net reference object

Overall, 17 test pits were excavated in MND North, 18 in MND West, and seven in the WR3 argillite areas to depths of 2.5 to 4 m. To provide a more thorough assessment of lateral and vertical material heterogeneity in the MND North and West test areas, 35 m to 60 m long trenches were also excavated using a trackhoe to approximately 4.5 m below ground surface (bgs) in the MND North (3 trenches) and MND West (4 trenches) areas. Three trenches and three test pits were excavated and sampled at SOD, along with six trenches and four pits on the WR3 Volcanic area in order to find material with lower levels of pyrite and increased potential for revegetation. Seven pits and 16 trenches were excavated with a dozer or excavator to depths of up to 4 m in the SXND arkose area. Trenches ranged from 30 m to 50 m long and were dug only in areas where arkose was visible at the surface. To evaluate potential in-pit sources of argillite that could be used (and thereby reduce haulage costs), mine pit blast hole data from planned argillite waste was reviewed to estimate potential pyritic sulfur content from iron and sulfur values. In-pit argillite sulfur values were similar to other argillite areas; consequently, approximately 400 m^3 of in-pit argillite material were spread on a test section approximately 30 cm thick on the tailings slope. Samples were collected at 10 different areas for PSD, pH and ABA analyses. Finally, 10 alluvium samples were collected from ongoing reclamation of flat area surfaces and tested for pH and ABA.

Table 1 summarizes the number of samples selected and tested in each of the rock armor borrow source areas. To supplement and compare the finer-grained fraction (i.e. < 3/8" sieve) with digital image results, 16 selected bulk samples were collected for laboratory PSD testing (ASTM C 136 and C 117) for the material fraction less than six-inches in diameter. Laboratory PSD tests were conducted by Kleinfelder, Inc. (Tucson, Arizona). Samples selected for pH and ABA testing were sent to ACZ Laboratories (Steamboat Springs, Colorado) or Energy Laboratories (Billings, Montana). Soil fertility analyses (IAS Laboratories, Inc., Phoenix, AZ) were also run to measure geochemistry (paste pH and EC), concentrations of plant micro- and macro-nutrients (Ca, Mg, Na, K, Fe, Zn, Mn, Cu, NO3-N, PO4-P, ESP, SO4-S, B). Total metals tests were run on the erosion test pad materials to identify any potential for phytotoxicity (Al, As, Be, Cd, Co, Cu, Fe, Mn, Ni, Se, V, Zn).

Table 1: Number of samples collected from each borrow source area

Test Type	MND North	MND West	WR3 Argillite	SOD	WR3 Volcanic	SXND	In-Pit Argillite	Erosion Tests[1]	Alluvium	Total
Digital Image PSD	25	34	2	14	22	28	10	54	0	189
Laboratory PSD	4	3	2	3	0	0	0	10	6	28
pH and ABA	27	35	4	3	2	24	6	0	10	111
Soil Fertility	0	0	0	6	8	11	4	10	0	39

[1] Erosion Test material was hauled from MND West argillite area

Erosion Analyses and Erosion Tests

Argillite material was evaluated for resistance to erosion using the computer code RUSLE2 (USDA-ARS, 2008) to estimate annual erosion rates from 3(H):1(V) side-slopes armored with the argillite material as a function of side-slope length (45, 90, 135, 180 m) and vegetation (with and without). In addition, the potential variability in initial versus long-term erosion loss was evaluated for a subset of scenarios by increasing the gravel cover content to represent erosion loss of finer-grained material.

The RUSLE2 model was run using climate data for the Sahuarita part of Pima County, Arizona with annual precipitation of 338 mm and a 10-year 24-hour precipitation event of 81 mm. Simulations were conducted for coarse, average and fine-grained argillite material based on the PSD data collected from the MND North and West areas. To be consistent with the USDA texture scheme used in RUSLE2, the argillite sand, silt, and clay distribution was recalculated as the fine-earth fraction (without particles larger than 2 mm). The gravel cover ratio was then set as the percent of the PSD larger than 10 mm. The saturated hydraulic conductivity (Ks) class of the material was assigned based on the geometric mean of six single ring cylinder infiltrometer test measured Ks of 0.91 cm/hr (2.5 x 10-4 cm/sec). Based on data from other reclaimed areas (Milczarek et al., 2009), the following vegetation estimates were used: a maximum canopy of 15%, above-ground biomass of 280 kg/ha, and above-ground biomass to root mass ratio of 4.8 (Cox et al., 1986). The maximum fall height (the effective height from which water drops from canopy), was assumed to be 30 cm, with a growing season from March 1st to October 1st.

Erosion rates resulting from initial reclamation (prior to vegetation) and long-term erosion rates after finer particles have eroded were calculated for the average, coarse and fine-grained argillite and argillite with alluvium mixed by subtracting the annual erosion mass per acre from the total mass of a 0.4 ha, 10 mm deep soil depth at defined slope lengths. As defined by RUSLE2, surface rock fragments are resistant to erosion and are comprised of all surface particles greater than 10 mm in diameter. Thus, the mass of soil that is greater than 10 mm in diameter is assumed to not change with time. A three-year period of time was chosen to evaluate the long-term reduction of erosion due to increased surface gravel content based on results by Ollesch and Vacca (2002) whose data illustrates an asymptotic decrease in erosion, reaching a steady erosion rate after the third year. The authors attributed the decrease in erosion in large part to the increase in surface gravel through selective erosion processes.

Field-scale erosion tests were conducted to assess erosion from argillite using the MND West rock armor source and a variety of ripping treatments. Ripping was evaluated to assess its effectiveness in controlling initial erosion and the potential to increase moisture retention and the NNP by mixing the alluvium into the argillite. Test pads were constructed on the western slope of Tailing Impoundment 1 and 2 and consisted of approximately 30 cm of alluvium cap covered with 30 cm of argillite rock armor. Slope lengths were approximately 90 m at 3:1 slope angles. The first erosion test compared un-ripped argillite to single- and triple-ripped argillite to depths of approximately 60 cm. Water was applied using the spray bar of a water truck to simulate a 51 mm rainfall (10-year event). The second erosion test compared single-pass 15 cm deep rips, single-pass 61 cm deep rips, and double-pass 61 cm deep rips. Water was applied using two large irrigation sprinklers to simulate 102 mm of rain in 60-minutes (100-year event). Runoff from the simulated rainfall was monitored and PSD was determined at specified locations before and after each erosion test using digital imaging (Table 1). In addition, single-ring cylinder infiltrometer (CI) tests using the method of Bouwer et al. (1990), were conducted prior to both erosion tests to determine the effective field saturated hydraulic conductivity of the argillite-alluvium cover and upper tailings. After the first erosion test, test pits were excavated through the rock armor and into the alluvium to evaluate the degree of alluvium and argillite mixing as a result of the ripping treatments.

Geochemical Analyses

Potential rock armor samples were determined to have acceptable geochemical characteristics if they possessed both neutral pH and positive NNP values, or AGP/ANP ratios greater than 1.0, based on pyritic sulfur data from the ABA tests. In general, rock samples with NNP values between 0 and 20 tons $CaCO_3$/Kton or AGP/ANP ratios between 1.0 and 2.0 are considered to fall into an "uncertain" category regarding whether a sample will turn acid over time (GARD, 2010). However, since most of the potential waste rock sources have been exposed to the elements and potential oxidation reactions for more than ten years, the measured pH values in combination with the ABA data represent a long-term test of the acid generating potential of the materials. That is, a sample with neutral pH and NNP values greater than 1 is likely to remain non-acid generating. The exception to this was the in-pit argillite material, which has yet to be exposed to the elements.

Revegetation Analyses

The revegetation capacity of potential rock armor borrow material was assessed by evaluating the percentage of fine-grained material that could increase the availability of plant-available water and nutrients; comparing the tested metals, nitrate, and sulfate concentrations with published phytotoxicity thresholds; and evaluating soil macro- and micro-nutrients. Limited information exists on the metal tolerance of native desert plants because metal toxicity is associated with metal availability, subject to plant genotypic and population variation, and not well-studied in non-agricultural plants. In addition, many factors affect the solubility and plant availability of metals in soil; the most common factors are pH and cation exchange capacity (CEC) which is in turn affected by clay and organic matter content. Generally, as pH increases, the solubility of metals decrease; and as CEC, clay and organic matter content increase, soluble metals are more tightly bound to soil particles and therefore less available for plant uptake (Greger, 2004). Genotypic variations also cause differences in metal tolerance within species. Plants found growing in soil with high metal concentrations have shown higher metal tolerances than the same species growing in soil with lower metal concentrations (e.g. Gregory & Bradshaw, 1965; Karataglis, 1980; Mleczek, et al., 2009), a phenomenon called environmentally-induced tolerance (Wu, 1990).

Rock Armor Investigation Results

Potential available borrow volumes from the six areas were estimated using Asarco geologic and topographic maps. Available borrow source material ranged from approximately 400,000 to 650,000 m^3 at each site, which indicated sufficient borrow material for initial design calculations of 60 cm of rock armor. These calculations used conservative estimates of material depth due to only the uppermost waste dump lift, approximately 9 m deep, under consideration for use in order to maintain consistency with field investigation results.

Material types encountered in the trenches were variable. At the MND North area, significant amounts of siltstone and alluvium were encountered at depths below 3 m in the center of the potential borrow area. Material types in trenches on MND West were more predominantly argillite, with minor amounts of siltstone, volcanics, and alluvium. Quartz monzonite was the dominant mineral at SOD, with argillite and minor volcanic material also observed. In the WR3 volcanic area, rhyolite and argillite were the primary rock types noted, with some zones of quartz and pyritic siltstone also present. Arkose was the predominate material observed at the SXND area.

Based on the inital PSD, pH and ABA data, several areas were excluded from further analysis. The WR3 argillite area showed significant oxidation and highly variable NNP values, which therefore failed the positive NNP criteria. The majority of WR3 volcanic borrow material consisted of fine-grained rhyolite or argillite (50% < 5 mm) which failed the PSD criteria of 50% greater than 12.5 mm; remaining coarse volcanic material suitable for armoring contained insufficient volume of material for the project.. The SOD area primarily consisted of quartz monzonite that failed the NNP criteria; suitable material volume was also insufficient..

Table 2 summarizes the mean pH and ABA data for the remaining areas that met the initial property criteria. ABA results for the MND North and West argillite samples indicated generally positive NNP values (< 15 percent of the samples showed negative NNP). In addition, samples that showed significant oxidation were generally correlated with negative NNP values; however, some samples with low to no visible oxidation also had negative NNP values. The SXND arkose samples showed similar NNP values to the MND argillite samples; however, the mean pyritic AGP was approximately 50 percent lower, which indicates the arkose material has less potential AGP and subsequent neutralization reactions that contribute to soil salinity.

Table 2: Summary of mean pH and ABA data for argillite and arkose sources

Borrow Source Area	Mean pH	Mean Pyrite Sulfur, $CaCO_3$	Mean ANP/AGP
MND North Argillite (n=27)	pH = 7.7 (91% samples pH > 7)	2.1% pyrite sulfur, 119 tons $CaC0_3$/1000 tons	1.73
MND West Argillite (n=35)	pH = 7.6 (97% samples pH > 7)	2.1% pyrite sulfur 94 tons $CaC0_3$/1000 tons	1.37
SXND Arkose samples (n=24)	pH = 7.8 (97% samples pH > 7)	1.1% pyrite sulfur 56 tons $CaC0_3$/1000 tons	1.83
In-Pit Argillite (n=6)	pH = 7.1 (75% samples pH > 7)	3.1% pyrite sulfur 40 tons $CaC0_3$/1000 tons	0.41
Alluvium (n=10)	pH = 7.6 (100% samples pH > 7)	0.15% pyrite sulfur 98 tons $CaC0_3$/1000 tons	34

The ABA results for the in-pit argillite showed similar total sulfur values (not shown) compared to the MND argillite, however, the in-pit material showed higher pyritic sulfur content and lower ANP such that all in-pit argillite samples showed negative NNP. This is likely due either to differences in mineralogy (less calcium carbonate) in the area of the pit where the argillite was mined, in addition to the the effects of weathering/oxidation on the older material on the dumps, with conversion of pyritic sulfur to sulfate with exposure to air and water over time. It was determined that using in-pit argillite material for rock armor would require extensive sampling and testing in different pit locations to verify either positive NNP values or low AGP values. Consequently, the in-pit argillite source was excluded from further consideration. Finally, ABA results for alluvium subgrade material indicated very low acid-generation and high acid-neutralization potential.

The final areas that met the initial property criteria consisted of the MND West, MND North and the SXND arkose areas. PSD results indicated that each of these areas contained, on average, waste rock with more than 50 percent of the rock fragments greater than 12.5 mm in diameter (Table 3). PSD data for the MND North and West areas indicated that the mean particle size (F50) is between 21 and 24 mm, with a mean top size diameter of 160 to 200 mm. A top size less than 200 mm in diameter indicates that these materials could be truck-dumped and regraded using conventional heavy equipment without having to be screened. Two different types of material were identified in the SXND arkose area: fine-grained and coarse-grained. The fine-grained SXND arkose material failed the PSD criteria of 50% greater than 12.5 mm. SXND coarse arkose material contained greater than 50 percent material over 37 mm diameter and a top size of nearly 360 mm; moreover, a larger proportion of particles were greater than 100 mm in diameter compared to MND material (Table 3). Of note, the standard deviation was generally high for MND North and SXND material; however, the mean particle size minus one standard deviation still meets the PSD criteria of 50% greater than 12.5 mm in diameter for these areas.

Table 3: Summary of estimated argillite and arkose particle size fraction results (in mm)

Location:	MND North Argillite (n=25)		MND West Argillite (n=34)		SXND Arkose (n=28)			
Fraction	**Mean Diam**	**St Dev**	**Mean Diam**	**St Dev**	**Mean Diam Fine**	**Mean Diam Coarse**	**Mean All Diam**	**All St Dev**
F10	1.3	1.4	1.5	1.8	0.3	0.7	0.4	0.5
F20	3.4	3.6	3.9	3.2	0.5	3.1	1.5	2.3
F30	7.1	6.3	7.6	4.3	1.3	8.9	4.5	5.9
F40	14	9.4	13	5.1	3.5	20	11	13
F50	24	13	21	6.9	8.4	37	23	25
F60	40	19	32	11	18	61	43	41
F70	64	48	45	18	36	94	73	62
F80	94	78	63	27	66	146	125	101
F90	128	100	92	38	121	204	202	133
Topsize	207	120	162	46	256	359	354	167

Soil fertility results for most of the MND North and West argillite and the SXND arkose samples showed, with the exception of copper, metal concentrations (i.e. boron, manganese, cadmium, and zinc) in the argillite and arkose material were generally below thresholds that would inhibit plant growth (data not shown). DTPA extractable copper values averaged 127 ppm, higher than published thresholds for potential phytotoxicity (> 30 ppm Barth, 1986; > 40 ppm Schafer, 1979). Other research, however, indicates that native plant species adapted to high-salinity or copper conditions may not be adversely affected, although plant-available concentrations above 200 ppm are considered toxic to native perennial plants (Paschke and Redente, 2002). Only one argillite and three arkose samples exceeded this value. Zinc and boron were also measured above potential phytotoxicity thresholds in some MND North and West argillite and SXND arkose samples. Of note, there was substantial volunteer vegetation on MND West, which indicates that the argillite material is capable of supporting plant life. An absence of vegetation on MND North was believed to be due to greater compaction of the material and less time passing after having been dumped at that location.

Erosion Analyses and Erosion Test Results

Erosion modeling and erosion tests were only performed on the argillite material; based on the coarse-grained nature of the arkose material, it was assumed that the average arkose material would behave better than the coarse-grained argillite material. The SXND arkose coarse-grained material showed significantly larger mean particle diameter (F50 = 37 mm) and a greater fraction of large rocks than any of the argillite material.

The RUSLE2 modeling indicated that predicted annual erosion rates increase with increasing slope length. On average, erosion rates approximately double by increasing the slope length from 45 m to 180 m. Whereas, the addition of vegetation is predicted to decrease the erosion rate by approximately 40%; it is assumed that an alluvium and argillite mixture will be necessary to achieve the desired vegetation densities. Predicted erosion from the average argillite and alluvium mixture with vegetation was approximately equal to erosion rates from the average argillite, non-vegetated condition. Nonetheless, argillite and alluvium mixture erosion rates are two to three times less than those predicted for alluvium only. Other simulations showed: a) furrowing along the contour on average decreases the predicted erosion by about 10%; b) an increase in gravel cover due to erosion of finer particles over a three-year period reduced erosion by 16% to 19% for vegetated slopes and 26% to 35% for unvegetated slopes of 90 m and 180 m lengths, respectively; and c) increasing the gravel cover by 10% reduces predicted erosion rates by approximately 25%. Finally, predicted uniform soil loss was less than 2 mm per year for all of the scenarios except for the finer-grained argillite non-vegetated condition. To conservatively address uncertainty in the RUSLE2 predicted erosion rates (i.e. the inability to accurately predict rill and gully erosion), the estimated erosion results were doubled (2X) as a safety factor and recommended slope lengths for the argillite material were limited to less than 90 m on 3(H):1(V) side-slopes.

The erosion test results showed that water accumulated on the argillite surface in all un-ripped and ripped argillite treatments after approximately 6 mm of water was applied. This is reflective of the moderate permeability of the argillite material (6.9×10^{-4} cm/sec from cylinder infiltrometer data). Water applied during both tests was highly variable. Erosion Test #1 over-applied water at the upper portion of the test pad (> 50 mm/30 min.), whereas Erosion Test #2 under-applied water and only achieved the target irrigation rate in the center and southern portion of each plot. Erosion in the form of rilling or cascading over furrows occurred only in un-ripped and 6-inch-deep ripped argillite rock armor during the 10-year simulated storm event and in the 24-inch-deep ripped argillite during the 100-year event. Rilling and cascading of pooled water occurred primarily where ripping had not been completed perpendicular to the slope. PSD data indicated that neither the coarse (> 12.5 mm particles) nor the fine-earth fraction (< 5 mm) were significantly relocated by the simulated rainfall in any of the ripping treatment plots. Nonetheless, there was some accumulation of fine-grained sediment in the furrows and loose fine-grained sediments were observed to be cleaned from the argillite surface (Figure 3). No significant differences were observed between ripping treatments or before versus after simulated rainfall.

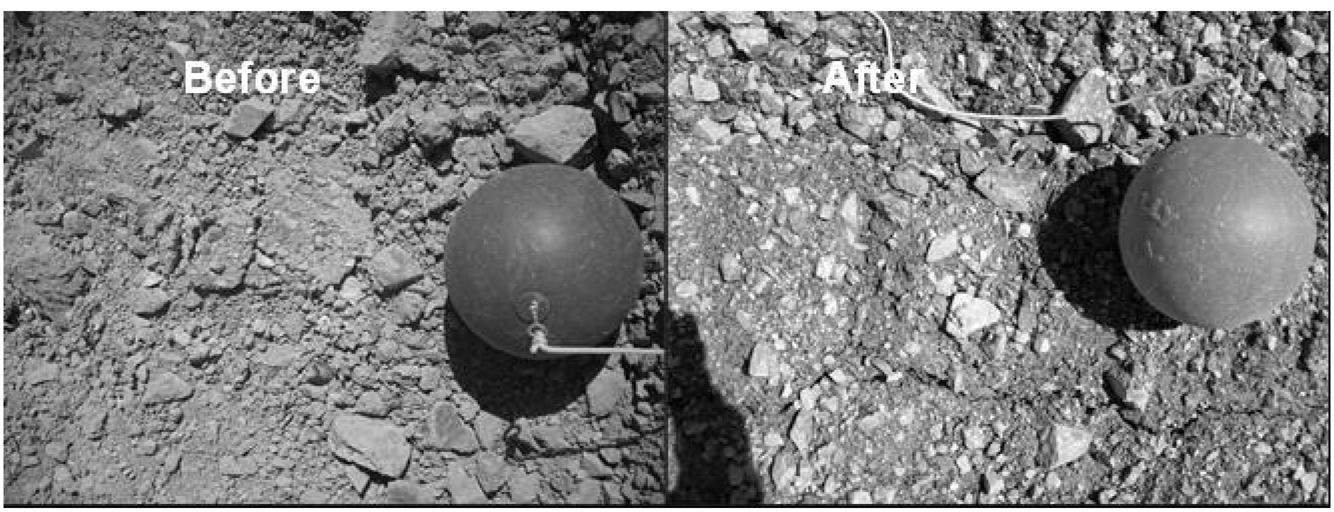

Figure 3. Comparison of argillite surface before (left) and after (right) field erosion tests

Based on the absence of rilling and cascading, the field erosion tests indicated that argillite ripped to a depth of 24-inches was the most resistant to the design-type rainfall events simulated. However, cascading of pooled water and rilling were observed where ripping was not completed perpendicular to the slope or to the specified depth (i.e. the furrows were shallow). Finally, the ripping treatments did not show effective mixing of the alluvium and argillite rock armor material.

Final Rock Armor Design

Based on borrow source material locations, haulage costs, and the desire to provide additional NNP and a plant growth media in proximity to the surface, a 30 cm layer of alluvium was selected as a subgrade for the waste rock armor material. Estimated borrow material requirements for side-slope armouring were approximately 140,000 m^3 per 10 cm depth. Argillite material was selected for slope lengths less than 90 m with arkose material selected for slopes greater than 90 m in length. Tailing side-slope reclamation occurred in a three-step process whereby the tailings slopes were regraded to 3(H):1(V) slopes, with placement of 30 cm of alluvium followed by 30 cm of argillite. Ripping was not conducted until all of the surfaces had been prepared. Quality control oversight was used to exclude visibly oxidized rock armor material at the source from placement on the side-slopes, and to ensure that ripping occurred on contours and to specified depths of 60-cm. Ripping was performed to control initial erosion rather than to promote argillite/alluvium mixing. Finally, a salt tolerant native seed mix has been hydroseeded on all of the argillite slopes and a small portion of the arkose slopes with sufficient fine-grained material. Initial germination results have been satisfactory and the slope revegetation program may be expanded in the future.

Conclusions

Results of PSD and geochemical testing on samples from six different waste rock areas indicated that argillite material from MND North and West areas and coarse arkose from SXND exhibit the most favorable characteristics for rock armor on the tailings slopes. Material from the SOD and WR3 volcanic areas did not have sufficient erosion resistance and the WR3 argillite and in-pit argillite materials showed poor geochemical characteristics (negative NNP or low pH values).

PSD results indicated that the MND North and West samples contained, on average, argillite waste rock with more than 50 percent of the rock fragments greater than 20 mm in diameter with a mean top size of 160 to 200 mm in diameter. Actual excavation of the older MND West argillite borrow area for production showed a decrease in particle size and in some cases chemical quality with depth, suggesting a breakdown of this material over time. SXND coarse arkose material contained greater than 50 percent material over 37 mm in diameter, with a larger proportion of particles greater than 100 in diameter and a top size of nearly 360 mm.

ABA results for the MND North and West argillite samples indicated generally positive NNP values and ANP/AGP ratios greater than 1.5. In addition, samples that showed significant oxidation were generally correlated with negative NNP values. The SXND arkose samples showed similar NNP values to the MND argillite samples; however, the mean pyritic AGP was approximately 50 percent lower, which indicates the arkose material should have lower rates of acid-generation and subsequent neutralization reactions that contribute to soil salinity. Soil fertility results for most of the MND North and West argillite and the SXND arkose samples showed, with the exception of copper, metal concentrations (i.e. boron, manganese, cadmium, and zinc) in the argillite and arkose material were generally below thresholds that would inhibit plant growth. Copper values above 200 ppm are considered toxic to native perennial plants (Paschke and Redente, 2002) and only one argillite and three arkose samples exceeded this value. Zinc and boron were also measured above potential phytotoxicity thresholds in a few MND North and West argillite and SXND arkose samples.

ABA results for alluvium capping material indicate low acid-generation and high acid-neutralization potential. Mixing the alluvium into the argillite or arkose rock armor would offer the benefit of increasing the fine-earth fraction to support water and nutrient retention and to reduce salinity and copper concentrations. However, ripping performed in the erosion test pads did not result in significant mixing of the argillite rock armor and underlying alluvium. Alluvium, therefore, was selected as a subgrade material to mitigate: potential subsurface erosion at the tailings/rock interfac; potential acid generation and drainage from the rock armor material and; to act as a plant growth medium.

Erosion modelling of the argillite rock armor material indicates that slope lengths less than 90 m should be maintained to minimize erosion. Whereas, the addition of vegetation is predicted to decrease the erosion rate by approximately 40%, the predicted erosion from the average argillite and alluvium mixture needed to support vegetation was approximately equal to erosion rates from the average argillite, non-vegetated condition. An increase in gravel cover due to erosion of finer particles over a three year period is predicted to futher reduce erosion by 26% to 35% for unvegetated slopes 90 m and 180 m lengths. Predicted uniform soil loss was less than 2 mm per year for all of the scenarios except for the finer-grained argillite non-vegetated condition.

The erosion test results showed that water accumulated on the argillite surface in all un-ripped and ripped argillite treatments after approximately 6 mm of water was applied. Erosion in the form of rilling or cascading over furrows occurred only in un-ripped plots or where ripping had not been completed perpendicular to the slope. PSD data indicated that neither the coarse (> 12.5 mm particles) nor the fine-earth fraction (< 5 mm) were significantly relocated by the simulated rainfall in any of the ripping treatment plots. No significant differences were observed between ripping treatments or before versus after simulated rainfall.

The final design consisted of specifying argillite waste rock material for side-slopes less than 90 m and arkose waste rock material selected for slopes greater than 90 m in length. Tailing side-slope reclamation occurred in a three-step process whereby the tailings slopes were regraded to 3(H):1(V) slopes, with placement of 30 cm of alluvium followed by 30 cm of argillite or arkose. Quality control oversight was used to exclude visibly oxidized rock armor material at the source from placement on the side-slopes, and also to ensure that post-placement ripping occurred on contours and to specified depths of 60 cm. Finally, a salt tolerant native seed mix was applied to argillite armored side-slopes and some arkose side-slope areas with initial germination success.

As a final note, argillite rock armor placement began to occur in May 2010. Two storms events in excess of the 2-year, 24-hour return period occurred on July 27 (70 mm over 1 hour) and July 30 (64 mm over 24 hours). Argillite erosion from approximately 60 m long side-slopes was minimal from these two large events even without ripping. At this time, argillite and arkose rock armor placement at the SXD portion of the Asarco Mission Mine is complete.

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