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Characterization of respirable dust samples generated from picks at differing stages of wear

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ABSTRACT: Respirable dust poses serious long-term health issues to personnel working in mining and civil projects where mechanized mining and tunneling machines are used for rock excavation. These machines, such as longwall shearers, roadheaders, and continuous miners use picks to cut rock. However, dust is generated each time the pick tip contacts the rock surface, contributing to the respirable dust in the work environment immediately at the rock surface, or further down in production, such as at transfer points. The purpose of this study is to characterize respirable dust particles generated at the pick tip at various stages of pick life, such as new, moderately worn, and worn-out. Understanding how much dust is generated and characteristics of dust particles in terms of size distribution, shape, and mineralogy throughout the life-cycle of the pick will provide a basis to mine and tunnel operators for changing out picks to mitigate dust generation at the source. This paper discusses the findings of size distribution, shape, and mineralogical characteristics of the dust samples from full scale cutting of an igneous rock block cut with picks at new and moderately worn levels of wear.

1 INTRODUCTION

Respirable and inhalable dust particles, or particles less than 10μm in aerodynamic diameter, pose a major health concern for occupational workers in mining environments. Breathing in respirable particles can cause irreversible and long-term diseases such as coal workers pneumoconiosis (Department of Health and Human Services 2011), silicosis (Ross and Murray 2004) and other lung diseases (Pope III et al. 2002). From the beginning of mining and striking rock, mining workers have coped with these various lung diseases, which the US Mine Safety and Health Administration (MSHA) has recognized and attempted to address. MSHA regulations such as *Lowering Miners' Exposure to Respirable Coal Mine Dust Including Continuous Personal Dust Monitors* established in 2014 (MSHA 2014) was implemented to update previous dust laws to be more applicable in the modern workforce. This new rule changed the permissible respirable dust concentration limit from 2 to 1.5 mg/m^3 and requires continuous personal dust monitors to be worn by mine operators.

Although there are regulatory bodies, such as MSHA to issue citations to mines that have workers exposed to more than 1.5 mg/m^3 respirable dusts in an 8 hour shift, there are still mine workers contracting lethal lung diseases today. With this, there is also an increasing trend for the number of workers with lung diseases since the 1990s and a continued rise in numbers recent years (Blackley et al. 2016; Lee et al. 2014; Zosky et al. 2016). Regulations have benefited the working environment for mining operators to limit exposures to dust, however, there is still a need to understand the effects of dust particles on the lungs and reduce exposure limits. The ability to lower dust level exposures in a mining operation is necessary to protect occupations workers

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The National Institute of Occupational Health and Safety (NIOSH) recommends enabling dust exposure mitigation techniques to protect mining workers. Their recommended techniques range from the least effective, where workers wear personal protective equipment (PPE), to the most effective, where dust is eliminated at the source (Cecala et al. 2019). The purpose of the research presented in this paper is to understand the characteristics of the inhalable and respirable dust particles at the source of mechanical excavations, or at the point of contact between the rock and cutters. Understanding these characteristics will aid mines to take measures that will eliminate the particles generated at the source, under pick tips, by managing the bit wear and replacement protocols in balancing cutting efficiency with amount of dust and fines generation. In the end, these measures will reduce the number of mine workers contracting harmful lung diseases.

Conical, or bullet, picks are commonly used on roadheaders, longwall shearers, or other machines are commonly used to break rock in mechanical excavations (Deshmukh et al. 2020; Talbo and Sevigné 1986; Roxborough, King, and Pedroncelli 1981). Dust is generated at the pick tip of the machines and various pick parameters, such as tip geometry, body profile, and tip angle change the dust characteristics generated during drilling (Zhou et al. 2020; Hanson and Roepke 1979; Plis, Wingquist, and Roepke 1988). Naturally during excavation operations, pick geometry changes are they wear out due to abrasion or other forms of failure. Therefore, pick characteristics change during cutting which require change in cutting forces and amount of dust generated.

There is little understanding on the dust characteristics generated from change in geometry from new picks to worn picks, such as the size distribution and shape of particles. This paper focuses on understanding the characteristics of dust particles generated from a new and moderately worn conical pick used for mechanical excavations on igneous rock. It is possible in the future that dust control measures, such as eliminating the dust at the source, with a different pick will help to protect workers in the mining industry. Other measures, such as implementing substitution with silica dust control coating or increasing administrative controls to use water jets, could be implemented to limit dust exposures (Cecala et al. 2019) during times if increased hazardous dust.

2 METHODS

2.1 *Sample preparation and full scale testing*

An igneous rock block was used for experimentation with the Linear Cutting Machine (LCM) at the Earth Mechanics Institute (EMI) at the Colorado School of Mines. The sample was a composition of an igneous silica based rock with minor occasional non-host calcite pebble intrusions. The sample also contained joint sets in multiple directions. The sample was tested in the rock mechanics lab at the Colorado School of Mines, which showed the sample's unconfined compressive strength (UCS) to be 95 MPa.

The rock sample was placed into a metal rock box and confined by casting the sample in concrete to firmly hold the rock in place. From here, the rock sample in the steel box was placed onto the LCM sled where the box was moved linearly such that the pick contacts the rock's surface at a constant speed and in a linear manner to simulate rock cutting in a full scale testing process. Multiple lines of cuts are made across the rock's surface as seen in Figure 1.

The spacing between the cut lines was selected to be 2 inches for this experiment, which is typical for a machine cutting in igneous rock with a USC of 95 MPa. The penetration, or depth, of the pick into the rock sample was selected to be 0.1 inches for the preliminary experiments. These parameters were chosen because they are representative of industry spacings and penetrations used for the specific rock type. The spacings and penetrations are determined by optimizing the specific energy and normal forces when cutting various hard rocks (Bilgin et al. 2006).

Figure 1. The Linear cutting machine with the dust curtain surrounding the pick and the cast igneous rock block installed.

2.2 *Dust collection setup*

In order to collect inhalable and respirable dust, a dust curtain was built around the LCM pick and saddle to hold in dust generated with cutting and to keep other unrepresentative lab dusts from being collected. Figure 1 shows the clear and translucent dust curtain around the pick and saddle while Figure 2 shows just the shell of the dust curtain with the front panel removed.

To collect dust, personal ELF Escort dust pumps running at 1.7 LPM were connected to 10mm nylon Dorr-Oliver cyclones. These cyclone are built for capturing particles with aerodynamic diameters smaller than 10 microns to closely simulate dust penetration in human lungs (Cecala et al. 1983). Filters in cassettes were then attached to the cyclones to collect dust particles, where the cyclone and filter-cassette setup was mounted to the LCM close to the

Figure 2. View of cyclone setups attached to saddle with tubing piped out of the curtain to pumps. The front panel and lower skirt of the dust curtain were removed for the photo. Blue star indicates location of the pick tip behind the clamp.

pick tip as seen in Figure 2. Additionally, 1.7 LPM was used because at this flow rate the 10mm nylon Dorr-Oliver cyclones have the highest collection efficiency and the NIOSH standards 0600 and 7500 testing procedures use 1.7 LPM for analyzing dust particles (Hinds 1999; NIOSH 1998). Tygon tubing from the cyclones were extended out of the dust curtain and over to their respective pumps because there was insufficient space in the dust curtain for the pumps as seen in Figure 2.

The various filters used to collect dust include professionally pre-weighted PVC filter cassettes, as well as PVC and PC filters loaded into cassettes at EMI. Cassettes were loaded prior to each test and removed for further analysis after each test. The pre-weighted filters were used to send back to the professional lab for analysis on the NIOSH 0600 and 7500 standards. A consistent sampling and analysis protocol was developed to assure reliability of the measurements, as the objectives of the study is to compare the dust generated by picks at different stages of wear.

The dust collection setup is limited to collect only inhalable and respirable dust particles, and is unable to collect all particles generated. With this, the cyclones used for dust collection are built to collect particles 0.4 to 10 micrometers in aerodynamic diameter on the filters and deposit any other airborne dusts, up to 100 micrometers in aerodynamic diameter, into the grit pot. The system is therefore limited to this size in particles and does not exclusively include nanoparticles. Additionally, the system cannot collect all the particles generated. Therefore, the samples collected are a representative sampling of the total dust generated.

2.3 *Pick wear measurement and wear quantification*

Conical picks were used for cutting the rock, where a new pick and moderately worn pick were tested. Conical picks were chosen for experimentation because they are common cutting tools used for breaking and removing hard rock. Conical picks are used on a wide variety of machines, including roadheaders, and are used in many civil and mining applications (Dewangan, Chattopadhyaya, and Hloch 2015; Su and Akkaş 2020).

As seen in Figure 3, a circle is superimposed at each of the pick tips, where the new pick tip has a diameter of 4.29mm and the worn pick tip has a diameter of 9.98mm. Diameter of the tip is used to quantify pick wear because the angle that makes the tip will stay the same throughout cutting. Only the tip itself will become more blunt over time. With this, the tip radius contacting the rock face surface determines the size of the pressure bubble under the pick tip at the contact point. The wider the tip, the higher the forces, higher specific energy of cutting (Bilgin et al. 2006; Kim, Rostami, and Swope 2012), and most likely the higher volume of fines generated in cutting the same rock at identical spacing and penetration. With this, the moderately worn pick was generated by artificially wearing down a new pick tip by hand with a Dremel and a lathe.

Figure 3. Comparison of a new pick tip to a moderately worn pick tip with 0.7x magnification for both pick tips with circle superimposed to show larger radius for moderately worn pick.

3 PRELIMINARY TEST RESULTS

3.1 *Size distribution*

A Microtrac particle size analyzer instrument was used to determine the size distribution of the airborne particles captured with the cyclones. The particles on the PC filters were rinsed with de-ionized water into the Microtrac instrument and the inhalable material from the grit pot in the cyclones was also added. PC filters were used for this analysis because the PC filters capture the respirable particles at the surface, instead of the PVC filters which capture particles within the woven fibers (Hinds 1999).

The size distribution for particles generated with the new pick and the moderately worn (assumed mid-life) pick are shown in Figure 4. The aerodynamic diameter of the particle is on the x-axis and the normalized frequency of particles with respective sizes, or the "percent channel", is on the y-axis. Therefore, the frequency of particle size detected in each channel is plotted against mass median aerodynamic diameter.

3.2 *NIOSH standards*

A third party, professional lab was utilized to perform NIOSH standard analyses on the dust collected during tests with the new pick and the worn pick. Pre-weighed PVC filters in cassettes were used to collect dust and then sent back to the lab to have the NIOSH 0600 standard procedure and NIOSH 7500 standard procedure performed on the samples. The NIOSH 0600 standard provides the dust concentration for the volume of air collected and the NIOSH 7500 standard provides the amount of μg of cristobalite, quartz, and tridymite in the collected samples. It is critical to perform these tests on the samples because these are the tests performed and used in industry that help regulate dust exposure techniques.

The data received back from the lab is presented in Table 1. As seen in the normalized results from the NIOSH 0600 standard, the concentration of the dust from the moderately worn pick in μg/min was almost double the concentration from the new pick. With this, the results from the NIOSH 7500 standard reveal that the moderately worn pick generated slightly more micrograms of cristobalite and quartz compared to the new pick, although neither pick generated any tridymite.

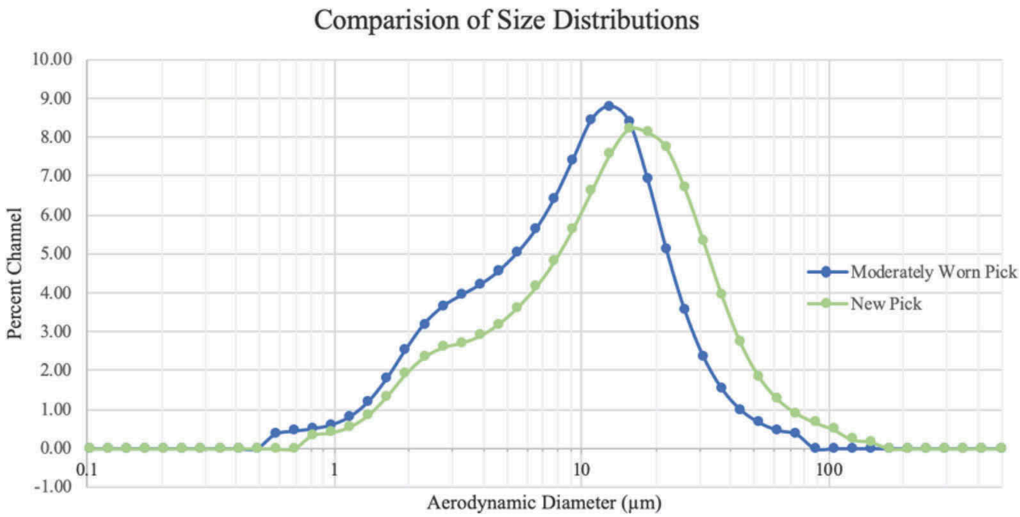

Figure 4. Size distributions of particles for new and moderately worn pick.

Table 1. Results from NIOSH 0600 and 7500 lab tests.

Analysis	Result	New Pick	Moderately Worn Pick
NIOSH Standard 0600		**μg/min**	**μg/min**
	Concentration	121	250
NIOSH Standard 7500		**μg/sample**	**μg/sample**
	Cristobalite	7.05	10
	Quartz	114	160
	Tridymite	0	0

3.3 *Optical imaging*

A Nikon optical microscope paired with the automated Clemex image analysis package was used at 500x magnification to analyze the dust collected on the surface of the PC filters. PC filters were used for this analysis because the PC filters capture the respirable particles at the surface, instead of the PVC filters which capture particles within the woven fibers (Hinds 1999).

By utilizing the Clemex image analysis package, a program was written to capture multiple frames along the surface of the filter, pick out the specific dust particles, and automatically measure particle traits. Significantly more dust particles were picked out and analyzed with the program in a short amount of time in comparison to picking out particles by eye and measuring by hand. With this process, ten frames equally spaced at the middle of each filter were captured where each photo was comprised of multiple focus layers. Then, with these captured photos, grey thresholding separated the particles from the background substrate of the PC such that only the shapes of the dust particles were analyzed. This was followed by a few imaging cleanup steps that ensured any particles touching one another were split into two entities. Finally, automated object measures were applied to the particles to achieve the “aspect ratio” and the “roundness” for each particle. Aspect ratio is calculated as the length of the longest dimension divided by the length of the shortest dimension. Roundness is calculated as the ratio of the surface area of the particle to the longest dimension across the particle’s surface as demonstrated in equation 1 below.

$$x = \frac{4 \text{ x } \mathrm{A}}{\pi \text{ x } L^2} \tag{1}$$

Where x = roundness (unitless); A = surface area of the particle (μm^2); L = length of longest distance across the particle’s surface (μm)

Over 90 particles were picked out on the new pick filter and over 100 particles were picked out on the moderately worn pick filters with the program and analyzed. The graphical data is presented in Figure 5 as histograms to see the number of particles that had specific values for the aspect ratios and roundness. The bin size is 0.2 for aspect ratio and 0.1 for roundness.

The aspect ratio between 1.2 and 1.4 was dominant in both the new pick and moderately worn pick, however, the moderately worn pick’s highest aspect ratio was 2.2, while the new pick’s highest aspect ratio was 3. The roundness measures between 0.65 and 0.75 were also dominant in both picks. There was also no deviation between the smallest and largest roundness measures as both the new and the moderately worn pick ranged from 0.35 to 1.05.

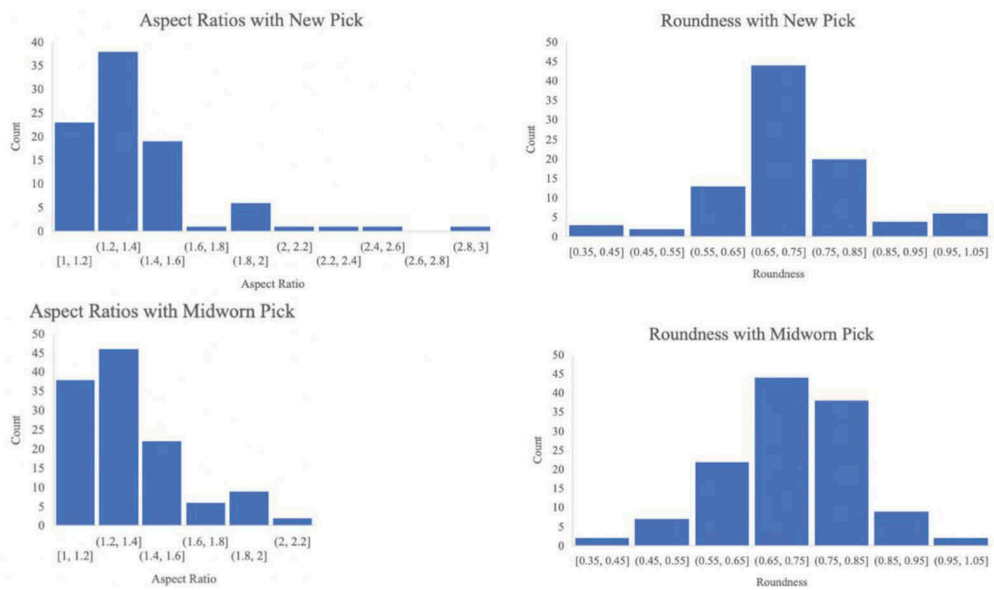

Figure 5. Aspect ratios and roundness measures for particles deposited on PC filters.

4 DISCUSSION AND ANALYSIS

4.1 *Size distribution*

The graphical representation of the inhalable and respirable size distributions for the new and moderately work pick show a shift in particle sizes. The new pick generates slightly higher particle sizes than the moderately worn pick. As seen in Figure 4, there is a similar size distribution shape of inhalable and respirable particles, however there is a shift in the curve where the moderately worn pick seems to generate smaller particles. The moderately worn pick generated the highest frequency of particles at 13.08μm in aerodynamic diameter, whereas the new pick generated the highest frequency of particles at 15.55μm. The moderately worn pick also generated particles that are as small as 0.578μm in aerodynamic diameter and the new pick generated particles that are as small as 0.817μm in aerodynamic diameter. With this, the moderately worn pick generates slightly smaller particle sizes than the new pick.

Smaller particles sizes generated from the moderately worn pick could be attributed to the higher forces needed for rock cutting. Therefore, higher stresses at the contact point leads to further crushing of the rock in this zone. It is anticipated that with further wear of the pick tip, the trend will continue to smaller particles.

Because the moderately worn pick generates a size distribution of smaller particles, it is considered that picks generate more hazardous dust particles as they wear out and the tip diameter increases. Particles smaller than 10μm in aerodynamic diameter, and particles smaller than 2.5μm, are significantly more dangerous to human health because they can penetrate the alveoli (Cecala et al. 2019). Therefore, more care and caution should be taken with cutting operations using moderately worn picks where more stringent dust control measures should be applied. Alternatively, to keep dust generation and amount of respirable particles in the air to a minimum, a more strict bit management protocol can be developed and followed.

There is some uncertainty in the shift of particle size distribution in the preliminary experiments. There was only one dust collection performed for each pick wear in the full-scale cutting tests, and while the general trends is intuitive, the quantitative results and conclusions drawn need to be confirmed with repeated tests. It would also be critical to test a fully worn pick tip wear to observe any possible trends of dust size distributions from new to fully worn pick.

4.2 *NIOSH standards*

The results obtained by the NIOSH 0600 and 7500 standards reveal a significant difference in concentration of airborne dust particles and an inconclusive difference in material composition. The NIOSH 0600 standard revealed that the moderately worn pick generated 250μg/min of dust while the new pick generated 121μg/min of dust. The concentration of dust from the moderately worn pick is over double the dust concentration from the new pick. Therefore, more care and caution should be taken with cutting operations using moderately worn picks.

Additionally, the generation of more dust particles for a moderately worn pick in this experiment parallels the findings in other experiments where a less sharp pick tip angle generates more dust (Zhou et al. 2020; Hanson and Roepke 1979). The results from the full-scale rock cutting tests in this experiment support the previous findings from other experiments. Therefore, it is recommended that more caution is taken when cutting with picks that are moderately worn in comparison to new picks because it is expected that more dust is generated with moderately worn picks.

The NIOSH 7500 standard revealed that the moderately worn pick generated airborne dust samples with comparable levels of cristobalite when compared to the new pick. With 10μg cristobalite per sample generated from the moderately worn pick compared to 7.05μg cristobalite per sample from the new pick, the difference could be independent of the pick wear. However, the NIOSH 7500 standard revealed that the moderately worn pick generated airborne dust samples with slightly higher levels of quartz when compared to the new pick. The moderately worn pick generated 160μg per sample of quartz compared to the new pick that generated 114μg per sample of quartz. The differences in mineral concentrations of quartz could result from pick wear of the from nature of different layers in the igneous rock block. Therefore, it could be alterations or changes in the rock itself that caused the difference in amount of quartz. It is inconclusive whether the slight increase in quartz from the new pick to moderately worn pick is due the rock or due to the changing pick tips. Further research needs to confirm the findings presented in this paper with additional cutting tests and with a fully worn pick to draw conclusions on any possible trends.

4.3 *Particle sizes in optical imaging*

The results obtained on the aspect ratios and roundness measures of particle shapes from the moderately worn and the new pick show no statistical significance. One-tailed statistical significance t-tests were performed on the raw data to determine if there was a difference between the groups. Using two-sample, unequal variance assumptions, the p-value for aspect ratio and roundness measures was much greater than 0.05, which was 0.26 and 0.39 respectively. This means that there is no significant difference in the aspect ratio of particles or in the roundness of particles when changing between new picks and moderately worn picks. The implications could be that transport properties of these particles are similar, which could affect operations downstream. Furthermore, if the impact of dust on health of workers is dependent on the shape of respirable particles, the preliminary test results show that there is no notable distinction between new and worn bits relative to the issue. Hence, no recommendations can be made that pertain to particle shape in relation to pick wear.

In order to supplement the limited study on particle shape, it would be necessary to use field emission scanning electron microscope (FE-SEM) analysis. Other researchers have utilized FE-SEM to look at particle shapes while determining particle shapes (Sarver, Keles, and Rezaee 2019; Sellaro 2014), which would complement the current research. The initial analysis indicates that there is some uncertainty in the particles picked up and analyzed with the optical microscope because it is possible that some of the particles were not fully separated and the optical imaging took frames of clusters, or clumps, of dust particles. At the micrometer scale, FE-SEM studies would help distinguish between single particles on the filter and clusters of particles. Meanwhile, other properties for particle size and shape distribution are under consideration, such as dispersing particles in a fluid medium to prevent coagulation.

5 CONCLUSIONS

Full scale cutting tests of an igneous rock sample with a new and moderately worn conical pick were completed in order to analyze the dust characteristics for both wear conditions and tip geometries. The moderately worn pick generated a size distribution that favored smaller particle sizes of inhalable and respirable particles compared to the new pick. The moderately worn pick also generated more overall dust, as the normalized concentration level was over double the levels of the new pick. The results of the preliminary analysis of the dust particles indicate that there are no differences in quartz and cristobalite concentrations between the moderately worn and new pick are due to the pick wear. With this, there is no statistically significant difference in the aspect ratio or the roundness measures of the particle shapes between the moderately worn and new pick. The main difference between the moderately worn and new pick is that more fines and respirable dust are generated, and a greater number of smaller particles are generated with the moderately worn pick. Therefore, in operations where picks are moderately worn, it should be understood that dust levels will be higher and more dangerous, such that the appropriate engineered dust mitigation measures can be taken to protect workers, or a modified bit management system is adopted. Limitations of this experiment include the nature of performing a single test on a single rock type. It is recommended to repeat this experiment to obtain more data from multiple tests and include a fully worn pick.

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