24-013

Can Fly Ash Pond Closure Expertise be Applied to Mine Tailings?

Paul C. Schmall
Keller North America, Rockaway, NJ

ABSTRACT

In recent years, several geotechnical methods have been successfully applied to ash pond closure. These include modified dewatering techniques with wellpoints and wells to physically drain the material, soil mixing to create a soil-concrete material for improved accessways as well as improved ground structures within ponds to act as barriers or gravity dams, and geotechnical instrumentation to serve as an early warning of the potential for liquefaction. Given the parallels between fly ash and sluiced in place mine tailings, the application of fly ash remediation method to mine tailings shows significant potential, as illustrated in this paper.

SHARED ORIGINS

In 2008, a fly ash containment stack containing millions of cubic yards of coal ash from a Kingston, Tennessee coal-fired plant failed, resulting in the release of over five million cubic yards of ash into an adjacent river, disruption to electrical power, natural gas, and water lines, and covering local roadways and a rail track. Community and environmental damages were widespread. This was the biggest environmental disaster in the history of the United States.

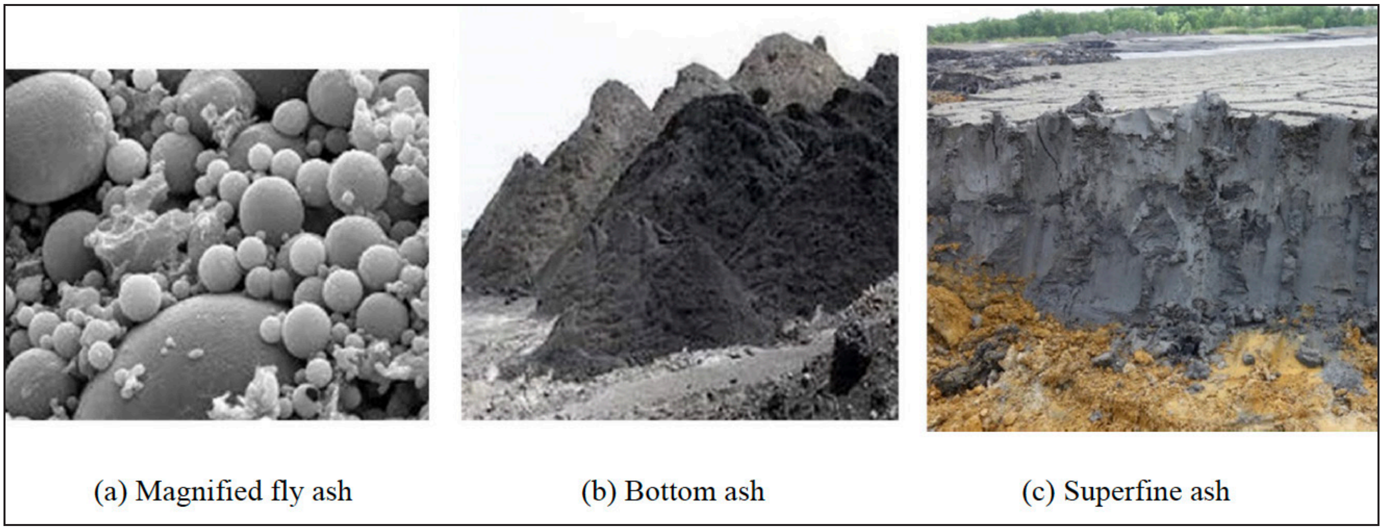
In 2014, a drainage pipe burst at a coal ash containment pond, part of a closed coal-fired plant in Eden, North Carolina. Thirty-nine thousand tons of coal ash and 27 million gallons of wastewater was released into the Dan River before the event ended. Ash containing metals was deposited up to 70 miles (110 km) from the spill site.

The sheer magnitude and far-reaching consequences of these two events precipitated the 2015 enactment of "The Disposal of Coal Combustible Residuals (CCRs) from Electric Utilities Rule," the purpose of which was to provide a comprehensive set of requirements for the safe disposal of CCRs from coal-fired power plants. The ruling addressed the risk from unregulated coal ash disposal, such as the leaking of contaminants into the groundwater and the potential for catastrophic failure of surface impoundments.

CCRs consist primarily of fly ash but also include bottom ash and what we will refer to as "superfine" ash. A typical pond is probably 80% fly ash (Figure 1a), with approximately 80% silt-sized particles, and is absolutely non-cohesive. Although the particles are predominantly silt-sized, the material tends to behave more like a fine uniform sand than a silt. Ash does not consolidate like a natural silt or a clay. Bottom ash (probably 10% of a typical pond) is a coarse sand, free draining, with more angular particles (Figure 1b). From an earthwork perspective, it's an excellent, problem free material to work with and within. Superfine ash (Figure 1c) is the finest ash that finds its way to the far end of the pond. It is so fine that it will hold onto water and will not respond to drainage methods (such as dewatering). Superfine ash constitutes probably 10% of the typical pond.

Depending upon the condition of the impoundment or if ash is stored in a sensitive area, pond closure may require the complete excavation and removal of the CCRs, partial excavation and consolidation of ash over a smaller footprint, or just regrading and capping. The specific requirements for closure are in part dictated by the CCR Rule and in part decided by each state.

The experience gained in CCRs since the ruling was first enacted is directly applicable to tailings storage facilities of similar characteristics. The similarity starts with their origins, considering only the mine tailings that, like CCRs, are sluiced in place. They have similar resulting traits. If the sluice pipe never moves over the life of a pond, coarser particles would, predictably, settle first and the finer particles would travel further in the pond. Many ponds are intended to be filled evenly, so the pipe is moved around the periphery of the pond to achieve this. This creates a



(a) Magnified fly ash (b) Bottom ash (c) Superfine ash

Figure 1. Types of ash

complex pattern of deposition with a high degree of intermixing of finer and coarser horizontal layering.

Because the materials are sluiced in place, they are very loose. Loose corresponds to contractive and when a highly contractive material is disturbed (sheared) in an undrained (or undrainable) condition, the grains will rearrange themselves into a denser configuration, leaving abundant free water which will allow the material to flow. Class F fly ash (which is what most of these ponds consist of) is slightly pozzolanic so the ash, once sluiced in place, will undergo very light cementation, which allows the ash to remain in a very loose condition, even after the pond height increases significantly. This metastable condition is rather fragile and leaves the ash susceptible to collapse. In an ash stack, (like Kingston), the tipping point can be reached when the stresses in a stack are greater than the strength of the material, and what has been called "static liquefaction" occurs. This failure can be initiated with very slight ground movements, or disturbances, which is why these materials are sometimes referred to as "brittle." The potential for static liquefaction is probably the greatest common concern between CCRs and mine tailings.

Mine tailings are more variable than ash, and generally exhibit better behavior and more favorable characteristics. Tailings will vary by the type of mining, the ore itself, and the particle size that results from the crushing and grinding process. Mine tailings typically tend to be more angular than fly ash particles. Despite this, they are still susceptible to uncontrollable flow events (i.e., static liquefaction) where once the material is mobilized and movement begins, it continues as long as unrestrained tailings have a place to go. The rearrangement of the particles upon movement generates enough free water to keep the material in motion. The particle make-up and hydraulic deposition is in essence what makes these two materials from very different sources behave in similar fashion geotechnically. We can, therefore, consider ash as a worstcase condition and apply the lessons learned to mine tailings.

FLY ASH CHARACTERISTICS AND BEHAVIOR

Complex horizontal layering of bottom, fly, and superfine ash is possible. The presence of bottom ash will facilitate drainage of ash and the presence of superfine ash will inhibit vertical percolation of water (which is necessary for drainage). Add other materials to a pond (such as gypsum which is also a byproduct of power generation) and the resulting drainage conditions can be very complex. An ash pond is hydrogeologically significantly more complex than any natural soil formation.

When saturated (Figure 2), the ash is a very dangerous material to work on with conventional construction equipment. Saturated fly ash exhibits very low undrained shear strength which is why it cannot support equipment or even foot traffic. Ash that is sluiced in place but drained will still have low shear strength, but this will be significantly higher than that of saturated ash. The presence or absence of water makes all the difference in the behavior of ash. The light cementation of the ash contributes (to some unknown extent) to its drained strength. The strength of the ash, and the subsequent ability to support construction equipment or be stable in a slope cut, hinges on the presence or absence of water (Figure 3).

Fly ash is silt-sized material that is highly susceptible to capillary action (or wicking of moisture up into the ash above the phreatic surface, or "water table"). It has a relatively high permeability for silt sized particles. Coal ash that increases in saturation through capillary action will be more vulnerable to instability. We see this consistently between ponds occurring from 1–3 ft (0.3–0.9 m) above the water table. Little is truly quantified about the strength behavior of ash in the range of moisture contents between drained and saturated, but it is well known that there is a "transition zone" in ash above the water table.

The vibrations of construction equipment can also rearrange the grains of fly ash into a slightly denser configuration and a barely unsaturated ash can be rearranged into a saturated ash and the water level in the material will seem to rise due to the repetitive motion or vibration of the equipment. This is what used to be referred to as "pumping," observed with repeated passes of construction equipment over an access road. When pumping occurs in ash, there is a corresponding drop in shear strength and there have been instances of sudden engulfment of construction equipment.

With continued construction activity, repetitive motion and/or vibration of equipment, liquefaction (*dynamic* liquefaction) can occur in what is initially nearly saturated ash. The vibration will rearrange the grains, which generates free water. If the water cannot dissipate quickly enough, the pore pressure will rise. When the pore pressure rises to the point where it is greater than the buoyant weight of the overlying ash, the material will lose all shear strength. The greatest potential for liquefaction to occur in ash is when the ash is highly layered and stratified with thin layers of finer, lower permeability or superfine ash. These layers hinder the free water from flowing to the surface and the pressure dissipating. Construction equipment can be suddenly engulfed without any warning if the liquefaction occurs just beneath the surface, as shown in Figure 4.

Figure 2. Saturated ash

Figure 3. Dewatered ash supporting equipment

Figure 4. Equipment engulfment as a result of vibration-induced liquefaction

LESSONS LEARNED FROM CCR

Every pond exhibits somewhat different behaviours and “has a unique personality.” The personality of the pond comes from:

- the source of the coal,
- the characteristics of the burner,
- the manner in which the ash was transported to the pond,
- the proportions and frequency of mixing bottom and fly ash,
- the shape of the pond,
- the location(s) of the sluice pipe(s),
- the thickness of the ash, and
- the chemistry of the ash and the water.

The variables are seemingly endless. What ultimately matters is how the ash behaves on an exposed slope cut or under the tracks of an excavator. To some extent, a geotechnical investigation can characterize a pond, but ultimately it is going to reveal itself during construction.

Prior to the CCR rule, there were hundreds of ash ponds with absolutely no geotechnical characterization. Access was not just difficult but also considered dangerous. There was never any need to understand the composition of the material if there was never any intention to do anything with it. Once there was a CCR rule and a need to understand the composition of the material, the cone penetrometer quickly became the tool of choice.

The CPT provides much finer resolution of the material than standard SPT borings. CPTs can provide a picture of the variability of the ash with depth and also variability of the ash across the pond and, with the near continuous logging, indicate where there are thin zones of coarser, more drainable ash. These are the places where the permeability of the ash is locally higher and are opportune places to provide drainage of the overlying materials with dewatering devices.

These more transmissive zones are generally only a small portion of the overall ash thickness but represent most of the ash’s ability to transmit or release water. In general, high transmissivity is identified on a CPT log by comparing the measured pore pressure response (u) to the hydrostatic pressure. As the CPT probe is advanced, it creates a pressure wave in front of it. In low permeability zones, the measured pressure will be higher than hydrostatic pressure because the pressure induced with the driving of the probe dissipates slowly. In more permeable zones, no pressure builds up with the driving of the cone and the measured pressure will tend to fall right on the hydrostatic line. These pore pressure response zones also tend to correlate to zones of relatively high tip resistance (q_t) which would be expected from coarser, more granular material. This is to be expected since most saturated ash columns will be very soft, while thin layers of coarser material will tend to be more pronounced to the cone. Figure 5 is a CPT log showing zones of high permeability. Figure 6 shows an amphibious CPT rig.

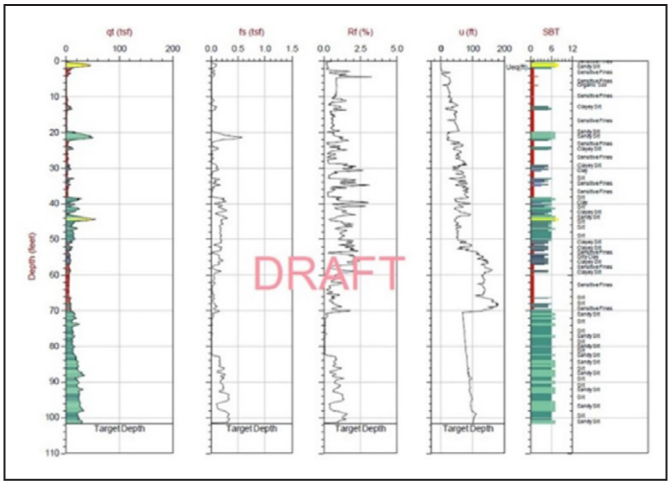


Figure 5. CPT log

Figure 6. Amphibious CPT rig (courtesy R. B. Jergens)

Prior to draining an ash pond, the pond filling history and CPTs should be reviewed to better understand what parts of the pond are likely to be coarser and what parts are likely to be finer. Historical photos are necessary for revealing the deposition history of a pond and identifying potential problem areas, which are usually where finer ash is likely to be deposited or materials are mixed. Historic photos can also reveal areas of coarser ash which are areas where dewatering wells or wellpoints should be located. Based on the pond deposition history, it is possible to predict with some accuracy how the pond will most effectively be drained. A pilot test or a series of wells spaced around the pond will help to confirm that prediction.

The best way to evaluate the drainability of a pond is with real field data obtained from a pilot dewatering program or pump test. This test usually consists of either a pumped deep well or series of wellpoints and measurement of the resulting drawdown in strategically located instruments. Data obtainable from such a test could include traditional aquifer parameters such as transmissivity and storage coefficient, which are of minimal value in the midst of highly variable conditions and when the objective is pumping down a pond of trapped water. More importantly, a pumping test provides an opportunity to measure the yield of a representative dewatering device, or a device constructed and installed the way the wells or wellpoints will be constructed and installed during production dewatering. Early on in CCR pond closures, pumping tests would be very elaborate in order to calculate aquifer parameters at a representative or worst-case scenario location within a pond. The authors' thinking shifted very quickly to conducting numerous yield tests at widely spaced locations around a pond in order to evaluate (qualitatively) the variability of the pond.

Following a geotechnical investigation and possibly pilot testing and test pits, one still has to consider that the conditions on an ash pond are still highly changeable because of the sensitivity of the material to water. The single most significant factor with changing conditions is due to variation in water level and saturation conditions and the subsequent impacts on ash shear strength. The specific yield of ash is relatively low, on the order of 8 to 12 percent of total volume. This is advantageous in that the behavior of the ash will change dramatically with a relatively small amount of drainage (i.e. removal of the specific yield). A small amount of recharge, however, can undo a lot of drainage effort which means a reversal of the shear strength gain that occurred with drainage. So, the characteristics of the ash can change dramatically with a relatively small change in water content. Those changes within a pond can occur with precipitation, how process water may be handled on a pond, the influence of the pool, the addition of construction water, or infiltration into a pond from permeable natural ground in contact with the ash.

IMPROVING THE ASH

Dewatering, in the opinion of the authors, is the most readily available, well proven, and cost-effective way to improve ash conditions. Historically dewatering of ash ponds has not been too successful. Prior to the CCR rule there were many failed attempts, with only two ash ponds that were actively and successfully dewatered. Conventional dewatering methods improperly applied have been problematic to the point where many people believe that pre- drainage techniques just don't work in ash. Building effective dewatering devices such as wellpoints or wells in ash is complicated. The traditional well filter pack design used in conventional construction dewatering doesn't always apply when the particles resemble ball bearings. Previous use of fabric filters in lieu of conventional sand filters has proven to restrict water flow and resulted in plugging of the wells or wellpoints. In light of these past difficulties, when it has been necessary to dewater fly ash, most operators have chosen to dig a network of ditches leading to a sump or sumps. Lowering the water with rim ditches and sumps requires taking the excavation down in very thin lifts. This technique is suited to long term pond maintenance activity or to closure projects with very long schedules where the slow drainage of the pond is not critical. Placing land-based equipment on a saturated ash surface in order to dig a drainage ditch presents a significant safety hazard, certainly with operators unfamiliar with ash.

Wellpoints (Figure 7) have been used extensively in fly ash dewatering. The main advantage of a wellpoint system is that it is a relatively economical system for finer ash where many low yield devices on close centers are necessary. The wellpoint system with closely spaced devices is also advantageous where it is necessary to lower the phreatic surface as closely as possible to the bottom of a pond with an underlying impermeable layer (either clay or rock). The main disadvantage of wellpoints is that they work on vacuum and are therefore limited in how high they can lift water. Typical drawdowns that are observed in fly ash would be approximately 4.5 to 5.5 m (15 to 18 ft).

Wellpoints are ideal for dewatering shallow ponds and for creating a dry crust that can support heavy equipment. On deeper ponds, multiple stages of wellpoints can be utilized, or deep wells can be installed that are not restricted with depth. They lend themselves to deeper impoundments, particularly where coarser, more transmissive ash may exist at greater depths. A series of widely spaced wells in this condition may be able to significantly lower pore water levels with minimal equipment on the surface that may interfere

Figure 7. Wellpoints

Figure 8. Deep wells

with closure operations. To date, the authors have installed wells on ash ponds at up to 45 m (150 ft) depths.

Deep wells (Figure 8) are typically the least expensive dewatering solution where deep coarser layers of bottom ash exist. They also present fewer piping obstructions to the earthwork contractor than wellpoints. The main disadvantage of deep wells is that they are generally not economical to install on close centers because the unit cost for each well, equipped with a submersible pump, is relatively high. Deep wells require safe access to the pond surface for large drilling equipment. This type of equipment requires a stable platform. Typically, this platform is created with wellpoints as described above or by pushing material onto the pond to create a floating road.

Horizontally directionally drilled (HDD) drainage pipes can be installed from the periphery of a pond but have had very limited success. On paper, this technique would have the advantage of a long drain line, submerged in the ash, with continuous contact with saturated ash. The reality is that horizontal devices have been only partially effective because of borehole smear effects and plugging of filter fabrics. HDD wells are very inefficient in pulling water from the formation without a properly installed well filter pack. With the distinct horizontal layering in sluiced-in materials, a vertically installed device that can be installed with drilling methods that minimize borehole smear effects, is better oriented to tap all of the horizontal permeable layers.

ACCESS SAFETY CONSIDERATIONS

Safely accessing a sluiced-in pond is typically the first challenge with any pond closure. The irony is that dewatering a dry crust on the pond to gain equipment access often requires equipment access to install the dewatering system. The author has had good success laying down a small access lane using geogrid and plywood suitable for foot traffic only. From this geogrid and plywood access lane, shallow wellpoints can be installed by hand to create a dry crust for access for equipment.

For deeper ponds where it is necessary to use a drill rig to install dewatering wells, it will be necessary to build floating access roads with geogrid or to dewater a dry crust with wellpoints. In the case where the pond is flooded, it is possible to put the entire installation operation on a barge or flexi-floats to install either wellpoints or wells (see Figure 9). This method eliminates the safety concern of working directly on top of the ash.

Amphibious equipment can be utilized when there is not a significantly thick dry crust to work from. The amphibious equipment will not sink in the ash; however, amphibious equipment is not intended to be free-floating. Amphibious excavators can tip when there is little traction.

ENGINEERED CONTROLS FOR WORKING IN CHANGEABLE CONDITIONS

Because water level and saturation conditions in an ash pond are highly changeable due to many climatological and stormwater management factors, and the subsequent effects on ash shear strength are very pronounced, engineered controls should be implemented to evaluate conditions at critical times. Those engineered controls are the use of CPTs, instrumentation, and field vane shear strength tests (2).

CPTs can be performed at various milestones during pond closure. A good example is the intermittent performance of CPTs during the excavation of a slope and stacking of ash during a hybrid closure (consolidation of ash on smaller footprint). The stability of the slope is driven by the shear strength of the ash and will be based upon water level assumptions as the excavation is brought down (and ash is stacked behind). The CPTs will verify drained strengths and saturated, undrained strengths.

CPTs will provide a detailed log of strength vs depth at one point in time. However, instrumentation is necessary to continuously monitor saturation conditions and sound an alert if changes are problematic. Water level in the ash must be considered constantly changing. Where wells and wellpoints are utilized to provide stability for the deep slope cut on the hybrid closure, the monitoring of the water levels is critically important. Water level rises must be immediately recognized. Vibrating wire piezometers are particularly useful when installed in conjunction with an automated data acquisition system connected to the internet. These systems allow for monitoring of ash conditions in real time and are easily configured to send alerts at predefined trigger levels. In situations where the water level will be lowered significantly, or where there is potential for perched water levels, piezometers at several depths may be warranted.

Several sizable slope failures have occurred on ash ponds concurrent with lowering of the pond open water (Figure 10). Ponds are pumped down slowly so as to not induce a "rapid drawdown failure." The thinking is that by pumping the pond down slowly, the water level out underneath the beach or the adjacent ash stack drops at the same rate as the open pool. That is not necessarily the case. Typically, there is no instrumentation out in the ash to confirm that the water level within the ash is at the same elevation as the water level in the pool.

Figure 9. Floating equipment for well installation

Figure 10. Examples of rapid drawdown failure

Figure 11. Soil mixing in ash

Concurrent with construction activities, the practice of real time pore pressure monitoring for working platform safety is increasing. Pore pressure monitoring can be performed as an early indicator of liquefaction. A combination of highly layered ash, low shear strength material at shallow depth and a construction vibration induced pore pressure rise is the likely setting for a liquefaction (dynamic) failure. In theory, if the pore pressure rises to the effective stress at transducer depth all shear strength is lost. Real time pore pressure monitoring and communication of the data has been practiced successfully to watch for that sudden, construction vibration-induced rise in pressure in pore pressure (3).

Where field activities are dependent upon the shear strength of the ash, hand-held vane shear tests (VST) can be performed in the upper 10 ft (3 m) of ash, to evaluate conditions for the use of heavy equipment. This can provide the best indication of dry crust thickness and strength. Low shear strength measurements or elevated and/or perched water levels can suggest increased potential for instability. Water levels should be monitored at regular frequency in areas of activity and VST should be repeated when it is suspected that conditions have been altered, either by construction activity, precipitation/infiltration/wetting, or other occurrence which may result in a change in water levels.

Geostructural Improvements in Ash

Although drainage (dewatering) is the most readily achievable improvement that can be made in ash, sometimes it is inappropriate, or a greater geo-structural improvement is needed. In those instances, soil mixing has been utilized with great success.

Soil mixing (Figure 11) involves the mechanical blending or mixing of a binding agent, typically Portland cement, with the in-situ soils (or ash) to create a soil-concrete product similar to weak concrete. There are a number of different basic techniques that can be implemented with wet soil mixing, where the binder is introduced as a fluid grout. Those techniques are single axis soil mixing, multi-axis, Cutter Soil Mixing (CSM) and shallow mass mixing. The same techniques are also used for ISS (in-situ stabilization), a process that is increasingly considered for stabilizing ash in place in a pond where it will remain in contact with groundwater (4).

Ash is actually an ideal material in which to perform soil mixing. The difficulty is using the massive equipment that is typically needed. To date, within the confines of ash ponds, soil mixing has been used to construct a deep gravity dividing wall bifurcating an active pond, a large and very high retaining wall, shear panels for seismic retrofitting of an ash impoundment built by upstream construction methods, and construction of a soil mixed shallow working platform.

CONCLUSIONS

When sluiced in place, mine tailings can be similar to CCR. Removal of the pore water from both CCR and mine tailings is the single most significant measure one can take to mitigate the potential for instability and liquefaction (1). Much has transpired in the CCR world in the last seven years with the pond closures that have occurred. In CCRs, we have refined ground improvement techniques such as dewatering and soil mixing to improve the characteristics of the ash. We also have engineered controls to verify conditions and facilitate safe work conditions.

REFERENCES

[1] Hardin, C. D. et al. 2019. Incremental, Performance Based Approach to Geotechnical Characterization of Ponded Ash Materials, Proceedings of WOCA 2019, St. Louis, MO.

[2] Hardin, C. 2016. Innovative and Practical Methods for Dealing with Wet and Soft Ash in CCR Impoundments. In Theory to Practice with Fly Ash Soil Mechanics" Environmental Research and Education Foundation (EREF.) Coal Ash Forum, Charlotte, NC.

[3] Perry et al. 2019. Extensive Real Time Monitoring of Ash Response to Construction-Induced Activity, Proceedings of WOCA 2019, St Louis, MO.

[4] Ryan Smith and Anthony Sak. 2019. Soil Mixing in Ash Pond Provides Pond Bifurcation, Proceedings of WOCA 2019, St. Louis, MO.

24-014

Canopy Air Curtain to Reduce Diesel Particulate Matter Exposure for Underground Blasters

Steven Mischler
CDC NIOSH, Pittsburgh, PA

Taekhee Lee
CDC NIOSH, Pittsburgh, PA

Shawn Vanderslice
CDC NIOSH, Pittsburgh, PA

INTRODUCTION

Diesel-powered equipment is widely used in the underground mining industry and their popularity results from properties including efficiency, versatility, reliability, and durability. In the U.S. approximately 7,700 diesel engines were used in 177 underground metal and nonmetal mines as of 2005 [MSHA 2005], and these numbers have likely increased since that time. Diesel engines have been shown to be a major contributor to submicron carbonaceous, respirable, and total particulate mass in the air of underground metal mines [Zielinska et al. 2002, McDonald et al. 2003], and their extensive use results in approximately 13,000 underground metal/nonmetal (M/NM) miners (MSHA 2005) in the U.S. being potentially exposed to aerosols and gases emitted by diesel engines (MSHA 2001, MSHA 2006).

Exposure to diesel exhaust has been linked to adverse health outcomes including cancer, cardiovascular, and respiratory diseases (Attfield et al. 2012, Silverman et al. 2012), and in 2012 diesel exhaust was categorized by the International Agency for Research on Cancer (IARC) as a Group 1 human carcinogen (IARC 2012). Exposure to diesel particulate matter (DPM) is especially concerning for underground miners since underground mine environments have been shown to have some of the highest levels of diesel exhaust in the

U.S. (EPA 2002, MSHA 2001, MSHA 2006, Pronk et al. 2009). Due to the potential for elevated DPM concentrations in mines, the Mine Safety and Health Administration (MSHA) promulgated a rule to limit exposures of metal/nonmetal underground miners to DPM to an eight-hour time-weighted average (TWA) of 160 $\mu g/m^3$ total carbon (TC) (MSHA 2001, MSHA 2006, MSHA 2008).

Since this rule went into effect, DPM exposures have been reduced, but are still elevated when compared to other occupations (Pronk et al. 2009, Noll et al. 2015). MSHA compliance data between 2005 to the present show that underground blasters represent 21% of all DPM overexposures in M/NM mines and are one of the highest exposed professions in mining often resulting from low ventilation in the area where blasters are working. Because mines have difficulty controlling DPM in these low ventilation areas, additional control technologies may be needed to reduce exposures. Administrative controls, where miners work on off schedules or upstream of diesel vehicles to avoid the exposures to DPM (Noll et al. 2015) is one possibility, but these types of solutions are not always feasible or practical.

A canopy air curtain is another potential control technology to help reduce exposures of blasters to DPM. Listak and Beck (2012) showed that this control technology reduced respirable dust concentration under a roof bolter's canopy by 67%–75% and recommended air velocities greater than 0.5 m/s for dust reductions of greater than 50%. Additional work showed that a canopy air curtain could be designed for a shuttle car, and some initial testing by the National Institute for Occupational Safety and Health (NIOSH) showed reductions of respirable mine dust between 66% to 70%. As seen in Figure 1, the canopy air curtain delivers clean air over the operator's breathing zone. A fan draws in air through a filter to capture the dust