ABSTRACT

A collaborative, multi-year research program to study coal and silica dust wetting characteristics at Illinois Basin coal mines began in 2009. Primary funding for the study is from the National Institute for Occupational Safety and Health (NIOSH) with ICCI providing matching support. This report covers the second year of the study focusing on wettability characteristics of dust from a mine in Indiana and improvement in engineering controls to minimize mine workers’ dust exposure.

Wettability characteristics of dust are important for developing engineering controls. Therefore, understanding the phenomena of wetting dust with water is critical. Two wettability tests were pursued: fixed-time wettability (FTW) and absolute wettability (AW). FTW simulates wetting under field conditions whereas AW assesses the maximum wettability of dust. About 80-85% of coal dust was wettable by water alone in the FTW test. Both wettability tests showed that the middle coal bench is least wettable compared to top and bottom coal benches. FTW data indicated that the contact time between coal particles and water droplets, and the surface tension of water, are important variables affecting wettability. X-ray diffraction (XRD) analysis showed that silica is present in the un-wetted fraction even though it is 100% wettable by pure water. It appears that silica wettability is limited by its association with other minerals in coal. Finer dust particles were more wettable than coarser particles.

Air flow patterns were analyzed using computational fluid dynamics (CFD) modeling of the continuous miner making a right turn. CFD analysis identified low velocity and recirculation zones with and without scrubber operation. Air leakage along the line curtain and the distance from the end of the line curtain to the face are important variables affecting air flow patterns.
EXECUTIVE SUMMARY

The overall goal of this multi-year NIOSH- and ICCI-funded study on characterization of coal and quartz dust in Illinois Basin coal mines is to minimize both coal and silica dust exposure to operating personnel in underground coal mines and to help the industry meet Mine Safety and Health Administration (MSHA) dust standards through appropriate engineering controls. Specific objectives for the second year study are to: 1) Develop physical and chemical characteristics of coal and silica dust made from bulk channel samples from an Indiana mine, 2) Develop similar data for dust collected from in-mine dust sampling, and 3) Identify and implement engineering controls for respirable coal and silica dust based on results from the first two objectives. This year’s study focused primarily on one Indiana mine identified as IN 6-1.

Bulk Sample Characterization

Characterization data of dust produced from bulk samples of coal, roof, and floor are needed for an understanding of their wetting behavior and development of efficient engineering controls. This study utilized standard protocols for bulk sample collection, storage, and characterization developed during Year 1. Bulk materials were collected and then processed according to developed protocols and used for wettability and other analyses including x-ray diffraction (XRD), scanning electron microscope (SEM), inductively coupled plasma atomic emission spectroscopy (ICP-AES), particle size distribution (PSD), Mine Safety and Health Administration (MSHA) P-7 quartz analysis, particle morphology, etc. PSD data showed that roof and floor materials produce finer dust than coal. XRD data showed the presence of quartz in all samples analyzed and mineral composition varied significantly within the mine. Quartz was found to be present in the un-wetted fraction even though pure quartz is 100% wettable. PSD data on un-wetted fractions revealed that finer particles are more wettable than coarser particles; however, this finding has to be investigated in greater depth.

In-Mine Sampling Characterization

This study required collecting in-mine airborne dust samples from different operating units for physical and chemical characterization. Samples were collected and subjected to characterization studies utilizing protocols developed over the last seven years. These included gravimetric samplers, a digital Thermo-Electron 1000AN personal dust monitor (PDM), and cascade impactors. Analyses showed that the continuous miner (CM) operator is exposed to higher dust concentrations than the roof bolter (RB) operator. Cascade impactor data showed that 50% of dust particles collected by in-mine sampling are less than 4 µm.

Wettability Characteristics

Wetting phenomenon is of critical significance for dust control since water is the most commonly used medium. Two wettability tests were pursued in this research: 1) Absolute wettability (AW) testing measures the maximum wettability of a given sample either with
pure water or, if required, with addition of a surface tension reducer; and 2) **Fixed-time wettability** (FTW) testing (Chugh et al., 2004) simulates wetting in underground mine environments, such as the face area and material dump points, where residence times for contact between dust and water or chemicals are generally low (10-20 seconds). Both tests assess wettability with water first, and then may use suitable chemicals to further enable wetting the un-wetted dust. Both FTW and AW data revealed that the middle coal bench is least wettable as compared to top and bottom coal benches. About 1-7% increase in wettability was found as contact time was increased from 10 to 25 seconds. Similarly, about 4-8% increase in wettability was found as the temperature of the wetting fluid was increased from 45 to 105 °F. The percent increase in both cases is significant since it may include mostly fine particles. Both FTW and AW provided valuable data on wetting characteristic which can be used to develop efficient engineering controls for improved dust control.

**Surface Charge Characteristics**

In this research, surface charge characteristics of coal particles are measured using a zeta meter, which provides zeta potential (ZP) values, the measure of the surface charge on a particle under a particular set of conditions. In the context of dust control, ZP is important since it determines whether a particle, normally wettable when no surface charges exist, would be wetted by a fluid under certain specific charged conditions. In addition, it also determines the potential of dust to agglomerate. In the past, it was observed that Si/Al ratios and coal and pyrite content affect the ZP of a particle, which in turn would affect the surface charge and thus wettability. ZP was evaluated for both -500 and -400+500 mesh samples and all values were found to be negative which is consistent with coal samples. It was observed that the middle coal bench has the largest negative potentials for both size fractions evaluated.

**Engineering Control Studies**

Computational fluid dynamics (CFD) modeling was used to assess and improve some of the engineering control concepts previously developed. In this research, CFD was used to analyze air flow patterns in the face area when the CM is making a right turn cut. Analysis identified low air velocity and recirculation zones. Air leakage along the curtain and the location of curtain in relation to the face significantly affect the volume of air at the end of the line curtain and thus air flow patterns in the face area.
OBJECTIVES

The overall goal of this research is to minimize both coal and silica dust exposure to operating personnel in underground coal mines and to help the industry to comply with MSHA dust standards. Specific objectives are to: 1) Develop physical and chemical characteristics of coal dust from bulk samples, 2) Develop similar data for in-mine dust samples, and 3) Identify and implement engineering controls for respirable coal dust based on results from the first two objectives. The research program has six tasks.

1. Develop physical, mineralogical, and elemental characteristics of coal and quartz dust created from bulk samples of coal, immediate roof, and immediate floor strata.
2. Develop surface and wettability characteristics of respirable size coal and quartz dust created from bulk samples of coal, immediate roof, and immediate floor strata.
3. Collect dust samples from in-mine sampling.
4. Develop physical, mineralogical, and elemental characteristics of coal and quartz dust fractions from in-mine dust samples.
5. Perform wettability studies on respirable dust from in-mine sampling.
6. Identify near-term strategies for coal and quartz dust control.

This report discusses results of the study for one Indiana mine (IN 6-1) and refers to the second annual progress report submitted to the National Institute for Occupational Safety and Health (NIOSH) of the Center for Disease Control (CDC) titled “Sources and Wetting Characteristics of Respirable Coal and Silica Dusts from Selected Interior Basin Coal Mines” (Chugh and Mondal, 2010) for more details. The NIOSH progress report is hereafter referred to as the NIOSH Report.

INTRODUCTION AND BACKGROUND

Coal and quartz dust control is a major issue in underground coal mines of the Illinois Basin. Current MSHA dust standards limit total dust exposure to 2 mg/m³ for an 8-hour period. Where silica content in dust exceeds 5%, the total dust exposure must be appropriately reduced. MSHA has recently released draft dust regulations that propose to reduce the total dust exposure standard down to 1 mg/m³. Similarly, it is proposed to reduce the quartz dust standard from 100 to 75 µg/m³. If these regulations are approved, mine operators will have to use significantly improved engineering controls to maintain current production rates and productivity levels. Thus, understanding wetting characteristics of coal dust is vital for the development of engineering controls. Unfortunately, very limited data are available on wettability characteristics of coal and quartz dust from the Illinois Basin.

A research team from the Department of Mining and Mineral Resources Engineering at Southern Illinois University Carbondale (SIUC) commenced a dust control research program in 2000. Since then, SIUC has developed several technologies for improved dust control. Wettability studies on coal dust led to the development of a new
scientifically sound approach for quantifying wettability (Chugh et al., 2004). Flooded-bed scrubber improvement studies led to the development of modified spray systems within the scrubber with lower water volume and reduced pressure drop. In field demonstrations, suction inlets to the scrubber were modified to minimize the amount of coarse material being sucked into the scrubber and to improve the capture of respirable dust (Chugh et al., 2006a). Novel SIUC filter screens, which offer less resistance and improved coal and quartz dust capture compared to industrial filter screens, have been developed.

Perhaps the most significant improvement came through the development of an innovative spray system concept for the continuous miner (CM) (Chugh et al., 2006b). The concept utilizes approximately the same amount of spray water as a conventional CM spray system. It locates different sprays spatially to develop “two lines of defense” minimizing dust escape and increasing the time period for dust, water, and air to interact with each other. The concept has been evaluated at five mines with 30-40% reduction in respirable dust at the CM operator location and 15% reduction in the last open crosscut (LOXC). In 2010, further development achieved significant improvements in these innovative sprays concepts. The newly developed system has been demonstrated to ICCI and industry professionals on a mock-up CM at the Illinois Coal Development Park in Carterville, Illinois. The entire system has been recently demonstrated in the field at a Knight Hawk mine in Southern Illinois.

Computational fluid dynamics (CFD) modeling has been used as an engineering control tool to assess developed concepts for improved dust control. At SIUC, CFD modeling has been used to: 1) Study air flow patterns in the face area of a room and pillar mining section, 2) Study dust dispersion characteristics in the mining area, and 3) Optimize the CM wet-scrubber filter screen inclination. Currently, efforts are focused on optimizing the innovative spray system on the CM.

Although significant dust control research has been done at SIUC, continuing efforts are needed to reach the overall goal of this project. Similar to the first year, this year’s research focused on developing physical, chemical and wetting characteristics for a specific mine. The developed data has been used to modify and/or develop engineering controls to minimize dust exposure to workers.

EXPERIMENTAL PROCEDURES

Description of Cooperating Mine

Mine IN 6-1 operates in the #5 seam of Indiana with production of 3 million tons per year. It uses the room-and-pillar method to extract coal at depths of 350 to 440 feet. The immediate roof is shale and the immediate floor is claystone. Pillars are 60-ft (c-c) with 20-ft wide entries. The peak mining rate is about 20 tons/minute and the productivity (tons/person hour) is the highest among Indiana mines. There is little or no water encountered in mine workings.
Bulk Sampling and Analysis Protocols

ASTM 4596-99 standard procedures were followed for collecting bulk samples of coal, roof, and floor strata in underground mines. Protocols developed for sample collection, storage, preparation, and analyses are summarized in Figure 1. A more detailed description is provided in the NIOSH Report.

In-Mine Dust Sampling and Dust Analysis Protocols

An important part of this study requires collecting in-mine airborne dust samples in different unit operations for physical and chemical characterization. In-mine dust sampling was done using gravimetric samplers, a digital Thermo-Electron 1000AN personal dust monitor (PDM), and cascade impactors. Descriptions of in-mine sampling protocols and data analysis techniques are included in the NIOSH Report.

Wettability Analysis

In the wetting process, air from an air-solid interface is displaced to form a liquid- or water-solid interface. Wetting behavior or wettability is essentially determined by forces at the solid-liquid and fluid-fluid interfaces. The wetting process occurs in three distinct stages. The first stage, adhesional wetting, refers to the establishment of three-phase contact at the solid surface. The second stage, spreading wetting, involves displacement of one fluid by the other at the solid surface. In the case of suspended coal dust in air, the solid surface is initially covered by air. When it comes in contact with the water droplet, the water droplet displaces the air-solid interface with the water-solid interface. Finally, immersional wetting represents transfer of a solid particle from one fluid phase to another. A description of forces acting at three interfaces is included in the NIOSH Report.

Wetting phenomenon is of critical significance for dust control since water is the most commonly used medium. Two wettability tests were pursued in this research: 1) Absolute wettability (AW) testing measures the maximum wettability of a given sample either with pure water or, if required, with addition of a surface tension reducer, and 2) Fixed-time wettability (FTW) testing (Chugh et al., 2004) simulates wetting in underground mine environments, such as the face area and material dump points, where residence times for contact between dust and water or chemicals are generally low (10-20 seconds). Both tests assess wettability with water first, and then may use suitable chemicals to further enable wetting the un-wetted dust.

Absolute Wettability

Four AW techniques were developed to evaluate wettability characteristics of dust samples. Technique 1 evaluates the absolute wettability of particles as a function of surface tension (surface tension of water is altered by predetermined amounts of methanol). The second technique, an extension of Technique 1, evaluates the wettability of particles whose surface properties have been altered by surfactant adsorption as a
function of surface tension of the wetting fluid. Technique 2 evaluates the wettability of as-received particles in water altered by predetermined amounts of surfactant. This method provides information on the effect of surfactant addition to water on the wettability of particles. Technique 3 evaluates wettability rates of particles in different wetting fluids. Each technique is described in detail below.

**Description of AW Technique 1:** Technique 1 evaluates the equilibrium partitioning of particles into wetted and un-wetted fractions as a function of surface tension. The proportioning process is shown in Figure 2. The calculation of wettability was conducted on a mass basis. Experiments were conducted in a flask with conical bottom using the following procedure:

1. Add 1 gram of sample dust to 200 ml of pure water wetting fluid.
2. Stir the solution with glass rod.
3. Allow wetted particles to settle at the bottom of the container.
5. Separate settled wetted particles from the conical container onto the filter paper.
6. Dry wetted particles collected on filter paper in oven for 24 hours at 105 ± 5 °C.
7. Add water, if required, to the conical container and repeat Steps 3 and 5 to ensure that all particles wettable by pure water are separated. If un-wetted particles remain, proceed to Step 8; otherwise, stop the process and calculate the absolute wettability of the sample in pure water.
8. Repeat Steps 2 through 6 while adding methanol to the water in 0.5-1% increments until all particles are wetted.
9. Calculate the absolute wettability of the sample and plot it as a function of methanol concentration (or surface tension of water).

**Description of Extension of AW Technique 1:** Wettability can be enhanced by the addition of wetting agents. The addition of surfactants lowers the surface tension of the fluid and also can be adsorbed onto the particle surface and alter its surface characteristics. Both the surface tension alteration and the particle surface properties modification affect the wettability of the particle. In order to differentiate the effect of surfactants on the particle surface property, a modification of the Walker test (Walker et al., 1952) was conducted. A commercially available surfactant from Brady Mining was used in the following procedure:

1. Prepare aqueous solutions containing different concentrations of predetermined surface active agents (wetting agents and surfactant at 0.001 wt% increments).
2. Pre-treat 1 gram of sample in the prepared concentration of surfactant solution.
3. Filter and dry samples for 24 hours at 105 ± 5 °C.
4. Perform Technique 1 on the pretreated samples.

**Description of AW Technique 2:** In order to evaluate the overall effect of surfactants on the wettability of dust samples, another modification of the Walker’s test was used. These experiments were conducted in aqueous solutions containing different concentrations of
predetermined surface active agents (wetting agents). Again, surfactant from Brady Mining was used in the following procedure:

1. Prepare aqueous solutions containing different concentrations of predetermined surface active agent in 0.001% increments.
2. Add 1 gram of sample into the prepared concentration of surfactant solution.
3. Allow wetted particles to settle to the bottom of the conical glass container.
5. Separate settled wetted particles from the conical container onto the filter paper.
6. Dry wetted particles collected on filter paper in oven for 24 hours at 105 ± 5 °C.
7. Repeat the process with increasing concentrations of surfactant solution until all particles are wetted.
8. Calculate the absolute wettability of the sample and plot it as function of surfactant concentration.

Description of AW Technique 3: Upon completion of equilibrium studies on wettability using the previous three techniques, wetting kinetics were evaluated using a modification of AW Techniques 1 and 2 by halting experiments at predetermined contact times and observing coal sample wettability as a function of time. Data points from this technique can be many since cumulative wettability increases with time; however, only the following contact times were used: 2, 5, 10, and 30 seconds; 1, 5, 10, and 20 minutes.

1. Add 0.5 gram of sample to 200 ml pure water wetting fluid.
2. Stir the solution with a glass rod for the predetermined time period.
3. Allow wetted particles to settle at the bottom of the container for the same duration of time.
5. Separate settled wetted particles from the conical container onto the filter paper.
6. Dry wetted particles collected on filter paper in oven for 24 hours at 105 ±5 °C.
7. Calculate the wettability of the sample and plot it as function of time.

Fixed-time Wettability

FTW tests were done using two procedures. FTW 1 is the standard wettability technique developed at SIUC (Chugh et al., 2004). This technique was modified slightly to study effects of contact time and temperature. The set-up for FTW tests is shown in Figure 3.

FTW 1 Procedure: The following procedure is followed for estimating the general wettability of dust samples. The same procedure is followed whether or not surfactant is used. Since samples are weighed along with the filter paper, inherent moisture content in the filter paper introduces an error of 10%. This correction was applied in all tests.

1. Add 1 gram of sample (either -500 or -400+500 mesh) dust into a 3-inch diameter beaker containing 200 ml of water or water with surfactant.
2. Magnetically stir water and dust for 20 seconds.
3. Allow the entire solution to sit for 5-10 minutes. Un-wetted material floats on the surface of the water and wetted particles settle to the bottom.
4. Decant un-wetted material without agitating settled particles.
5. Filter both wetted and un-wetted fractions on standard filter paper.
6. Dry both fractions at 105 ± 5 °C for 24 hours.
7. Weigh the dry un-wetted fraction and calculate the percent wetted.

**FTW 2 Procedure:** By varying certain parameters in the FTW 1 procedure, their effects can be studied. Step 2 of the FTW 1 procedure is done at four different time intervals – 10, 15, 20, and 25 seconds – to study the effect of contact time. Also, the FTW 1 procedure was performed at four different water temperatures – 45, 65, 90, and 105 °F – to study the effect of temperature. Aluminum pans were used to eliminate the moisture content error of filter paper. PSD, XRD, ICP-AES, SEM, and ZP analyses on the parent material and its corresponding un-wetted fractions were performed for selected samples.

**Surface Charge Distribution Characteristics**

Surface charges on particles, or zeta potential (ZP), were measured using a zeta meter following the procedure described below. It uses the principle of electrophoresis and estimates the surface charge on particle under a particular set of conditions. It is important to analyze charges on particles since they influence surface characteristics that affect agglomeration or colloidal behavior of particles as well as wettability. For dust control, ZP is important since it determines whether a particle, normally wettable when no surface charges exist, would be wetted by a fluid under given charge conditions. In addition, it also determines the potential of dust to agglomerate. In the past, it was observed that Si/Al ratios and coal and pyrite content affect the ZP of a particle, which may affect surface charges and dust wettability.

1. A solution of 0.02 g/ml is prepared by adding 1 gram of sample to 50 ml of water.
2. The solution is stirred for a long time making it homogenous throughout.
3. The GT-2 cell of the zeta meter is filled with the solution and electrodes are attached.
4. Voltage is adjusted to keep specific conductance above 500 micro-mhos/cm.
5. The micrometer is adjusted so that the illuminator light passes through the sample inside the cell.
6. Electrodes are energized and the direction and velocity of particles is observed.
7. Observations are recorded including ZP and standard deviation.

**Engineering Controls**

SIUC has previously performed CFD studies to analyze air flow patterns in the face area when the CM is making straight cuts. During this year’s research, a similar CFD analysis was performed on the CM making a right turn cut. The overall approach, boundary conditions, analysis parameters, and assumptions can be found in the NIOSH Report. Eight different models were simulated as shown in Table 1.
RESULTS AND DISCUSSION

Task 1 – Physical, Mineralogical, and Elemental Characterization of Bulk Samples

Bulk samples collected from IN 6-1 mine were subjected to PSD, XRD, ICP-AES, SEM, and Quartz P-7 analyses. Results of each analysis are discussed below. The material designation followed throughout the report is shown in Table 2.

Particle Size Distribution

PSD analysis was performed on -500 mesh coal, roof, and floor samples as shown in Figure 4. Roof and floor strata dust particles are finer as compared to coal dust particles. About 30% of coal dust particles are less than 10 μm, which is the respirable fraction. The same fraction makes up 60% or more of roof and floor strata dust particles suggesting that mining roof and floor strata generates more respirable fines than mining the coal seam. Therefore, mining roof and floor strata should be avoided.

X-Ray Diffraction

Bulk samples were subjected to XRD analysis performed with a Philips X’Pert Diffractometer (Model PW3040-PRO) operating at 45 kV and 40 mA. These samples were dry-mounted in aluminum holders and scanned from 7-90° 2θ at 0.0133 degrees/second with copper K-alpha radiation. XRD is a qualitative analysis and data for one C-TB sample is included in Figure 5.

Different minerals in the samples are given in Table 3 along with their chemical formulae. Quartz is a common mineral in all coal, roof, and floor strata samples. Mineral composition in samples may vary between two different sections of a mine as well as within coal, roof, and floor strata. It is important to quantify the relative abundance of different minerals and their chemical association with other minerals. Therefore, studies are planned to perform semi-quantitative XRD analysis on quartz.

MSHA Quartz P-7

Bulk samples prepared in the laboratory were sent to MSHA for quartz analysis using MSHA’s Quartz P-7 technique. Preliminary results are given in Table 4. The upper bench of coal has the highest quartz percent.

ICP-AES

Table 5 shows elemental data for coal samples collected at two different locations (L1 and L2). Some data are reported in ppm as their concentrations were low.
Task 2 – Wettability Characterization of Bulk Samples

Surface and wettability characteristics of dust samples prepared from bulk samples were analyzed in this task using two wettability tests.

Fixed Time Wettability

FTW tests were performed on -500 (< 25 µm) and -400+500 (25-37 µm) mesh samples of roof, floor, and coal strata. Surface tension ($\sigma_t$) due to changing temperature, stirring intensity, mass fraction of sample, and contact time were the four parameters hypothesized to affect wettability. As results showed that effects of stirring intensity and mass fraction of sample are not significant, they are not discussed in this report.

General Wettability (FTW 1): Figure 6 shows general wettability data with each bar being the average of three tests. Each test was conducted at room temperature (~69-73°F) with a contact time of 20 seconds. The wettability of -500 mesh samples averaged 95%, which is about 1-2% higher than the -400+500 mesh sample. Figure 6 also shows that wettability of samples collected from two different locations in the mine are 1-15% different. In general, wettability of C-MB is lower than C-TB and C-BB samples. Repeat testing confirmed these results.

Effect of Contact Time (FTW 2): In mine environments, typical contact time varies between 10 and 25 seconds. Therefore, tests were performed at four contact times: 10, 15, 20 and 25 seconds. Both -500 and -400+500 mesh size samples were tested. Results are shown in Figure 7 with each data point representing the average of three tests. Overall, data suggests that contact time significantly affects the wettability for IN 6-1 mine dust. An average increase of ~7% in the wetted fraction with an increase of 15 seconds in contact time was found for -400+500 mesh samples. For -500 mesh dust samples, the increase was about 1%. Based on studies of samples from Illinois and Indiana, contact time between dust particles and water droplets is an important variable that affects wettability; however, improvements vary from mine to mine and within the same mine.

Effect of Temperature (FTW 2): CM spray water temperature changes since it is used to cool motors prior to dust control use. Since $\sigma_t$ of water decreases as temperature increases, experiments were conducted in the range of 7.2-40.5°C (45-105°F). Spray water temperatures higher than 105°F were not considered desirable for safety reasons. Wettability results shown in Figure 8 are based on the average of three tests.

By definition contact time does not affect absolute wettability; it affects only the fraction that gets wetted. Temperature of the wetting fluid on the other hand affects both wettability and wettability rates. As water temperature increased in the range tested, wettability increased from about 94% to 98% for -500 mesh C-TB and from 74.5% to 83% for -500 mesh C-MB. This data indicate that the effect of water temperature on coal dust wettability should be considered but results may be site specific. The concept can be used in engineering controls to enhance wetting of coal dust in the face area.
**Absolute Wettability**

**AW Technique 1:** Cumulative wettability results from tests on -500 mesh and -400+500 mesh coal samples collected from IN 6-1 mine are shown in Figures 9 and 10, respectively. In general, wettability increased with decreasing surface tension (adding methanol) of wetting fluid; however, for -500 mesh samples, wettability of C-MB is lower than both C-TB and C-BB in the surface tension range tested, and for -400+500 mesh samples, the C-TB was least wettable. Similar results came from an Illinois mine.

**Extension of AW Technique 1:** Studies were performed on -500 mesh and -400+500 mesh samples pretreated with a surfactant concentration of 0.001 wt%. Results are shown in Figures 11 and 12. In general, C-MB was less wettable as compared to C-TB and C-BB. While the wettability of all samples significantly improved due to pretreatment, wettability data for C-MB appears anomalous as pretreated samples are less wettable in pure water than untreated samples. While it is possible that the pretreatment might make the sample more hydrophobic, additional studies are underway to confirm these findings. The surfactant also had a larger effect on the coarser fraction. This is expected since the total surface area of the finer fraction is much larger than the coarser fraction and as a result would require a larger amount of surfactant to effect a similar change as that observed in the coarser fraction. Only one data point could be generated for C-TB and C-BB samples since its wettability in pure water is above 95%.

**AW Technique 2:** Experiments were conducted on -500 mesh coal dust samples. Figure 13 represents wettability as a function of surfactant concentration. All samples were completely wetted at surfactant concentration of 0.005 wt%. The C-MB sample was least wettable similar to observations in first two techniques.

**AW Technique 3:** Both -500 mesh and -400+500 mesh coal dust samples collected from two locations (L1 and L2) in the same mine were tested. Data on wettability as a function of time are plotted in Figures 14 and 15 showing an exponential increase in wettability in all cases. Data analysis shows that wettability rate is proportional to the remaining wettable fraction. As a result, there is a decrease in the wettability rate with an increase in wetting time. The following equation describes the observed trend:

\[
\frac{dW}{dt} = -kW
\]

where W is the wettable fraction, \(\frac{dW}{dt}\) is the wettability rate at time t, and k is the intrinsic wettability rate constant.

**Zeta Potential, XRD, and PSD Analyses on Wettability Test Samples**

Tables 6 and 7 provide ZP data for -500 and -400+500 mesh samples. All ZP values were found to be negative and it is observed that the middle coal bench has the largest negative potential for both size fractions. XRD analyses were performed on wetted and un-wetted fractions of one sample from the wettability tests. Analysis showed that quartz is present.
in both fractions. This indicates that it is not the quartz alone but its association with other minerals that defines wettability since pure quartz is 100% wettable. PSD analysis results for -500 mesh C-MB bulk dust sample and the corresponding un-wetted fraction from FTW tests are shown in Figure 16. Finer particles are more wettable than coarser particles. A similar conclusion was reached previously when assessing wetting characteristics using AW wettability for another mine. PSD of wetted fractions as a function of contact time did not show any trend.

**Task 3 – Collection of In-Mine Dust Samples**

In-mine sampling was conducted using protocols developed at SIUC, which are described in the NIOSH Report. Total and respirable dust concentration samples were collected near CM and RB operators for three cuts as shown in Figure 17. A cascade impactor and dust pumps were run for about 30–36 minutes for each cut.

**Total and Respirable Dust Concentration**

Dust concentration results are presented in Table 8. In total, three dust pumps were hung at each location, two for measuring total dust concentration and one for measuring respirable dust concentration. Reported dust concentration results are the average concentration of three cuts. Total dust concentration is in the range of 11-32 mg/m³ and respirable dust concentration is about 2 mg/m³. Dust concentration at the CM operator location is higher than at the RB location.

**Particle Size Distribution (Cascade Impactor)**

Air was sampled downwind of CM and RB locations at several distances. Figures 18 and 19 present PSD data for two cuts. About 50% of dust particles are less than 4 µm downwind of the CM for Cut 1. Similar data for Cut 2 was about 25%. About 30% of dust particles are less than 6 µm downwind of the RB for Cut 1. Similar data for Cut 2 is about 20%. About 64% of dust particles are less than 10 µm at 30ft downwind of the CM for Cut 1. Similar data at 130 feet downwind of the CM is about 75% indicating that finer particles travel longer distances. Similar observations were also made for Cut 2. There was no significant variation in dust distribution on the downwind side of the RB. PSD for dusts are different at CM and RB locations. It was concluded that the CM generates much finer dust than the RB.

**Task 4 – Physical and Chemical Characteristics of In-Mine Dust Samples**

**Particle Size Distribution (Wet Sieve Analysis)**

In-mine dust samples collected using gravimetric samplers and cascade impacters do not provide a sufficient amount of dust to study characteristics such as PSD, mineralogical content, and elemental analysis. To develop a correlation between bulk and in-mine dust sample characteristics, a minimum amount of 5 gram of dust is needed. To obtain an adequate sample size, the project team decided to collect dust that had accumulated on the inside of the CM wet scrubber body and on top of the CM. It was thought that this
dust should be representative of the airborne dust around the wet scrubber suction inlets. Using this approach, in-mine dust samples of about 0.6 kg were collected. These samples were wet-sieved to produce the PSD data shown in Figure 20.

Initially, wet sieving was done to separate particles in the range shown in Figure 20. About 4.6% of dust particles are less than 37 µm and about 2.7% of dust particles are less than 20 µm. Particles less than 37 µm were further subjected to PSD through Microtrac analysis which can analyze particles up to 0.02 µm.

**Particle Size Distribution (Microtrac Analysis)**

PSD data on in-mine samples collected from inside the scrubber are plotted in Figure 21. About 50% of these particles are less than 10 µm and about 30% of particles are less than 5 µm. Thus, it appears that dust generated in the face area contains a large fraction in the respirable range. This should be considered for designing engineering controls.

**Task 5: Surface and Wettability Characteristics of In-Mine Dust Samples**

FTW tests were performed on in-mine dust samples (-635 mesh, < 20 µm) collected from the CM scrubber. Results are shown in Table 9. The wetted fraction was in the range of 95-99%, similar to that observed for dust from bulk samples (97-99%). Since dust samples from within the scrubber represent dust generated from a large number of cuts from different sections of a mine and this dust has been in contact with water for a long time, observed high wettability values may not be representative of respirable dust that miners are typically exposed to.

**Task 6: Engineering Controls for Coal and Quartz Dust**

This task of CFD analysis has two major objectives: 1) Identify low air velocity (LAV) and recirculation (RC) zones, and 2) Study the effect of air leakage at the line curtain (LC) location with and without extension to the face. Effects of LAV and RC zones were evaluated by plotting velocity vectors at five feet above ground level. Air leakage and LC extension effects were evaluated by calculating airflow volume at the discharge end of the LC ($V_{LC}$). Model descriptions and conditions are found in Table 1.

**Low Air Velocity and Recirculation Zones**

**Model A1:** Velocity vectors in Figure 22 show two zones (A and B) to be both LAV and RC zones. Zone B is important since it is a high dust concentration region. There is a negative exposure impact if operators are working in either zone. The air separation point, defined as the distance traveled by air from the end of the LC to the point where it reverses direction towards outflow, is about 13 feet with only a small amount of air reaching the face where cutting is occurring.

**Model B1:** Model conditions are similar to A1, but include an air leak of one foot at the top and bottom of the LC along its entire length. Figure 23 shows that Zones A and B are
slightly enlarged, thus increasing dust recirculation. Due to leakage along the LC, the air separation point is decreased from 13 feet in Model A1 to 8.5 feet. The consequences of leakage are very low air volume reaching the face and increased recirculation in Zone A.

**Model A2:** In this model, the CM is in position to make a right turn cut but its scrubber is not operating. Figure 24 shows that Zones A and B identified in Model A1 remain the same; however, the air separation point has increased to 17 feet because of the resistance offered by the CM body to incoming air from the end of the LC. Another LAV Zone C is identified where the haulage unit (HU) operator is positioned for the first load of coal. This zone may vary as the CM advances. The CM operator is generally in a safe zone but there is an indication of dusty air getting back to the operator from the cutting face.

**Model B2:** Model conditions are similar to Model A2 but with the same air leak described in Model B1. Figure 25 shows the same enlarged Zones A and B and a decrease in the air separation point from 17 feet in Model A2 to about 10 feet. However, the CM operator is not exposed to as much recirculated air in this model as compared to Model A2. From the first four models, it is clear that air leakage at the LC shortens the air separation point and decreases the amount of fresh air reaching the cutting face.

**Model A3:** In this model, the scrubber is turned on while the CM is operating. Figure 26 shows that with the scrubber on, air flow patterns change drastically, similar to results obtained for the CM making a straight cut in the last open cross-cut (Kantipudi, 2009). Zone A is still a recirculation zone and Zone B is ventilated with fresh air coming from the end of the LC with partial recirculation. Zone C is increased compared to when scrubber is not operating. Air velocity at the end of the line curtain also increases from 5.2 feet/sec without the scrubber to about 6.5 feet/sec with the scrubber. Thus, more air is traveling further before exiting towards the outflow region. In addition, air makes a more sweeping turn diluting dust in the cutting area and further upwind, but it is not being pulled into the scrubber suction inlets. Thus, the scrubber is sucking fresh air coming from the end of the LC. As a result, the HU operator is exposed to high dust concentrations as the scrubber’s efficiency for capturing dusty air is diminished.

**Model B3:** In this model, the scrubber is turned on and air leakage is included along the LC as before. Figure 27 shows results similar to Model A3, except that air velocity at the end of the LC is decreased by 3 feet/sec. Air velocity in Zone A is also decreased but Zone B seems to be unaffected.

**Effect of LC Air Leakage on $V_{LC}$ and Air Flow Patterns**

Models A1 and B1: For Model A1 with no LC air leakage, $V_{LC}$ was 7,500 cfm or 33.5% of intake air volume, which is typical of underground conditions. For Model B1 with LC air leakage, $V_{LC}$ decreased by 85% as compared to Model A1, which is significant for the same intake volume. Thus, when air leakage occurs along the LC, only about 5% of the intake air volume is reaching the end of the LC.
**Models A2 and B2:** For Model A2, \( V_{LC} \) was 7,300 cfm, which is similar to Model A1. For Model B2, \( V_{LC} \) decreased by 83%.

**Models A3 and B3:** For Model A3, \( V_{LC} \) was 8,300 cfm. Thus, scrubber operation increases \( V_{LC} \) by about 11%. For Model B3, \( V_{LC} \) was about 4,800 cfm, a decrease of 41% as compared to Model A3. The distance between the LC and the coal rib, \( D_{CW} \), can be adjusted to increase the volume of air at the end of LC to meet MSHA’s minimum requirement of about 7,000 cfm; however, \( D_{CW} \) cannot be increased to the point where it blocks HU operator visibility. Thus, air leakage along the LC is also an important parameter which affects both air flow patterns and dust dilution in the face area.

**Effect of Line Curtain Extension on \( V_{LC} \) and Air Flow Patterns**

**Model A4:** Two additional models simulated extending the LC about 7.5 feet from its previous position. Figure 28 shows that with the line curtain extended, the air separation point is increased to 23 feet while RC in Zone A is decreased. In addition, Zone B is ventilated with fresh air with minimum recirculation. \( V_{LC} \) is about 7,300 cfm, similar to results without the LC extended.

**Model A5:** Model conditions are similar to Model A4 but with the scrubber operating. Figure 29 shows that extending the LC pushes more air toward the cutting area. Zone B is better ventilated with fresh air due to scrubber operation. \( V_{LC} \) is about 8,400 cfm, again similar to results without the LC extended. From Models A4 and A5, it is concluded that LC extension is a good practice to maintain fresh air in the face area. The limitation of this concept is that LC cannot be extended to the point where the CM operator is not visible to the HU operator.

**CONCLUSIONS AND RECOMMENDATIONS**

This multi-year project is concerned with developing characteristics of coal and silica dust that can be used to develop engineering controls that minimize the incidence of coal workers’ pneumoconiosis (black lung). During the first two years, the study focused on developing physical and chemical characteristics including wettability. In the second year, bulk and in-mine samples were collected and dust characterization studies done for a second mine using protocols developed during the first year of the study. Engineering control studies focused on analyzing air flow patterns in a room and pillar mine area when the CM in making a right turn cut. The following conclusions and recommendations summarize findings to date.

**Conclusions**

- Immediate roof and floor strata contain large amounts of quartz ranging from 20 to 25%. Coal also contains quartz but in much smaller amounts (2-5%).
- XRD data showed that quartz is evident in all samples analyzed and mineral composition was found to be varying within different sections of a mine.
XRD data showed that quartz is present in dust made from bulk samples and its corresponding wetted and un-wetted fractions. This indicates that it is not the quartz alone but its association with other minerals that defines wettability since pure quartz is 100% wettable.

PSD analysis of in-mine samples showed that most of the dust generated in the face area is in the respirable range with 50% of particles less than 10 µm. PSD analyses also showed that finer particles are more wettable than coarser material.

Absolute and fixed time wettability tests performed for dust characterization determined that wettability of coal dust with water was about (~90%). Similar data for dust from immediate roof and floor material was about 96%. On an average, C-MB is less wettable than C-TB and C-BB samples. This finding is true for both absolute and fixed time wettability.

An increase in contact time increased the wetted fraction by 1-7% for samples analyzed. This improvement varies for mine to mine and also within a mine. Increasing water temperature increased the wetted fraction by 4-8%. Both contact time and temperature are considered to be important variables for increasing the wettability of coal dust particles.

Surface charge studies indicated that more hydrophobic particles have more negative charges and cationic surfactants would be appropriate for improving dust wetting efficiency.

CFD analysis identified low air velocity and re-circulation zones when the CM is making a right turn cut. In addition, LC position and scrubber operation significantly affect air flow patterns in the face.

Air leakage along the LC can drastically reduce the volume of fresh air reaching the face and increase recirculation zones. Extending the LC to just behind the CM chassis when making this cut is a good practice and should be considered.

CFD analyses can be expanded to other cut types and a database created to use in optimizing the CM cut sequence, CM cut advancement, scrubber operation, and LC position for improved dust control.

**Recommendations**

- Development of engineering controls should consider increasing the contact time between water droplets and dust particles. Second line of defense sprays and dual filter screens in the scrubber achieve that to some extent. These concepts should be developed further before marketing to the industry for control of silica dust.
- The significance of wettability tests in dust control needs to be further investigated. Contact time may be a more critical variable than wettability characteristics, although wettability characteristics may identify the need for additional contact time.
- There is widespread knowledge in the industry that dust control is better in summer months than in winter months. This may be due to higher water spray temperatures, which improves wettability of dust as shown in this report. Additional research is required to show if increasing spray water temperature is more economic than using chemicals for dust suppression.
### Table 1: CFD model descriptions.

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Right turn cut with LC only</td>
<td>without LC air leakage</td>
</tr>
<tr>
<td>A2</td>
<td>CM about to make right turn cut, scrubber <strong>not</strong> operating</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>CM about to make right turn cut, scrubber operating</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>CM about to make right turn cut, scrubber <strong>not</strong> operating, LC extended</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>CM about to make right turn cut, scrubber operating, LC extended</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>Right turn cut with LC only</td>
<td>with LC air leakage</td>
</tr>
<tr>
<td>B2</td>
<td>CM about to make right turn cut, scrubber <strong>not</strong> operating</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>CM about to make right turn cut, scrubber operating</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2: Material designation for different horizons.

- Immediate roof top bench: IR-TB
- Immediate roof bottom bench: IR-BB
- Coal top bench: C-TB
- Coal middle bench: C-MB
- Coal bottom bench: C-BB
- Immediate floor top bench: IF-TB
- Immediate floor bottom bench: IF-BB

### Table 3: Typical mineral matter in bulk samples from IN 6-1 mine.

<table>
<thead>
<tr>
<th>Mineral Name</th>
<th>Chemical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>SiO$_2$</td>
</tr>
<tr>
<td>Pyrite</td>
<td>FeS$_2$</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>(Al$_2$Si$_2$O$_5$)(OH)$_4$</td>
</tr>
<tr>
<td>Illite</td>
<td>(K,$\text{H}_3\text{O}$)(Al,Mg,Fe)$_2$(Si,Al)$<em>4$O$</em>{10}$[($\text{OH}$)$_2$,($\text{H}_2\text{O}$)]</td>
</tr>
<tr>
<td>Calcite</td>
<td>CaCO$_3$</td>
</tr>
<tr>
<td>Halite</td>
<td>NaCl</td>
</tr>
</tbody>
</table>

### Table 4: Quartz analysis for Mine IN 6-1.

<table>
<thead>
<tr>
<th>Type of material</th>
<th>Percent Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-TB</td>
<td>4.8</td>
</tr>
<tr>
<td>C-MB</td>
<td>1.7</td>
</tr>
<tr>
<td>C-BB</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Table 5: Elemental analysis on bulk samples from IN 6-1 mine.

<table>
<thead>
<tr>
<th>Type</th>
<th>Si (%)</th>
<th>Al (%)</th>
<th>Ba (ppm)</th>
<th>Ca (%)</th>
<th>Cu (ppm)</th>
<th>Fe (%)</th>
<th>Mg (%)</th>
<th>Pb (ppm)</th>
<th>Zn (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-TB (L1)</td>
<td>2.61</td>
<td>0.94</td>
<td>77.9</td>
<td>0.07</td>
<td>80.5</td>
<td>2.2</td>
<td>0.09</td>
<td>7.9</td>
<td>32</td>
</tr>
<tr>
<td>C-MB (L1)</td>
<td>1</td>
<td>0.58</td>
<td>23.6</td>
<td>0.06</td>
<td>39.9</td>
<td>1.98</td>
<td>0.02</td>
<td>4.7</td>
<td>17.5</td>
</tr>
<tr>
<td>C-BB (L1)</td>
<td>1.81</td>
<td>0.93</td>
<td>76.6</td>
<td>&lt;0.01</td>
<td>48.9</td>
<td>2.96</td>
<td>0.09</td>
<td>9.3</td>
<td>85.4</td>
</tr>
<tr>
<td>C-TB (L2)</td>
<td>3.22</td>
<td>1.19</td>
<td>68.1</td>
<td>0.53</td>
<td>32.6</td>
<td>0.52</td>
<td>0.07</td>
<td>&lt;0.01</td>
<td>732.6</td>
</tr>
<tr>
<td>C-MB (L2)</td>
<td>0.83</td>
<td>0.48</td>
<td>18.4</td>
<td>0.02</td>
<td>29.5</td>
<td>3.2</td>
<td>0.02</td>
<td>6.7</td>
<td>177.7</td>
</tr>
<tr>
<td>C-BB (L2)</td>
<td>1.61</td>
<td>0.79</td>
<td>47.1</td>
<td>0.08</td>
<td>41.9</td>
<td>2.14</td>
<td>0.06</td>
<td>3.7</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Table 6: ZP for -500 mesh material made from IN 6-1 mine bulk sample.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Zeta Potential (mV)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-TB</td>
<td>-36.2</td>
<td>2.156</td>
</tr>
<tr>
<td>C-MB</td>
<td>-59.6</td>
<td>3.743</td>
</tr>
<tr>
<td>C-BB</td>
<td>-44.6</td>
<td>3.585</td>
</tr>
</tbody>
</table>

Table 7: ZP for -400+500 mesh material made from IN 6-1 mine bulk sample.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Zeta Potential (mV)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-TB</td>
<td>-13.1</td>
<td>1.82</td>
</tr>
<tr>
<td>C-MB</td>
<td>-29.5</td>
<td>2.781</td>
</tr>
<tr>
<td>C-BB</td>
<td>-20.4</td>
<td>2.156</td>
</tr>
</tbody>
</table>

Table 8: Total and respirable dust concentrations at RB and near the face area.

<table>
<thead>
<tr>
<th>Location</th>
<th>Concentration (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near RB (T)</td>
<td>10.9</td>
</tr>
<tr>
<td>Near RB (T)</td>
<td>13.4</td>
</tr>
<tr>
<td>Near RB (R)</td>
<td>1.8</td>
</tr>
<tr>
<td>10 and 50 feet from the face (T)</td>
<td>31.5</td>
</tr>
<tr>
<td>10 and 50 feet from the face (T)</td>
<td>23.2</td>
</tr>
<tr>
<td>10 and 50 feet from the face (R)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

(T=total dust concentration, R = respirable dust concentration).

Table 9: Wettability of in-mine samples collected from CM scrubber.

<table>
<thead>
<tr>
<th>Mesh Size</th>
<th>Wetted fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-400+500 (25 µm - 37 µm)</td>
<td>94.5</td>
</tr>
<tr>
<td>-500+635 (20 µm - 25µm)</td>
<td>95.2</td>
</tr>
<tr>
<td>-635 (&lt; 20 µm )</td>
<td>98.2</td>
</tr>
</tbody>
</table>
Figure 1: Channel sampling, dust preparation, and characterization protocols.

Figure 2: Partitioning of hydrophilic and hydrophobic fractions in the AW test.
Figure 3: FTW set-up.

Figure 4: PSD of -500 mesh material made from bulk samples from IN 6-1 mine.

Figure 5: XRD Analysis of -500 mesh C-TB bulk sample from IN 6-1 mine.
Figure 6: Results from FTW-1 testing of bulk sample from IN 6-1 mine.

Figure 7: Wettability as a function of contact time for sample from IN 6-1 mine.
Figure 8: Wettability as a function of temperature for samples from IN 6-1 mine.

(a) -500 mesh, C-TB
(b) -500 mesh, C-MB

Figure 9: Wettability as a function of surface tension, -500 mesh IN 6-1 coal.

Figure 10: Wettability as a function of surface tension, -400+500 mesh IN 6-1 coal.
Figure 11: Wettability of -500 mesh coal from IN 6-1 mine pretreated with 0.001 wt% surfactant as a function of surface tension.

Figure 12: Wettability of -400+500 mesh coal from IN 6-1 mine pretreated with 0.001 wt% surfactant as a function of surface tension.
Figure 13: Wettability of -500 mesh coal from IN 6-1 mine as a function of surfactant concentration in the wetting fluid.

Figure 14: Wettability of -500 mesh coal from L1 in IN 6-1 mine as a function of exposure time.
Figure 15: Wettability of -400+500 mesh coal from L2 in IN 6-1 mine as a function of exposure time.

Figure 16: PSD for bulk dust sample and corresponding un-wetted fraction.
Figure 17: In-mine sampling locations for three cuts at IN 6-1 mine.

Figure 18: PSD results from in-mine sampling near CM.

(a) Cut 1
(b) Cut 2
(a) Cut 1
Figure 19: PSD results from in-mine sampling near RB.

(b) Cut 2

Figure 20: PSD of wet-sieved in-mine samples from IN 6-1 mine.

Figure 21: Microtrac PSD analysis of in-mine sample from IN 6-1 mine.
Figure 22: Velocity vectors – Model A1.

Figure 23: Velocity vectors – Model B1.

Figure 24: Velocity vectors – Model A2.

Figure 25: Velocity vectors – Model B2.

Figure 26: Velocity vectors – Model A3.

Figure 27: Velocity vectors – Model B3.
Figure 28: Velocity vectors – Mode A4.

Figure 29: Velocity vectors – Mode A5.

REFERENCES


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