Particle Size Controls Oxidation Rate of Tailings Surface and AMD Production – Hydrologic Characterization of Ore Knob Tailing Pile

Mehrnoosh Behrooz, Robert C. Borden

[1]*North Carolina State University, Civil, Construction and Environmental Engineering, Mann Hall, 2501 Stinson Drive, PO Box 7908, Raleigh, NC, USA, smbehroo@ncsu.edu, rcborden@eos.ncsu.edu*

Abstract In the late 1950s, sulfidic tailings produced from the Ore Knob Mine (NC) were deposited in a 9 ha, 21 m high tailings pile. As the water percolates through the pile, groundwater within the pile becomes enriched in Fe (1800 mg/L) and SO_4 (4700 mg/L). Water discharges from the pile at the downstream embankment face as a series of AMD spring or seeps. Spatial variability in tailings physical characteristics causes variability in hydrological properties. This paper evaluates the connection between particle size distribution and oxidation depth and the effect of hydrological properties of the tailings.

Key Words Particle size, Acid mine drainage, Ore Knob

Introduction

Mining activity and refining processes often produce tailings containing sulfidic minerals. Oxidation of these minerals can lead to the formation of acid mine drainage (AMD) with high concentrations of dissolved iron, sulfate, acidity and heavy metals (Blowes et al. 1992; Nordstrom and Alpers 1999; Pyatt and Grattan 2001). The particle size of the tailings can have a significant impact on AMD production. Finer particles have a greater surface area which potentially increases the oxidation rate. However, the higher air filled porosity of coarse grained tailing leads to higher oxygen penetration rates and greater AMD production. More rapid water infiltration in coarse tailings can potentially dissolve and expose fresh unoxidized mineral surfaces, increasing oxidation rates (Rose and Cravotta 1999; Stumm and Morgan 1995). This paper describes AMD production at the Ore Knob Tailings pile near Jefferson, NC and the apparent correlation between particle size distribution and AMD production and transport within the pile.

Ore Knob, near Jefferson, North Carolina, is the location of a massive fissure-type sulfide deposit. The Ore Knob deposit was discovered before the US Civil War. Between 1871 and 1883, it was worked intensively, yielding 12000 ton of copper from 11 openings and one main shaft. Further mining activity was limited until the mine was reopened in the late 1950s. The extracted ore was ground in a processing facility located in the Little Peak Creek watershed. Copper, gold, and silver were extracted and the residual tailings were pumped to an impoundment located on Ore Knob Branch. The Ore Knob Tailings Pile and well locations are shown in Fig. 1. Available information suggests that the impoundment was constructed by first installing a small dam across Ore Knob Branch at the approximate location of the existing embankment face. A drop-inlet was constructed about 490 m from the embankment face. Some portion of water entering the tailings pile from the surrounding watershed enters this drop-inlet and is transported through the pile near the embankment face through a 24-inch reinforced concrete pipe (RCP). During active operation, the tailings slurry is believed to have been discharged from a distributor pipe running near the northern end of the current pile. As water from the slurry flowed south towards the drop inlet, coarse grained sediments dropped out first followed by progressively more fine grained material. As a result, tailings near the current embankment are coarse grained with high water permeability while sediments at the southern end of the pile are fine grained. Over time, the embankment forming the dam was progressively raised to provide additional storage for the accumulated tailings. The current elevation near the embankment face is approximately 6 m higher than near the drop-inlet causing water to pool in the southern portion of the pile, forming a small wetland. The tailings pile covers approximately 9 ha with a maximum tailings depth of approximately 21 m at the center of the embankment face. The Ore Knob site has recently been placed on the US Environmental Protection Agency (EPA) National Priorities List (NPL) of waste sites requiring cleanup. All data provided in this study were collected before EPA began active work at the site.

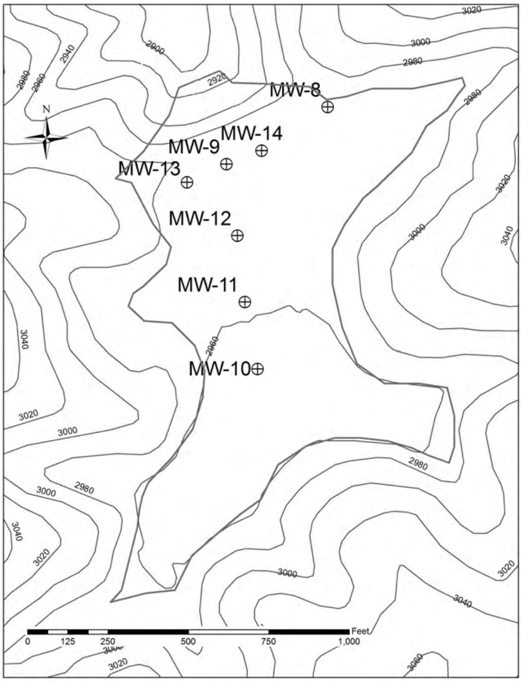

Figure 1 *Ore Knob tailing pile showing wells location*

Methods

Monitoring wells installed by hollow stem auger drilling. Depth to the reduced layer and hardpan were determined by visual observation and standard penetration test results. Hand auger borings were installed at additional locations to fill in data gaps. Ground water samples were collected using diffusion bag samplers constructed with Regenerated-cellulose dialysis membrane. Bag samplers were installed at three depths in each well separated by inflatable bladders to reduce mixing. Well installation, sampling and chemical analysis procedures are described in details in Borden and Behrooz (2008).

Results and Discussion

Water flowing through the tailings pile originates as surface runoff and baseflow from tributaries around the pile (See fig. 1), and infiltration directly through the tailings pile surface. Where the tributaries enter the pile, small pools or wetlands have formed where water is temporarily stored prior to infiltration into the pile. This water then percolates through the pile and discharges at the downstream embankment face as a series of AMD springs or seeps. Two distinct layers are present at tailings pile. Unoxidized tailings are dark gray versus brown-yellow oxidized tailings. Tailings characteristics vary spatially from fine grained (D_{50} = 25—150 μm) sediments in the upstream areas to more coarse grained (D_{50} = 90—300 μm) near the downstream embankment. In fine grained area (MW10 and MW11) oxidized yellow-brown tailings are observed in upper 0.12 m. In contrast, in coarse grained area (MW9, MW13, and MW14), oxidized zone is developed to 1 m.

The oxidation process is more intense in coarse grained area. Although fine gained tailings expose higher surface area to oxygen, larger particle size trap more air and show higher air filled porosity which results in the more intense oxidation. A hardpan is also formed at the interface of oxidized and reduced layers. Thickness of hardpan layer varies from 0.1 m at upstream location to 0.25 m at downstream location. Slug test results (Hvorslev’s method, Schwartz and Zhang 2002) are generally consistent with sediment particle size distribution. In MW10 and MW11, the fine grained tailings have a lower hydraulic conductivity is lower compared with downstream locations (MW9, MW13, and MW12) with more coarse grained tailings. Fig. 2 shows the relation between par-

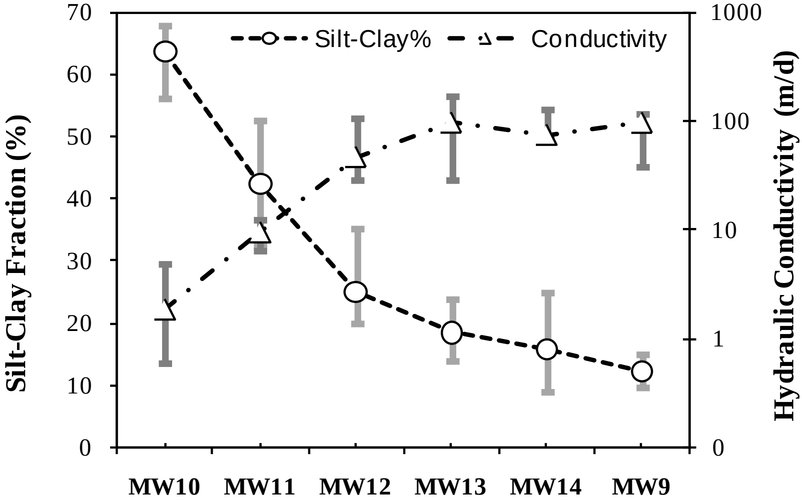

Figure 2 *Silt-clay percent and hydraulic conductivity in different locations at Ore Knob tailings pile (error bars are the range of observed values)*

ticle size distribution and slug test results. The finer grained, lower permeability sediments are hypothesized to have a lower rate of AMD production due to the lower infiltration rate and slower oxygen diffusion rate.

Fig. 3 shows average values of pH, dissolved iron (Fe), dissolved sulfate (SO_4) and hot acidity (acidity) measured in monitor wells screened in the top, middle and bottom of the saturated zone. In the most upgradient well (MW10), the ground water has a near neutral pH (6.53 to 6.63) with very low concentrations of iron and hot acidity. However, sulfate concentrations are relatively high. This suggests that AMD generated in the upstream watershed has been effectively treated prior to entering the tailings impoundment. As ground water migrates downgradient through the tailings pile, dissolved iron, sulfate and acidity increase dramatically. As ground water migrates from MW10 to MW14, SO_4 increases by an average of 40.7 mM (3900 mg/L) and Fe increases by 38.2 mM (2100 mg/L) or a ratio of 1.08 moles of SO_4 per mole Fe. This ratio is consistent with the oxidation of a monosulfide mineral (e.g. pyrrhotite) in the tailings pile. In the downgradient wells (MW13, MW9 and MW14), pH values are moderate (5.8 to 6.1), even though the groundwater contains extremely high levels of hot acidity. This apparent contradiction occurs because the acidity is present in the form of Fe^{+2}. Free protons (H^+) are not released until Fe^{+2} reacts with oxygen when AMD is discharged at the land surface. In all the downgradient wells, pH is lowest and Fe, SO_4 and acidity are highest in the top sample interval. This is consistent with recharge of concentrated AMD through the vadose zone. Readers should be aware that some mixing probably occurs in the monitor wells so the observed differences between the top, middle and bottom samples are probably the minimum that actually occurs within the pile.

Conclusion

Tailings characteristics vary spatially with more coarse grained (D_{50} = 90—300 µm), higher permeability (K= 100 m/d) sediments near the downstream embankment and more fine grained (D_{50} = 25—150 µm), lower permeability (K= 2.0 m/d) sediment in the upstream areas. The coarse sediments have a higher water infiltration rate and lower water retention which results in more rapid oxygen diffusion and greater AMD production. A distinct weathering profile has developed on the pile surface with an oxidized zone extending to 1 m in the coarse sediments which is underlain by a 0.25 m thick hardpan. In the finer grained sediments, the oxidized zone is only 0.12 m thick with a 0.1 m thick hardpan. A hydro-geochemical model is being developed to help understand the interrelationships between sediment characteristics, water flow, oxygen diffusion, and AMD production.

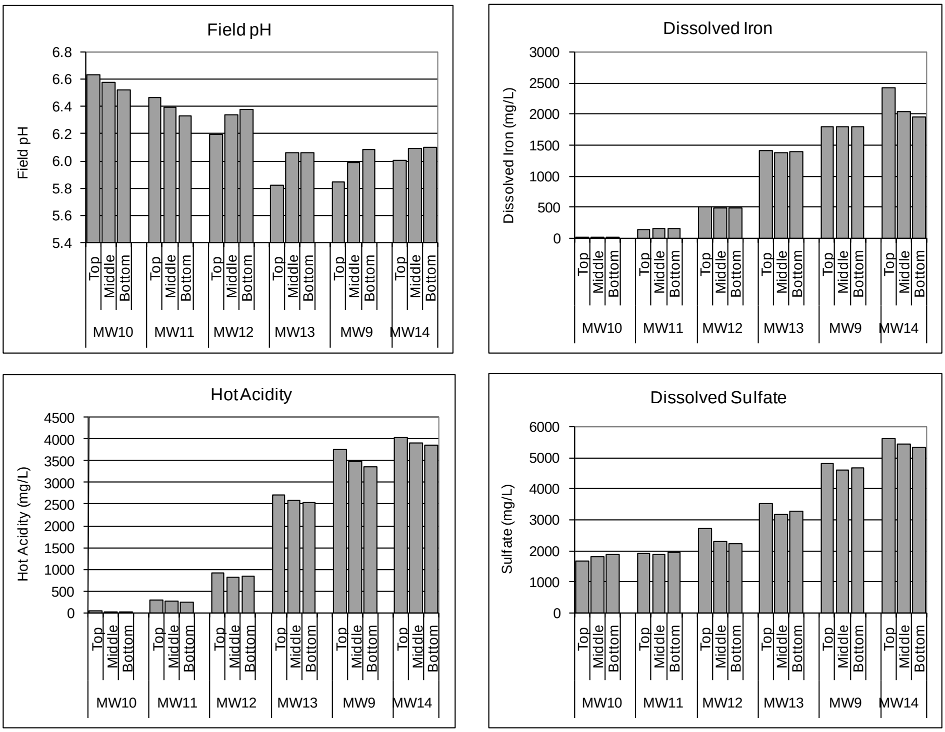

Figure 3 *Average values of field pH, dissolved iron, hot acidity and dissolved sulfate in ground water samples*

Acknowledgements
We gratefully acknowledge the financial and technical support provided by the U. S. Environmental Protection Agency and the North Carolina Division of Water Quality 319 Program.

References
Blowes DW, Jambor JL, Appleyard EC, Reardon EJ, Cherry JA (1992) Temporal observations of the geochemistry and mineralogy of a sulfide-rich mine-tailings impoundment, Heath Steele Mines, New Brunswick, Explor. Mining Geol 1:251—264

Borden RC, Behrooz M (2008) Ore Knob Mine Tailings Pile – Hydrologic and Geochemical Characterization, Report submitted to NC Dept. Environment and Natural Resources, 319 Program, Raleigh, NC

Eaton AD, Clesceri LS, Greenberg AE (1989) Standard Methods for the Examination of Water and Wastewater, 17th Edition. American Public Health Association, Washington, DC: 1989

Nordstrom KD, Alpers CN (1999) Geochemistry of acid mine waters. In: Plumlee, G.S., Logsdon, M.J. (Eds.), The Environmental Geochemistry of Mineral Deposits – Part A: Processes, Techniques, and Health Issues, Rev. Econ Geol 6(A):133—160

Pyatt FB, Grattan PJ (2001) Some consequences of ancient mining activities on the health of ancient and modern human populations. J. Pub. Health Med 23:235—236

Rose AW, Cravotta III CA (1998) Geochemistry of coal- mine drainage. In: Smith, M.W., Brady, K.B.C. (Eds.).

Schwartz FW, Zhang H (2003) Fundamentals of Ground Water, John Wiley & Sons, New York, 583 pp

Stumm W, Morgan JJ (1996) Aquatic Chemistry, Chemical Equilibria and Rates in Natural Waters, 3rd ed. Wiley, Canada