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Tailings Dust Emissions

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Tailings Dust Emissions

WERC 2017

TASK # 3

The Dust Busters

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Tailings Dust Emissions

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EXECUTIVE SUMMARY

Fugitive dust emissions from the storage and handling of mine tailings presents environmental and safety concerns, which must be addressed to promote the land sustainability and the health and safety of individuals around a tailings storage facility (TSF). The investigated dust control methods were agglomeration, binder slurry injection, and topical spray.

The Dust Busters determined that pelletizing was the most practical method of agglomeration. In order to produce durable pellets from the mine tailings, which consist primarily of silica, a binder must be added. A variety of binders were considered including magnesium and calcium chloride, bentonite, barite, cement, vinyl polymers, acrylic polymers, starch, carboxymethyl cellulose, and a commercial lignosulfonate/bitumen blend. Portland cement proved to be the most effective binder in regards to the pellet’s cost, structural integrity, and longevity. However, due to the abrasive nature of the tailings, pelletizing is not cost effective in comparison to other dust suppression techniques.

Binder slurry injection incorporates a pugmill mixer to inject a binding agent into the tailings slurry. Addition of a binder allows the slurry mixture to form a rigid crust that prevents fugitive dust once dried on the existing tailings dam. While the injected slurry is effective at minimizing dust emissions, it is not economically feasible due to high capital costs.

The most effective, environmentally safe, and economically feasible solution to reduce the dust associated with tailings storage facilities is a topical spray solution consisting of a vinyl copolymer. The vinyl copolymer, at relatively low concentrations, produces a robust yet permeable crust along the surface of the tailings, which is unmatched in comparison to the other binding agents. By applying the binder as topical solution rather than injecting the binder into the slurry, the capital cost for effective dust suppression is reduced by eliminating the additional process equipment required for both pelletizing and binder slurry injection. Treating 400 acres per year with a vinyl copolymer application costs $110,000. Existing equipment and personnel are adequate to change from the current magnesium chloride treatment to a vinyl copolymer treatment. Current yearly treatments using the magnesium chloride cost approximately $240,000-$720,000 assuming 1-3 applications per year across the 400 acre area; thus changing to a vinyl copolymer treatment will save $130,000-$390,000 per year.
INTRODUCTION

Mine tailings storage facilities (TSF) are the accumulation of waste products from mining and beneficiation operations. Subsequently, the storage and handling of this waste product is of great importance when minimizing the environmental impact of mining operations. Tailings consists of gangue material and are discharged as a slurry to the TSF. The composition of the ore within a mine varies; consequently, the composition of the slurry also varies. The variability of the tailings requires a TSF that can handle a plethora of different slurry compositions.

Mine tailings, being a waste product of no economic value, are stored in the most cost effective way possible in order to meet environmental regulations. Having responsible and enforced environmental regulations is of great importance to protect not only the environment, but also the health of individuals and biota in and around the tailings facility.

DESIGN BASIS

Many site-specific parameters affect the design, stability, and operations of the TSF. As a result of these differing parameters between mines, the type of storage facility is unique to the site and is dependent upon geographical features of the area. Upstream (Fig. 1), downstream (Fig. 2), and centerline (Fig. 2) are three common raised embankment designs used to contain the tailings. If the facility is located in a low risk seismic and arid area, then an upstream raised embankment is an optimal choice because of its low initial cost. Upstream tailings dams start with an initial free draining foundation consisting of the coarse mine tailings. They are constructed using hydrocyclones where the underflow material is used to build the dam and the overflow is sent to the beach and the tailings pond of the facility. The elevation of this dam should only grow three to five feet a year to ensure dam stability; this is important to prevent a liquefaction failure event. The dam will grow from the outside rim towards the pond. This requires a large, gradual sloping beach to ensure the water drains towards the pond and never encroaches on the dam.
Chino Mine Visit

The Freeport-McMoRan Chino Mine is a copper mine located 15 miles east of Silver City, New Mexico. Chino’s TSF (Fig. 3), which the Dust Busters had the opportunity to tour, is constructed with an upstream design. In this design, the underflow stream from the hydrocyclone is deposited upon the embankment, which gives rise to a new wall that supports the top of the slope to the beach. As the elevation of the embankment increases over time, the embankment shifts toward the center of the tailings storage facility.

At the Chino mining facility, a 45 weight percent solids tailings slurry is pumped 16 miles from the thickener to the TSF at a rate of 12,000 gpm. A process flow schematic of the hydrocyclone skids is given in Figure 4. Once the slurry has reached the TSF, it is divided and fed to four hydrocyclone skids that produce two streams: an underflow stream and an overflow stream. The underflow streams, with flow rates of 470 gpm per skid, are used in the building of the dam and have a coarse solids content of 80 weight percent. The overflow is discharged to the beach at a rate of 2530 gpm per skid and consists of 37 weight percent fine solids. The Dust Busters were given the opportunity to take samples of the underflow to use for bench scale testing. Therefore, all experimentation was conducted using actual copper mine tailings, improving the accuracy of the testing results.

The majority of the dust emissions are from the 400 acre area of the dam comprised of the outer berm and the road. The Chino mine builds its dam at a rate of 3-5 feet per year while
only working on half of the dam at a time. The hydrocyclones are elevated on cranes, which allows for them to be easily relocated along the 4-mile long dam face [2].

**Figure 4. Process Flow Schematic of Hydrocyclone System**

**Nature of the Material**

Chief concerns with tailings are its abrasive, incompressible, and poor flow characteristics. Using the environmental scanning electron microscope and energy-dispersive X-ray (ESEM-EDX) available through the nanotechnology department at the University of Arkansas, the composition of the dry tailings sample was confirmed to consist of primarily silica. Another complication that arises when dealing with mine tailings is the variability in the granule size, as evidenced by the images from the SEM as shown in Figure 5. The copper wire in Figure 5 is 152.4 microns. The largest particle size is about 600 microns and the smallest particle size is about 70 microns.

**Figure 5. Copper Mine’s Underflow Tailings under SEM (left) and light microscope (right)**
The behavior of the tailings slurry emulates the material’s handling difficulties. The underflow solids quickly dewater, resulting in a sand-like sludge. However, the hydrocyclone underflow will flow freely as long as it keeps moving and does not dewater. The slurry material exits the hydrocyclone and freely flows down the slope of the beach. The angle of repose of the underflow material poured on a flat surface was found to be 20 degrees as shown in Figure 6. A slump test (Fig. 6), a common test used to characterize concrete, was conducted on a settled sample of the underflow slurry. The resulting angle of repose was essentially 90 degrees. As the angle of repose increases, the slurry’s ability to flow decreases.

Figure 6. Angle of repose of the tailings underflow slurry

**Current Common Dust Mitigation Methods**

The most commonly used methods to mitigate dust at mine tailings storage facilities is the topical spray application of magnesium chloride or other salt solutions. The salt solutions are applied with a composition of 35 volume percent salt and 65 volume percent water [3]. The liquid mixture is sprayed via spray trucks at approximately 0.5 gal/yd² as needed. Although the salts are effective dust suppressants, they have a short effective life span when compared to other dust suppressants. Salt solutions are reapplied 2 to 3 times per year or as needed.

Hay crimping controls erosion and prevents fugitive dust emissions [4]. A crimper, tractor attachment, uses a serrated disk with blades that are approximately 20 cm apart from one another. The crimper pushes the hay into the tailings and causes the hay to be locked in a vertical position. Anchoring the tailings with hay reduces the dust emissions. Hay’s cellular structure allows for the retention of water within the cell wall. With prolonged water retention, the tailings remain wet for longer periods of time and tailings dust emissions are reduced. The recommended application rate is 2 tons of hay per acre.
**Key Materials Considered**

**Magnesium Chloride and Calcium Chloride:** Magnesium chloride, MgCl₂, consists of Mg²⁺ ions and Cl⁻ ions. Polar water molecules are able to surround and pull apart the Mg-Cl bonds in solution which forms a clear, deliquescent liquid. This liquid forms a thin coating on each particle of dust, holding the fines in place [5]. Chlorine ions absorb moisture from the air, keeping the road damp even under dry conditions. The moisture film provides a cohesive force that binds aggregate particles together, resulting in a hard and compact surface. MgCl₂ starts to absorb water from the air at 32% relative humidity, almost independent of temperature.

Accumulation of chloride can cause negative effects on the chemical properties of the soil and its ability to retain water, both of which are important to plant growth and erosion control. On the other hand, magnesium and calcium can improve soil structure by causing soil particles (particularly clays) to form aggregates, improving drainage. Biota is negatively impacted by absorption of chloride through the plant roots, or from accumulating on the surface.

**Bentonite:** Sodium bentonite clay belongs to the smectite group which is a group of clay minerals that is able to expand and contract their structures in one dimension as they absorb or lose water [6]. The structural layers of swelling clays have a small negative charge and therefore attract H₂O molecules or other polar molecules into the interlayer area, causing expansion. Bonding, between the shared interior oxide anions and the cations, links the layers together and yields the unique sheet structure characteristic of clay minerals. The interparticle porosity of bentonite clay is estimated to be less than 3% [7]. There are no apparent environmental concerns with bentonite clay.

**Cement:** Portland cement is one of the most common materials used in modern day society. It is made by taking limestone and shale, mud, or clay and heating it to extreme temperatures. During the heating, water and carbon dioxide are released. When portland cement is mixed with water, a hydration reaction occurs. Coarse and fine aggregate are added to help with the strength of the concrete once it cures. There are two main components of the portland cement that are essential to the properties of the hardened product. Tricalcium silicate is the first to react with water, and is responsible for the initial strength, and dicalcium silicate begins to react with the water after the tricalcium silicate reaction. This reaction can take up to thirty days to go to completion. It takes seven moles of water to react with two moles of tricalcium silicate or dicalcium silicate [8]. Portland cement is basic on the pH scale, so one concern was how it
will affect the free water recycled back to the mine. During the visit to the Chino Mine, it was understood that the recycled water in the reclamation pond had a pH around 10. Tests were conducted in the pelletizing process to observe the pH of free water using cement and using no binder. The pH of the free water with no binder was 7.5 and the pH with cement was 9. Since this measured pH is similar to that of the reclamation pond, the pH is not a significant concern.

According to the EPA, between 1,984 and 2,425 pounds of carbon dioxide is emitted for every 2,205 pounds of portland cement produced in the U.S. [9]. Thus, the carbon dioxide emission should be considered as an environmental concern.

**Vinyl Polymers and Copolymers:** The main vinyl polymer considered was Polyvinyl acetate, an amorphous thermoplastic made by free radical polymerization. The acetate groups on the polymer are hydrophobic. They repel water and agglomerate together suspended in the water to create a strong film. The porosity of the planar copolymer film is between 80-87 percent [10]. The polymer solution has no negative effects on biota or the soil, and is entirely biodegradable. Copolymers are created by crosslinking polymers to combine desired behaviors and characteristics of various monomer chains. The strength of the crosslink bonds is responsible for the durability and the longevity of the polymer film.

**Acrylic Polymers:** Acrylic polymers exhibit dust control characteristics by forming a film over the top of a substrate through coalescence [11]. This film forms as the water evaporates from the polymer and water mixture. The acrylic polymers are spherical in shape, and as the mixture dries, the polymer spheres are packed closer together. Eventually these spheres begin to deform and partially combine with one another. This phenomenon forms a film on the surface of the substrate and works to keep the dust from leaving the surface.

**Starch:** Starches are polysaccharides that consist of repeating glucose units. The starch molecules have a linear structure called amylose and a branched structure called amyllopectin. Both structures use hydrogen bonding and radially arrange themselves in layers to form granules. When starch is heated in water, the water absorbs into the starch granule from the outside to the center. Once the granule is fully hydrated, the hydrogen bonding between the linear and branched structures maintains the integrity of the granule and begins to swell from the center. It then gelatinizes, and the swollen granules form gels and films to hold molecules together [12].

**Carboxymethyl Cellulose:** Carboxymethyl cellulose (CMC) is a derivative of cellulose [13]. The ionic sodium carboxymethyl cellulose is used in the mining industry as a binder for
metal ore pellets and a modifier in the flotation process. CMC minimizes pellet deformation, increases the strength and durability of pellets, and provides control over the water content within the pellets. CMC is used as a modifier in flotation tanks to change the physical properties of the ore rock. The organic CMC is used to modify the viscosity of the solution in order to separate the valuable minerals, such as copper, from the gangue material.

**Lignosulfonate:** Lignosulfonate is a water-soluble anionic polymer byproduct of the paper manufacturing process. It acts as a dust suppressant due to its large size and affinity for binding with other polar and nonpolar compounds. The smaller dust compounds adsorb to the lignosulfonate and form a larger, heavier complex that is not as friable, suppressing the dust. While this compound is water soluble, it becomes insoluble after prolonged exposure to solar heating. This polymer is effective at dust suppression in arid environments and is inexpensive. However, the increased demand in other industries for lignosulfonate is causing the price to rise over time and makes the product increasingly difficult to obtain. Lignosulfonate negatively affects the environment if poorly handled or applied. If large quantities of lignosulfonate were to be released in surface water, it would decrease the oxygen levels reducing biological activity of the applied area. Other considerations are that it is corrosive to aluminum, odorous and sticky, and does not bind well with areas that are previously treated with a chloride solution [14].

**Asphalt:** Asphalt is the bottom of the barrel product of crude oil and is relatively inexpensive. One concern with the use of asphalt material is the possibility of leaching to occur. Polycyclic aromatic hydrocarbons (PAH) and heavy metals found in asphalt have had the tendency to leach out of the asphalt during rain. The PAH can contain carcinogens and other toxic compounds. Tests have been conducted to determine how much leaching occurs, and most studies have shown that the amount leached into the water is within the regulatory limits [15].

**PELLETIZATION AND AGGLOMERATION**

**Process Considerations**

One practical way to mold mine tailings into natural clods or peds would be to use an industrial sized pelletizer or briquetting machine. Pelletizers are commonly used in the iron, feed, and wood industries to create pellets. Briquetting machines are used to form coal and charcoal briquettes (Fig. 7). The various types of pelletizers found in industry are ring die (Fig. 7), extrusion, piston press, and flat die pelletizers.
Each pelletizing or briquetting process poses their own advantages and disadvantages associated when handling mine tailings. The abrasiveness of the tailings, caused primarily by the silica content, is problematic for both pelletizing and briquetting machines. Several vendors in the pelletizing and briquetting industry mentioned every die or rotating part in these machines that comes into contact with the tailings would need to be replaced once every 2 to 4 weeks. The tailings granules do not bind with themselves except under high pressures. The use of an external binder is required to create a strong pellet that is resistant to rain. The fluid properties of the slurry is dependent on the water content. This can be an issue inside a pellet mill. Most pellet mills have a narrow window of water content in which the mill can function. A layer of non-friable pellets is effective at abating loose dust at the tailings storage facility from blowing in the event of high force winds.

One major component of the pelletizing process is choosing which stream to pelletize. As mentioned previously in the paper, the hydrocyclone has two exit streams: the overflow and the underflow. After conducting tests of pelletizing underflow and overflow streams, it was concluded that the only feasible option for pelletizing is the underflow. The difference between the slurried and dry underflow material is that during the pelletizing, the excess water in the slurried underflow is pressed out, and the dry underflow would just be the material on the dam after the water has drained from it. The reasoning for choosing the underflow is the relative particle size.

**Experimental Equipment**

Bench scale pelletizers were machined to replicate industrial scale pelletizers in order to determine their efficacy. At first, pellets were made using a hand press with a lever arm that forced the mine tailings through a cylindrical cavity. A simple punch and die was used in conjunction with the press to form the pellets. The applied pressure was approximately 7000 psi.
However, large scale pelletizers can generate a force much larger than this. To simulate an industrial pelletizer, and to minimize the amount of binder required, the pressure was increased by transitioning to a twelve ton hydraulic press (30,000 psi).

The next type of pelletizer that was created to simulate a large scale continuous design was an extruder. The extruder forces the tailings through a ½ inch orifice from a 1 inch ID feed chamber (Fig. 8). A knife was used to cut the extrusion into segments.

The extrusion process was unsuccessful. When pressure was applied, free water would drain out of the bottom, and moist tailings would clog the orifice of the extruder.

An agglomeration drum was considered to create a nodule or ped. Agglomeration drums are traditionally used in the heap leaching process for ore extraction. After talking with several vendors, they feel that they may be able to agglomerate this material with the addition of a correct matrix of specialty binding agents. One downside of the agglomeration process is that due to the volume of material to process, it would require more than one drum, and each drum would cost approximately $1,000,000 [17]. This agglomeration process was researched on the bench scale in the lab at the University of Arkansas with unsuccessful results. Vinyl copolymers and clay were used to help the material bind with itself, but no successful nodule was made with any amount of binder. Therefore, the process of agglomeration drums was eliminated.

The hydraulic press was then used to generate one inch diameter pellets with the apparatus in Figure 9. This method generated suitable pellets, but does not mimic any large-scale practical processes.

Figure 8. Extrusion-Style Pelletizer

Figure 9. Hand Press (left) and Hydraulic Press (right)
Experimental Procedure and Results

The binding agents that were considered for pelletizing were a commercial lignosulfonate/bitumen blend, bentonite, cement, asphalt, corn starch, and spray starch. Experiments were conducted using these pellets to simulate the environment at a TSF. These tests included simulating rain, wind, and the hot, arid environment. The Southwest United States, although arid, is prone to short, heavy rainstorms. To simulate the worst case scenario of this environment, the pellets were tested under a hose with a nozzle attachment at a rate of 1 L/min. The pellets were exposed to the rain simulation until the pellet dissociated or an hour passed. The friability of the pellets was qualitatively tested in conjunction with the rain simulation, and the friability was rated on a scale of 1 to 5 with 5 being the most friable.

Table 1. Dissociation and Friability Test Results

<table>
<thead>
<tr>
<th>Pellet</th>
<th>Binding Material (wt%)</th>
<th>Length (in)</th>
<th>Diameter (in)</th>
<th>Time to Dissociate</th>
<th>Friability Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1% Bentonite</td>
<td>1</td>
<td>1</td>
<td>3 min 18 sec</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Tailings Only</td>
<td>1</td>
<td>1.125</td>
<td>1 min 23 sec</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>0.5% Cement</td>
<td>1</td>
<td>1.125</td>
<td>3 min 11 sec</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>1% Cement</td>
<td>1</td>
<td>1</td>
<td>5 min 5 sec</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>1.5% Cement</td>
<td>1</td>
<td>1.0625</td>
<td>Did not dissociate</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>2% Cement</td>
<td>1</td>
<td>1.25</td>
<td>Did not dissociate</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>0.5% Lignosulfonate/Bitumen Blend</td>
<td>0.5</td>
<td>1</td>
<td>Did not dissociate</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>2.5% Asphalt</td>
<td>0.5</td>
<td>1</td>
<td>7 min 45 sec</td>
<td>4</td>
</tr>
</tbody>
</table>

A qualitative test was conducted to determine a 3 inch layer of pellets’ ability to mitigate fugitive dust emissions at elevated wind speeds using a leaf blower (approximately 60 mph winds). A wind tunnel was built with plywood and polycarbonate (Fig. 10). This design produced a uniform wind profile.

Figure 10. Wind Tunnel Apparatus
A 3 inch layer of the various pellets was placed atop a 500 g sample of dry tailings. The leaf blower was used to simulate up to 60 mph winds for a period of approximately 1 minute. This test proved that at wind speeds of approximately 30 mph pellets were effective. However, as the wind speed was increased, the pellet bed was disturbed and the concealed dust was entrained. The final test that was conducted on the pellets was the thermal resistance test. Since most mines are located in arid and hot environments, the pellets would be exposed to temperatures of over 100 °F for long periods of time. These conditions were simulated on the pellets by placing them in an oven at 150 °F for 8 hours and observing the effect on the friability and strength of the pellets. The results proved that all the pellets tested were thermally resistant.

Bentonite was a viable option for binding the mine tailings. Pellets formed using bentonite at compositions as low as 0.5 weight percent were strong and not friable. During the rain test the bentonite pellets disassociated after a few minutes. Like the bentonite, asphalt proved to be an effective binder and created a non-friable, strong pellet. The asphalt pellets lasted for seven minutes during the rain simulation. Corn starch and spray starches were also considered for testing. The starches required heating before addition with the tailings, and this is not viable for the full scale process. Another viable option that was considered was a pellet with 0.5 weight percent of a commercial lignosulfonate/bitumen blend. The main concern with the blend and lignosulfonate in general stems from the availability limitations. No supplier was found to provide the lignosulfonate at a competitive cost compared to the other binders considered. Portland cement was the final and most cost effective binder. Cement created a strong and non-friable pellet that did not disassociate during the rain test. Concerns associated with cement include its pH effects on the retention pond water and its carbon dioxide emissions. However, these effects were deemed insignificant in comparison to the environmental benefits of dust control. Regardless of the effectiveness of the binder in producing pellets, the pelletizing process as a whole is not economically feasible. A commercial pelletizer does not exist that is able to effectively process the high volume and abrasive nature of the tailings slurry without substantial operating cost.
Bench Scale Apparatus

Dust Busters designed and fabricated a single cavity bench scale apparatus (Fig. 11). The inner semicircle allows the hydraulic piston to compress the tailings and form a pellet. Removal of the inner semicircle allows for the ejection of the pellet by the hydraulic piston.

To represent the full scale production of the hydraulic press, Dust Busters designed a hydraulic piston press. This design is able to process the abrasive material and is rated for the required high pressure.

Full Scale Design

To create these pellets, 2 percent of the underflow from one hydrocyclone skid will be utilized. The underflow stream will be fed to a pugmill mixer, with counter-rotating blades, where it will be mixed to a composition of 1.5 weight percent portland cement. The blended stream will then be sent to one of six pelletizers (Fig. 12). To feed this machine, a hopper with mechanical agitation is positioned over the die to ensure that the slurry continuously moves, preventing clogging of the hopper and completely filling the cavities beneath them.
A rotating die with cavities will be filled with tailings from this hopper. As the die rotates, one piston will compress the material in the cavity, and another piston will discharge the pellet from the die. Pellets that are 1 inch in diameter will be created and the free water present in the slurry will be distributed onto the free draining surface of the dam (Fig. 13).

The pellets will be used to create a 3 inch cap on the dam of the TSF (400 acres) and will be spread out using a front end loader. The packing density of the pellets is 88.5 lb/m³, therefore 389 million pounds of pellets will be required to cap the entire facility once. As the dam grows, pellets can be dispersed where needed to mitigate dust emissions.
Economic Analysis

The pelletization solution was found to have high capital and operating costs. The abrasive nature of the tailings wears out the dies in one month. Maintenance, materials and capital costs for pelletization process can be found in Table 2. The capital cost includes the six pelletizers and six pug mill mixers. Four separate commercial vendors were consulted about the economic feasibility of the pelletization process. All vendors confirmed the Dust Busters’ conclusion that the material was too abrasive in nature to operate normally in a commercial pelletizer, resulting in extreme maintenance costs. Two operators would be required for the operation of the pugmill mixers and pelletizers. The cost listed for the portland cement includes both raw material cost and the cost of transportation to the mining facility.

Table 2. Pelletizer Cost Analysis [18]

<table>
<thead>
<tr>
<th>Pelletizing Costs</th>
<th>Assume 1 Month Part Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replacement Die ($/year)</td>
<td>$34,800.00</td>
</tr>
<tr>
<td>Replacement Rolls ($/year)</td>
<td>$36,000.00</td>
</tr>
<tr>
<td>Replacement Wear Ring ($/year)</td>
<td>$5,400.00</td>
</tr>
<tr>
<td>Total Maintenance Per Machine ($/year)</td>
<td>$76,200.00</td>
</tr>
<tr>
<td>Portland Cement Binder Cost ($/year)</td>
<td>$291,443</td>
</tr>
<tr>
<td>Operator Costs (2 added shift positions)</td>
<td>$600,000.00</td>
</tr>
<tr>
<td><strong>Total Maintenance + Binder + Operator Cost 6 machines ($/year)</strong></td>
<td><strong>$1,351,495.00</strong></td>
</tr>
<tr>
<td>Capital Cost - 6 Pugmill Mixers</td>
<td>$510,000.00</td>
</tr>
<tr>
<td>Capital Cost - 6 Pelletizing Machines ($)</td>
<td>$578,400.00</td>
</tr>
<tr>
<td><strong>Total Capital Cost</strong></td>
<td><strong>$1,088,400.00</strong></td>
</tr>
</tbody>
</table>

UNDERFLOW SLURRY INJECTION

An alternative solution investigated was the injection of a binder into the underflow slurry exiting the hydrocyclone. The mixture creates a cap on top of previously existing piles of tailings, which dries and forms a porous but rigid crust. This solution ensures that each newly poured section of the TSF would be protected by the dust control method.

Bench Scale Experimentation

The most important consideration when designing the underflow slurry injection process was determining the binding additive. Cement and asphalt were quickly eliminated during initial testing as the resultant slurry mixture was impervious to water and would lead to rainwater runoff. Starch was also eliminated due to the difficult process of gelatinizing the mixture, namely the requirement of heating that would add an additional, and expensive, step to the full scale
design. The remaining materials (commercial vinyl copolymer, commercial acrylic polymer, bentonite, lignosulfonate, and chloride salts) were then subjected to bench scale wind, rain, and thermal resistance tests.

**Slurry Wind Resistance Testing Procedure:** Dry tailings were measured and loaded onto 8 inch by 11 inch plots of sandpaper trays to mimic the rough texture of the dam surface. A 500 g underflow slurry mixture and each binder were poured on the dry tailings to mimic the slurry cap. The slurry samples were allowed 24 hours to dry and were then loaded into the same wind apparatus used with the pellet wind testing (Fig. 10). The plots were subjected to 30, 45, and 60 mph wind speeds. The remaining mass on the plots were recorded and the mass retained was calculated. The visibility of the dust emissions was rated on a scale from 1 (holding together) to 5 (immediately blowing off).

**Water Longevity Testing:** Slurry samples were placed on testing trays and subjected to a simulation that replicated 1 inch of rain. Three rain cycles were used to analyze the longevity of the slurry solutions. Each sample was given a rating from 1 (crust integrity maintained) to 5 (complete loss of crust integrity). The goal of this performance test was to determine the longevity of each proposed mixture. By simulating multiple rain events, the Dust Busters were able to effectively model the durability and estimated lifespan of each method of dust control.

**Thermal Resistance:** To determine the slurry’s ability to withstand high temperatures, the slurries were mixed and placed in a heating oven at 150 °F for 8 hours. A rating system based on crust integrity was used to judge the slurries ability to withstand high thermal exposures. The system ranges from 1 (no observable changes) to 5 (complete loss of crust integrity).

**Results:** During testing, the angle of the jet stream lifted a portion of the tailings. These portions flew off as chunks. The chunks were collected because they retained their shape, and their masses were recorded separately from the rest of the sample. At a TSF, the tailings would not be susceptible to a direct jet stream shearing off except for at the berm near the top of the tailings dam. The average humidity in Arkansas is greater than the expected humidity in New Mexico, which skews the results of deliquescent materials such as MgCl₂. The commercial vinyl copolymer outperformed all other considered binders based on cost and effectiveness.
Table 3. Results of underflow slurry injection testing

<table>
<thead>
<tr>
<th>Additive</th>
<th>Mass Retention Percentage</th>
<th>Dust Visibility Rating</th>
<th>Rain Resistance Rating</th>
<th>Thermal Resistance Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Vinyl Copolymer</td>
<td>95%</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>½ Dosage Commercial Vinyl Copolymer</td>
<td>96%</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1 wt% Bentonite</td>
<td>96%</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Chloride Salts</td>
<td>96%</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Lignosulfonate Blend</td>
<td>0%</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Commercial Acrylic Polymer</td>
<td>46%</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**Bench Scale Mixer:** To effectively mix the binders with the slurry, several industry experts and vendors recommended that a pugmill mixer would offer the best performance [19]. A bench scale pugmill was fabricated to examine how it handled the underflow slurry (Fig. 14).

The mixer shaft and feed hopper were constructed from plywood. The two corrugated augers were made from high-density polyethylene so that modifications could be easily made. A small electrical motor was used to drive the augers. A helical auger was not ideal because all the material would pile up at the discharge end of the mixer, even with slow rotation of the augers. To solve this issue, sections of the helices were removed to increase residence time. This increases mixing as well. At the discharge, a PVC chute allows the slurry to flow onto a tailings sample where the slurry dries and forms a crust.

**Full Scale Design**

The underflow stream exiting the hydrocyclone will be sent to a portable pugmill mixer (Fig. 15). The binder blended slurry will exit the mixer and be spread on the dam of the TSF using the proper earth moving equipment. This process will only be used to create a cap over the tailings dam and will not run continuously.
The area of the dam that the underflow slurry would cap is 400 acres. The underflow volumetric flow rate for each hydrocyclone is 63 ft³/min. Assuming that the four hydrocyclone skids operate in six month cycles, each hydrocyclone is responsible for 50 acres per cycle. A minimum 2 inch layer is desirable. Assuming that the hydrocyclone skids are moved once a week, each hydrocyclone is responsible for 2 acres/week. The volume required for one hydrocyclone to form a 2 inch layer per week is 14,000 ft³. At these process conditions, it would require 3.73 hours to create a 2 inch layer. The mass flow rate of the underflow is 9,850 lbm/min. 2,206,400 lbm of underflow would be treated with a binder for the last 4 hours of operation in a week. The full scale slurry process is illustrated in Figure 16 below.

**Figure 16. Process flow diagram for full scale underflow slurry injection**

**Economic Analysis**

The underflow slurry injection process is expensive due to high capital costs. One pugmill mixer costs $330,000; four mixers are required to process the underflow slurry from the
four hydrocyclones. The operation of the mixers requires an additional operator shift position, costing $300,000 per year. The purchase cost of the vinyl copolymer is the least expensive portion of this solution method, costing $111,000 per year (Table 4). This is based on an application rate of 137.5 gal/acre of tailings coverage. However, this solution method is not recommended due to the high capital costs as shown in Table 5.

Table 4. Injection Binder Cost Comparison

<table>
<thead>
<tr>
<th>Binder</th>
<th>Lignosulfonate/Bitumen Blend</th>
<th>Diluted Commercial Vinyl Copolymer</th>
<th>Commercial Vinyl Copolymer</th>
<th>MgCl₂</th>
<th>Bentonite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of binder needed per year</td>
<td>19,968 gal</td>
<td>55,472 gal</td>
<td>110,944 gal</td>
<td>342,619 gal</td>
<td>2295 tons</td>
</tr>
<tr>
<td>Cost</td>
<td>$6.20/gal</td>
<td>$2/gal</td>
<td>$2/gal</td>
<td>$0.70/gal</td>
<td>$0.06/lb m</td>
</tr>
<tr>
<td>Cost per year ($/year)</td>
<td>$121,400</td>
<td>$111,000</td>
<td>$221,900</td>
<td>$238,200</td>
<td>$275,400</td>
</tr>
</tbody>
</table>

Table 5. Final Injection Solution Cost Analysis

<table>
<thead>
<tr>
<th>Slurry Injection Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Cost - Pugmill Mixer</td>
</tr>
<tr>
<td>Total Capital Cost (2 Mixers)</td>
</tr>
<tr>
<td>Vinyl Copolymer Cost ($/year)</td>
</tr>
<tr>
<td>Operator Cost (1 shift position added)</td>
</tr>
</tbody>
</table>

**TOPICAL SPRAY**

The final solution method considered for mitigating the fugitive dust emissions was topical spray solutions.

**Bench Scale Experimentation**

The bench scale experimentation for the topical spray solution was performed using the same methodology as the slurry experimentation, utilizing the wind resistance test, water longevity test, and thermal resistance test. Sample sizes of 88 in² were also used for consistency among the samples. Table 6 below illustrates the results of the bench scale testing.

Table 6. Results of topical spray testing

<table>
<thead>
<tr>
<th>Additive</th>
<th>Mass Retention Percentage</th>
<th>Dust Visibility Rating</th>
<th>Rain Resistance Rating</th>
<th>Thermal Resistance Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Vinyl Copolymer</td>
<td>96%</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>½ Dosage Commercial Vinyl Copolymer</td>
<td>96%</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Chloride Salts</td>
<td>95%</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Lignosulfonate Blend</td>
<td>0%</td>
<td>4</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Acrylic Polymer</td>
<td>92%</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
The diluted commercial vinyl copolymer was selected as the most effective binder to be used in the topical spray, as it performed well under all three performance tests. An additional benefit of the vinyl copolymer is its lack of environmental concerns. The polymer is not harmful to biota and is entirely biodegradable, eliminating the possibility of further waste generation. This means that the treated tailings can easily be reclaimed without concern of the binder eroding machinery or further contaminating the tailings waste.

**Full Scale Design**

The full scale implementation plan maintains simplicity as shown in Figure 17. The proposed topical spray is a commercial vinyl copolymer which would be delivered to the TSF as a concentrated liquid. This would be provided via a 5,000 gallon tanker truck. The vinyl copolymer could be stored in bladder tanks on site and would be spread on the tailings using a commercially available hydroteeder vehicle with a 3,000 gallon working capacity.

The polymer and water would be fed to the truck at a concentration of 11% vinyl copolymer by volume; no additional mixing is required. It is recommended to spray the vinyl copolymer onto any area with dust issues. The time between applications can be up to one year. For an upstream dam like the Chino Mine, the outside face and top of the dam are the main contributors of dust emissions. The benefit of using the topical spray application method for dust control is that it can be easily transferred to all mining facilities without changes to the application process. Additionally, the topical spray can easily be reapplied as needed, making it the most flexible and guaranteed successful control method.
Economic Analysis

The key advantage of this solution method is the low cost of the process in comparison to the high capital costs associated with the pelletization and injected slurry solutions. As shown in Table 7, the majority of the cost comes directly from the raw materials.

Table 7. Cost Comparison for Topical Spray [20]

<table>
<thead>
<tr>
<th>Binder</th>
<th>Lignosulfonate/ Bitumen Blend</th>
<th>Diluted Commercial Vinyl Copolymer</th>
<th>Commercial Vinyl Copolymer</th>
<th>MgCl₂</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Cost per year ($/year)</td>
<td>$121,400</td>
<td>$111,000</td>
<td>$221,900</td>
<td>$238,200</td>
</tr>
</tbody>
</table>

The only associated capital costs are those for the spray booms required, though many mining facilities may have these available on site. The use of topical spray does not require any additional operational costs, as the same operators managing the current dust mitigation plan would also be responsible for managing this plan. Therefore, the actual cost of implementing this process would be limited to the material costs for facilities already utilizing a topical spray solution.

CONSIDERATIONS

Safety, Legal, and Regulatory Considerations

The proposed fugitive dust control plan will be accomplished in compliance with the applicable federal, state, and local regulations. The major statutes that will affect the dust control plan are the New Mexico Air Quality Bureau regulations, United States Environmental Protection Agency (EPA) regulations, and Mine Health and Safety Administration (MHSA) Program Policy Manual for Metal and Nonmetal Mines.

Under the provisions of New Mexico Air Quality Bureau, the Freeport-McMoRan Chino Mines Company is federally enforced to maintain the 20.2.3 New Mexico Administration Code (NMAC) Ambient Air Quality Standards as well as the 40 CFR 50 National Ambient Air Quality Standards. This includes max-daily tailings handling, allowable particulate emissions, and haul road emissions. The emissions regarding dust control include total suspended particles (TSP), particulate matter less than 10 microns (PM₁₀), and particulate matter less than 2.5 microns (PM₂.₅). The Freeport-McMoRan Chino Mines Co. will need to apply the commercial vinyl
copolymer if visible dust is apparent in the air. General monitoring, recordkeeping, reporting, and testing requirements are established in the New Mexico Environment Department Title V Operating permit [21]. The Freeport-McMoRan Chino Mines Co. is required to inspect each area to ensure fugitive dust emissions are minimized. [22]

In Title 30 of the CFR, Mineral Resources, Chapter 1, MSHA establishes survey and control measures for Metal and Nonmetal Mines [23]. The standards require mine operators to conduct dust surveys as frequently as possible to determine the adequacy of the control measures. The purpose is to help assure that the employees are not exposed to harmful concentrations of airborne contaminants. These standards apply to those air contaminants covered under 30 CFR §§ 56/57.5001 (a) and (b).

**Community Outreach**

Upon implementation of the proposed dust suppression technique, a task force will be created to monitor the dust buildup in Silver City, New Mexico and implement this technique in the city limits and surrounding area where possible. In 2013, a sustainability plan was developed in Silver City, New Mexico that spans to 2030 [24]. This plan involved working with the NM State Climatologist to document the impact of dust on this region. It is recommended that this task force consist of this NM State Climatologist, a representative of local Silver City leadership, an emergency services representative, an environmental representative from the Chino mine, and a representative from The Department of Transportation [25].

This task force will use this documentation and the recommended method of dust suppression to minimize the dust effects on the region and its inhabitants. This region is severely affected by dust buildup which causes many road closures and accidents on the local U.S 180 Interstate. Constant monitoring and implementation of this dust suppression technique would drastically reduce the problems generated from dust in this region and positively affect the lives of the people in this region. The proposed task force will also head efforts to display these positive changes to the local community by developing short reports, updating the local inhabitants on the progress and effectiveness of this new plan.

This taskforce will also be in charge of relaying this information to surrounding regions with similar dust issues. This committee will be charged with making sure these other regions are made aware of the successes and failures of dust control using this method. With constant communication between committee, many regions can effectively mitigate dust emissions.
CONCLUSIONS AND RECOMMENDATIONS

1) The most effective, environmentally safe, and economical solution for tailings dust control is a topical spray solution consisting of a vinyl copolymer that forms a permeable but rigid crust atop the tailings.

2) The efficacy of the vinyl copolymer, compared to current methods, is higher due to its longevity and economic value.

3) The vinyl copolymer spray will save the Chino mine approximately $130,000-$390,000 per year on dust treatment material and will not create additional capital costs due to the presence of available on-site spraying equipment.

4) The vinyl copolymer is a sustainable and environmentally friendly solution due to its compatibility with biota and ability to be reclaimed in the mining process.

5) The Dust Busters recommend that TSFs apply the commercial vinyl copolymer product at 11% by volume in water at a rate of 1,250 gal/acre. If this treatment does not prove adequate for the particular mine, the application should be increased by 50 percent.

6) Pelletizing mine tailings should not be pursued due to not being a viable option fiscally, logistically, or as an effective measure for controlling the dust.

REFERENCES


[20] Faulkenberg, Chad, and Fabio Neto, President and Technical Director, Soilworks, personal communication.


[22] Kimbrell, Joseph, Permit Specialist, NMED-Air Quality Bureau, personal communication.


March 15, 2017

The Dust Busters
Attn: Mr. Ralph E. Martin
Department of Chemical Engineering
University of Arkansas
Fayetteville, AR

Mr. Martin:

I have thoroughly read your report “Tailings Dust Emissions”. The report details your ideas to control fugitive dust from mine tailings storage facilities. The report does not address the problem of accumulating mine tailings that take up land space. But rather, it just addresses the problem of fugitive dust entering the air causing hazards to humans, animals, plants, and the environment in general. You are addressing a very important problem that needs a logical and economic solution. Not only is this particular dust a health and safety hazard, but it deteriorates the quality of the soil to which it spreads if allowed to blow with the wind.

Your report is comprehensive enough to make a logical decision as to which method of treatment is most desirable. I agree with your assessment process and conclusion. Spraying the solution of vinyl copolymer should be an effective solution and the most economical of the choices studies.

Following are my questions and concerns:

1. Is this a long term solution?
2. Does the crust deteriorate over time?
3. Is it necessary to reapply periodically? If so, how often?
4. I know it was not part of the study, but if there is a possible use for the dust, obviously that would be a great benefit.

If you have any questions, please call.

Sincerely,

H. Duane Allen
President
March 17, 2017

The Dust Busters
Department of Chemical Engineering
University of Arkansas
Fayetteville, AR

Attention: The Dust Busters

Professional Audit

I have read and examined your report Tailings Dust Emissions*. The key objective of your report is easily determined from the reading. The different approaches currently in use and different approaches you looked at are also identified. Your methodology seems to be sound. I was thoroughly impressed with your ingenuity in building pieces of equipment for your testing.

Your report is thorough enough to make a logical decision of which method of treatment provides the best value at this time with the least amount of capital expenditure. Spraying of vinyl copolymer should appear from your study and testing to be the most economical and still be an effective solution.

My questions and concerns are:
1. Some of the terms used in the report are very technical and I would suggest these terms be explained either at the time they are introduced in the study or in a “definitions page”.
2. How many suppliers are available to supply the vinyl copolymer?
3. If there is only a single source supplier, could this lead to a rising cost as they realize they have a captive audience?
4. Are there long term studies on the long term effect of the vinyl copolymer to the soil surface and surrounding environment?
5. Are there any EPA regulations in regards to the use of vinyl copolymer in this manner?

Thank you for the opportunity to review this report. If you have any questions, please feel free to call.

Regards,

Don Jameson
Principal Technical Advisor
Halliburton/Baroid
405-496-9432
Don.jameson@halliburton.com
Marlene Crosby, Director of Gunnison County, CO Public Works

From: Marlene Crosby <MCrosby@gunnisoncounty.org>
Date: Thu, Mar 16, 2017 at 9:32 PM
Subject: RE: Report Audit
To: Natalie Tucker <nmtncker@email.uark.edu>

Good evening Natalie,

I apologize for the late response. Our offices got a major computer upgrade, and my entire system changed. Today when I got your e-mail I had to go looking for your document.

Frankly, I was amazed at the document. Some of it was beyond my capacity to understand, but the work you have done is amazing. I have no comments.

Good luck with your paper.
Marlene

Walter Hawkins, Chemical Engineer, FEECO

On Mon, Mar 13, 2017 at 9:58 AM, Walter Hawkins <hwkins@iecompanies.com> wrote:

Sam,

I read your report and found it to be thorough and accurate. I also agree with the groups conclusion as to topical treatment being the most practical and cost effective.

Sincerely,

Walter Hawkins
Chemical Engineer
Innovative Environmental Companies
FEECO International
Fabio Neto, Technical Director at Soilworks

Hello Zak,

I read your paper and have only a few facts to point out that were missed during your dissertation. I must be really honest with you that probably by my own fault, I was disappointed due to believe you were writing a paper providing supporting data about the efficiency of our product, as you mentioned by name on your very first communication. Not only that did not happen, which leads the public to believe that any polymer product can do the job, which is simply not true. We dedicated our time and resources to you and your team in good faith and received no actual mention on your study.

With that being said, and taking in consideration that you never actually said that you would mention our product or the statement from Chino saying that our product Gorilla-Stool is by far the best product found to date to control dust in mine tailings here are the facts that you missed in your paper:

- Not all polymers are equal and the explanation you gave on both vinyl and acrylic polymers was as clarifying as to have included all polymers as a homopolymer.

- Magnesium chloride is highly corrosive and as you mentioned uses the moisture in the air to attract it to the ground. It requires a relative humidity above 32% to start being effective. Given that, as you also stated, most mines are in arid regions with low humidity, how effective can Mag chloride be in the desert? Plus Mag Chloride is water soluble and washed away at any signs of precipitation.

- One other very important part of the process that was forgotten is that the mining industry is constantly advancing in discovering improvements to extract metals and most of the alternative products used for dust control mentioned, would make that reprocess of the tailings material harder if not impossible. Our product is easily reprocessed and tested rigorously to make sure it does not interfere with their extraction processes.

I wish you and your team the best of luck on the competition.

Zakary Galligan <zfgalligan@email.uark.edu>

Mr. Neto,

First, I would like to apologize for the imperfect communication, but the competition rules do not allow us to disclose product names in the written report. We have to keep all products and equipment generic.

That being said, if asked at the competition we ARE allowed to mention your product. As the report states, we do recommend your vinyl copolymer application. At the competition, the judges and Freeport McMoran attendees will know it is your product.

We want to thank you for dedicating your time and resources to our team. We appreciate any and all input and are taking into consideration everything discussed.

Again we apologize for the miscommunication and hope this clears things up.

Thanks,
Zak Galligan