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Respirable coal mine dust characteristics in samples collected in central and northern Appalachia

Victoria Johann-Essex[a], Cigdem Keles[a], Mohammad Rezaee[b], Meredith Scaggs-Witte[a], Emily Sarver[a,*]

[a] Department of Mining and Minerals Engineering, Virginia Tech, Blacksburg, VA 24061, USA
[b] John and Willie Leone Family Department of Energy and Mineral Engineering, Earth and Mineral Sciences (EMS) Energy Institute, The Pennsylvania State University, University Park, PA 16802, USA

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ABSTRACT

Increased incidence of lung diseases among underground coal miners in parts of Appalachia in the US has prompted new research respirable dust characteristics. Between 2014 and 2015, 210 samples of respirable dust were collected in various locations of eight underground coal mines in three distinct Appalachian regions. The mines vary in terms of mining method, coal seam thickness, and mined strata geology. A computer-controlled SEM-EDX routine was used to analyze the dust to determine distributions of particle size, aspect ratio, and mineralogy classification. Statistical analysis of results showed that significant differences in dust characteristics exist between and within mine regions, and by sampling location. Most notably, samples from mid- and south-central Appalachia had relatively higher percentages of alumino-silicates and quartz, consistent with cutting more rock along with the coal in these mines; whereas, samples from northern Appalachia had higher percentages of carbonate, which is largely attributed to heavy rock dusting in the sampled mines. Compared to other regions, samples from mid-central Appalachia also had higher percentages of very small particles and samples from south-central Appalachia had higher percentages of elongated particles. Overall, samples collected near production activities or in return airways had higher percentages of small particles than in other sampling locations. Based on samples collected right at the mine face, results additionally suggest that cutting rock strata may produce an inordinate amount of respirable dust as compared to cutting coal.

1. Introduction

Respirable dust is the fraction of airborne particulates that can be deposited anywhere in the lung gas-exchange region (WHO, 1999). While the size range of respirable particles is specific to an individual, for the purposes of dust sampling and regulatory limits respirable dust has been operationally defined as particles having an aerodynamic diameter < 10 μm and a median cut point (d_{50}) of 4 μm, when collected with a size selective sampler such as a cyclone (ACGIH, 1999). Respirable dust is a prominent occupational health hazard (IARC, 1997; ISO, 1995; OSHA, 2010, WHO, 1999). Exposures in coal mining environments can result in lung diseases such as Coal workers' pneumoconiosis (CWP, sometimes referred to as "black lung") and silicosis, which are linked specifically to dust with significant fractions of crystalline silica (i.e., quartz) (Castranova and Vallyathan, 2000).

Coupled with better ventilation and dust abatement strategies, regulatory limits on respirable dust exposures have resulted in substantial declines in disease incidence for several decades in the US (CDC, 2006; NIOSH, 1974; Suarthana et al., 2011; WHO, 1999). However, since the late 1990s, a resurgence in disease incidence has been noted (CDC, 2006; Suarthana et al., 2011; Blackley et al., 2014). The most disconcerting trends have been observed in parts of central Appalachia (e.g., MSHA districts 4 and 12), and many new cases of CWP and/or silicosis appear to be advanced or presenting in younger miners (Attfield et al., 2011, CDC, 2006; Suarthana et al., 2011; Blackley et al., 2014; Laney et al., 2012). A cluster of 60 new cases of progressive massive pneumoconiosis (PMF), which is the most severe form of CWP, was reported in 2016 by a single clinic in eastern KY (Blackley et al., 2016).

Potential factors contributing to these trends have been speculated, including changes in specific dust characteristics (e.g., Colinet et al., 2010; Antao et al., 2005; Laney and Attfield, 2010; Mischler et al., 2013; Sapko et al., 2007). For instance, extraction of increasingly thinner coal seams has resulted in more roof and floor rock being cut

* Corresponding author.
E-mail address: esarver@vt.edu (E. Sarver).

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(Bennett et al., 1979; Landen et al., 2011; Page and Organiscak, 2000; Pollock et al., 2010). Because local geologic strata often include sandstones, shales and slates surrounding the coal seams, mining more rock may expose workers to higher concentrations of respirable quartz and silicate particles – both of which may play a role in development of pneumoconiosis-type diseases in coal miners in this region (Cohen et al., 2016; Joy, 2012; Landen et al., 2011; Laney et al., 2012; Pollock et al., 2010). Moreover, exposure conditions might be significantly different now than in past years. As mine sizes and work forces have gradually decreased in central Appalachian, miners may be working longer hours, in varying job roles, and moving between operations, all of which could lead to exposures to variable dust concentrations and compositions (Page and Organiscak, 2000; Suarthana et al., 2011; WHO, 1999; Laney et al., 2012).

Apart from dust mass concentrations and specific constituents, dust particle size and shape could also be important (Corn et al., 1972). Recent studies suggest that, within the respirable range, smaller particles may be more harmful to health than larger particles (e.g., Mischler et al., 2016); and advances in mining equipment have certainly resulted in more powerful cutting (i.e., of coal or rock during mining and drilling), which can yield smaller particles (Colinet et al., 2010; Sapko et al., 2007). It is also established that dust particle deposition mechanisms in the lungs (e.g., sedimentation vs. impaction vs. interception vs. diffusion) can be dependent on both size and shape (e.g., elongation, angularity, roughness) (Watkins-Pitchford and Moir, 1916; Beeckmans, 1965; WHO, 1997).

Considering all of the above, a better understanding of dust characteristics might provide key insights into observing miner health outcomes. To this end, a large collection respirable dust samples were gathered and characterized from coal mines in central and northern Appalachia. The samples were evaluated via computer-controlled scanning electron microscopy with energy dispersive X-ray (CCSEM-EDX) using a routine previously developed by the authors (Johann-Essex et al., 2017). Resulting data were analyzed in order to determine whether significant differences exist in particle size, aspect ratio, and mineralogic class distributions 1) between distinct mine regions, 2) within mine regions, or 3) between sampling location categories. Findings are discussed with respect to various mine factors that may control dust characteristics. Relationships between mineralogy and particle size and aspect ratio were also explored, as was spatial variability between replicate samples.

2. Materials and methods

2.1. Dust sample collection

Between July 2014 and July 2015, a total of 210 respirable dust samples were collected by the research team in eight underground coal mines. Six mines were classified as being in central Appalachia (MSHA districts 4 and 12) and two were in northern Appalachia (MSHA districts 2 and 3). Some key characteristics of each mine are highlighted in Table S.1 of the Supplemental information (SI), and the general geographic locations of the mine regions are shown in Fig. S.1. The Northern Appalachian (NA) mines sampled for this study are longwall operations (with continuous miner development sections), generally characterized by relatively thick coal seams having few partings of shale, but some pyrite and other heavy mineral content; high production rates; and large workforces. The Central Appalachian mines included in this study, on the other hand, are continuous miner operations with relatively thin coal seams having more shale partings, oftentimes a sandstone roof and floor, and less pyrite and other heavy minerals; low production rates; and small workforces. Due to the thin coal seams and usual continuous miner cutting heights, these mines often cut significant floor and/or roof rock. Two distinct sub-regions were defined within central Appalachia: mid-central Appalachia (MCA, MSHA district 4) and south-central Appalachia (SCA, MSHA district 12). MCA mines are typically very small and have even thinner coal seams than SCA mines; they are also known to have somewhat higher respirable silica (mass) content in dust samples collected for compliance (see Table S.1).

Dust samples were collected using standard equipment (described below) in various locations within each mine (see Fig. S.2). All locations were designated in one of four general categories: in the "intake" (including near the headgate of a longwall); near the coal "feeder" or conveyance system; near major "production" activities (e.g., coal cutting by continuous miner or along the midface of a longwall, and roof-bolting); and in the "return" (including near the tailgate of a longwall), which on occasion had an operating trickle duster (i.e., to apply inert rock dust to mine surfaces[1]). In most instances, sampling equipment was hung from roof bolts toward the center of the airway being sampled. Occasionally, this was not possible due to safety concerns or interference with mine activities, so samplers were hung near the rib or on a piece of operating equipment (e.g., roof bolter).

In all cases, samples were collected in sets of at least two. For sets containing only two or three samples, they were generally taken side-by-side (i.e., cassettes just a few centimeters apart and oriented in the same direction), such that the samples can be considered true duplicates or triplicates. In some mines, four samples were collected in a set using the configuration shown in Fig. 1. At least one sample set (i.e., 2–4 samples) was collected in each location category in each mine (Table S.2). In most mines, more than one location in a category was sampled (e.g., roof bolter and continuous miner samples are both categorized as "production"). In several instances, the same mine location was sampled multiple times (i.e., multiple sample sets were collected, each at a different time). In total, 76 sample sets were collected: 25 in the NA region, 22 in MCA, and 29 in SCA.

Samples were typically collected over timeframes of approximately 2–4 h, and all samples within a set were collected simultaneously. Dust was collected directly onto 37-mm diameter polycarbonate (PC, 0.4 μm pore size) filters in two-piece cassettes. The PC filters are appropriate for SEM work because their smooth surface and homogenous pore-size provides an ideal background for imaging and EDX analysis (US EPA, 2002). Escort ELF dust sampling pumps were used with nylon 10 mm Dorr-Oliver cyclones to remove particles larger than 10 μm (i.e., as specified for dust sampling in coal mines per 30 CFR part 70). It should be noted that the cyclone yields a gradual curve for separation efficiency, with d_{30}, d_{50} and d_{80} cut sizes of about 5, 4 and 3 μm, respectively, at the 1.7 L/min sampling flow rate. This means that capture efficiency is higher for smaller particles, and therefore the size distribution of captured particles is likely skewed toward smaller sizes on an absolute basis. However, results of samples collected under the same conditions can be compared relative to one another.

2.2. Dust characterization

Dust samples were prepared for SEM-EDX analysis by mounting a 9-mm filter subsection (cut from the center of each sample) to an aluminum stub, and sputter coating with Au/Pd for electrical conductivity. A computer-controlled routine (developed by Johan-Essex et al., 2017, based on a manual method by Sellaro et al., 2015) was used to characterize approximately 500 respirable dust particles per sample, such that distributions in size (i.e., cross-sectional diameter), aspect ratio (i.e., ratio of the long to intermediate particle diameter), and mineralogy classification could be determined. The CCSEM-EDX routine includes five defined mineralogy categories, which are expected to cover

[1] Dusting mine surfaces with inert rock particles is a common practice in underground coal mines to reduce explosibility hazards related to coal dust. Rock dusting is required by federal regulation in the US (Title 30, Code of Federal Regulations, Section 75.403). Rock dust products are most often made from high purity limestone or dolomite (i.e., carbonate minerals) and may have considerable content in the respirable size range (Colinet and Listak, 2012).