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Characterization of Respirable Dust Generated from Full-Scale Laboratory Igneous Rock Cutting Tests with Conical Picks at Two Stages of Wear

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Abstract
Respirable dust poses long-term health issues to personnel working in mining and civil projects where mechanized mining and tunneling machines are used for hard rock excavation. Machines, such as longwall shearers, roadheaders, or continuous miners, use consumable picks to cut rock. However, rock dust is generated in the work environment each time the pick tip contacts the rock surface. Additionally, the generated dust can be reintroduced into the air 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 two stages of pick wear: new and moderately worn. Understanding dust characteristics in terms of concentration, size distribution, and particle shape 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 dust characteristics generated from preliminary full-scale cutting tests in a laboratory of an igneous rock block cut with conical picks at new and moderately worn levels of wear. The moderately worn pick generated a size distribution that favored smaller particle sizes compared to the new pick. The moderately worn pick also generated more overall dust, as the concentration level in mg/m^3 was over double the amount of the new pick. Lastly, both picks generated particles that had similar aspect ratios and roundness measures.

Keywords Dust · Respirable · Characterization · Particle shape

1 Introduction

Respirable, thoracic, and inhalable dust particles less than 100 µm in aerodynamic diameter pose a major health concern for occupational workers in underground mining and civil environments. For example, exposure to respirable particles, usually containing silica, can cause irreversible and long-term complications such as coal workers pneumoconiosis [1], silicosis [2], and other lung diseases [3, 4]. The US Mine Safety and Health Administration (MSHA) has recognized the danger of and addressed these lung disease issues by implementing exposure limits. With this, MSHA continually monitors mines and ensures that sites are abiding to airborne contaminant and quartz exposure limits as outlined in Title 30 of the Code of Federal Regulations to protect workers [5].

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Although there are regulatory bodies such as MSHA to cite and address dust exposure issues, there has been an increase in lung disease cases since the 1990s with a continued rise in numbers in recent years [6–10]. Regulations have benefited the working environment by limiting exposures to dust for many years; however, there are many research projects investigating other reasons besides dust concentration measurements for the unknown increase in occupational worker diseases.

With this, conical, or bullet, picks are commonly used on roadheaders, longwall shearers, or other machines to break rock in mechanical excavations [11, 12]. Dust is generated at the pick tip and various pick parameters, such as tip geometry, body profile, and tip angle, change the dust concentrations generated during drilling [13–17]. Additionally, during excavation operations, pick geometry naturally changes as they wear out from abrasion or other forms of failure. Therefore, pick geometry characteristics change during cutting from the beginning of the pick's life to the end of the pick's life, when they are replaced. There are noted changes in cutting forces and the amount of dust concentration in the process as the bit experiences different levels of wear [18, 19].

Aside from concentration, there is little understanding about the dust characteristics generated from change in geometry from new picks to worn picks, such as the size distribution and shape of the generated particles [20, 21]. The most recent mining conical drill bit research includes experiments on coal or sandstone samples where dust concentration or rock chip size distributions are analyzed, but do not include analysis of respirable particle shapes or size distributions [14, 22–24]. Therefore, this preliminary research focuses on understanding the characteristics of dust particles generated from a new and a moderately worn conical pick used for mechanical excavations on igneous rock. The findings presented are an elaboration and extension on the particle size distributions and particle shape analyses that were presented at the 2021 North American Mine Ventilation Symposium [25].

There is evidence that the concentration of dust and the mineralogy (such as quartz content) a worker is exposed to can adversely affect the lungs [9, 26]. There is also some evidence that the size of the particle can adversely affect human lungs more readily, such are particles less than 10 μm in aerodynamic diameter [27–29]. Particle shape is also known to give particles various dynamic shape factors, which dictate how the particle settles through air, or in this case, settles and affects a human lung [30–33]. With this, although particle size distributions and particle shapes create complex interactions within the human respiratory system when viewed together, this research hopes to reveal an understanding of the rock dust particle size distribution and shape so that the information will be readily available once the complex interactions are more widely understood. Therefore, results from the research provided cannot provide concrete evidence as to which pick wear generates the more dangerous dust to workers in relation to characteristics standing alone. Rather, a preliminary understanding of rock dust particles is revealed such that future decisions can be made in the underground environment to better protect workers and hopefully reduce cases in respiratory diseases.

2 Methods

2.1 Sample Preparation and Full-Scale Testing

An igneous rock block was used for experimentation with a 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 contacted the rock's surface at a constant speed of 250 mm/s (10 inch/s) and in a linear manner to simulate rock cutting in a full-scale testing process. The length of each cut line is about 1.1 m (3.5 feet) and therefore, each cut line takes 4.2 seconds. Multiple lines of cuts are made across the rock's surface as seen in Fig. 1 at 50.8-mm (2-inch) spacings, which is typical for a machine cutting in igneous rock with a USC of 95 MPa. Ten cut lines, or one pass across the rock surface, were generated for each test, meaning dust was generated and collected while cutting the ten lines from left to right with the new pick. Then, another ten cut lines, or one pass from right to left, were made with the moderately worn pick where dust was generated and collected. The penetration, or depth, of the pick into the rock sample was 2.5 mm (0.1 inches) for the experiments. These parameters were used because they are representative of industry spacings and penetrations used for the specific rock type and are determined by optimizing the specific energy and normal forces when cutting various hard rocks [34].

With this, the LCM ensures constant cutting speed during the cuts with a linear variable displacement transducer (LVDT) sensor. The sensor measures the location of the rock box (sample displacement) in real time during testing and the speed is validated after each cut. Additionally, the penetration down into the rock sample is fixed by inserting steel plates between the cross frame and the machine's main structure. For a 2.5-mm (0.1 inch) penetration depth,

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

a 2.5-mm plate would be used to assure the accuracy of the measured penetration, while it allows for stiffness of the cutting unit, since the vertical load is spread over a large area provided by the metal sheet. For other penetration values other than 2.5 mm, multiple of the 2.5 mm sheets, or inserts with appropriate thickness (i.e., 5, 10, 12.5 mm), are used.

The test for each pick consisted of the same parameters (speed, cut line length, spacing of cuts, number of cut lines generated, penetration) for one pass, or one set of ten cut lines. In other words, dust was collected during the time when the first cut commenced and the last cut finished for one pick type. After each pass, a new set of dust collection equipment was installed. With this, the first pass with the new pick lasted 8 min, a second duplicate pass with the new pick lasted 11 min, and the last pass with the moderately worn pick lasted 6 min. Due to the nature of the experiments, there was not enough rock material to perform another duplicate test with the moderately worn pick. Therefore, an average of the two sets of dust collected from the new pick was used and the dust collected for the one set of ten lines of cuts was used for the moderately worn pick dust analysis. For these reasons, the tests and analyses performed are considered preliminary experiments, as they have not been repeated in sufficient numbers to establish a statistically significant dataset. However, over the long run with additional tests in similar and different rock types and with various testing parameters, it is anticipated that the general trends could be identified. Additionally, it can be noted that the variation in collection times between tests is negligible because the concentrations are calculated and normalized with the consistent flow rate of pumps collecting dust and time for each test run. Lastly, the size distribution and particle shapes are analyzed using a representative sample extracted from the total dust collected.

2.2 Dust Collection Setup

In order to collect airborne respirable dust, a curtain is installed around the LCM pick and saddle to confine the dust generated from 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 Fig. 2 shows the inside 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 10 mm nylon Dorr-Oliver cyclones. These cyclones are designed for collecting particles with aerodynamic diameters smaller than 10 microns to closely simulate dust penetration in human lungs [35]. Filters in cassettes were then attached to the cyclones to collect dust particles, where the whole setup was mounted to the LCM close to the pick tip as seen in Fig. 2. Pumps ran at 1.7 LPM to obtain the highest collection efficiency for the 10 mm nylon Dorr-Oliver cyclones and additionally, the NIOSH Manual of Analytic Methods (NMAM) standards 0600 and 7500 testing procedures call for 1.7 LPM [33, 36]. 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 Fig. 2.

Fig. 2 View of cyclone setups attached to saddle with tubing piped out of the curtain to pumps. The front panel was removed for the photo

The filters used to collect dust include pre-weighted PVC filters for gravimetric analysis and polycarbonate (PC) filters for image and laser diffraction analysis. The pre-weighted filters were sent to a professional lab for analysis of the NMAM 0600 and 7500 standards. The PC filters were used for optical analysis of the particle shapes because PC filters provide a unique background that makes it easy to distinguish particles [37–39]. A consistent sampling and analysis protocol was developed to assure reliability of the dust collection, 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 experiments were unable to collect all particles generated. With this, the cyclones used for dust collection are built to collect particles 0.4 to 10 µm in aerodynamic diameter on the filters and deposit any other airborne dusts, up to 100 µm in aerodynamic diameter, into the grit pot. The system is therefore limited to this size range 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 (assumed mid-life) pick was tested. Conical picks were chosen for experimentation because they are common cutting tools used for breaking rock. Conical picks are used on a wide variety of machines and are used in many mining and civil applications [12, 37, 40].

As seen in Fig. 3, a circle is superimposed at each of the pick tips where the new pick tip has a diameter of 4.29 mm (0.169 in) and the worn pick tip has a diameter of 9.98 mm (0.393 in). Diameter of the tip is used to quantify pick wear because the angle that makes the tip will stay the same throughout cutting and only the tip itself will become more blunt over time [41]. 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, the higher specific energy of cutting [31, 38], and most likely the higher volume of fines generated in cutting the same rock at identical spacing and penetration.

The moderately worn pick was generated by artificially wearing down a new pick tip by hand with a Dremel and a lathe. After testing, the new and the moderately worn pick tips were again measured to see if there were any changes in bit profile as a result of testing. There was no change in pick tip diameter for the new or the moderately worn pick at the end of testing.

3 Preliminary Test Results

3.1 Size Distribution

A laser diffraction 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 and the inhalable material from the cyclone's grit pot was added into the laser diffraction instrument. 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 [33].

The size distribution for particles generated with the new pick and the moderately worn pick is shown in Fig. 4. The aerodynamic diameter of the particles was calculated using the Cunningham correction factor and slip correction factor. Aerodynamic diameter is on the x-axis and the normalized frequency of particles with respective sizes, or the "percent channel," is on the y-axis.

3.2 NMAM Standards

A third party, professional lab was utilized to perform NMAM 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 NMAM 0600 standard procedure and NMAM 7500 standard procedure performed on the samples. Both the NMAM 0600 and NMAM 7500 standards provide the dust concentration in mass of dust or mineral per unit volume (mg/m^3) for the respective collected samples. It is critical to perform these tests on the samples because these are the tests performed and used in industry to regulate and mitigate dust exposures.

The results obtained from standardized tests are presented in Table 1. As seen in the results from the NMAM 0600 standard, the concentration of the dust from the moderately worn pick in mg/m^3 was almost double the concentration from the new pick. With this, the results from the NMAM 7500 standard reveal that both picks generated dust that contained both quartz and cristobalite, silica containing minerals.

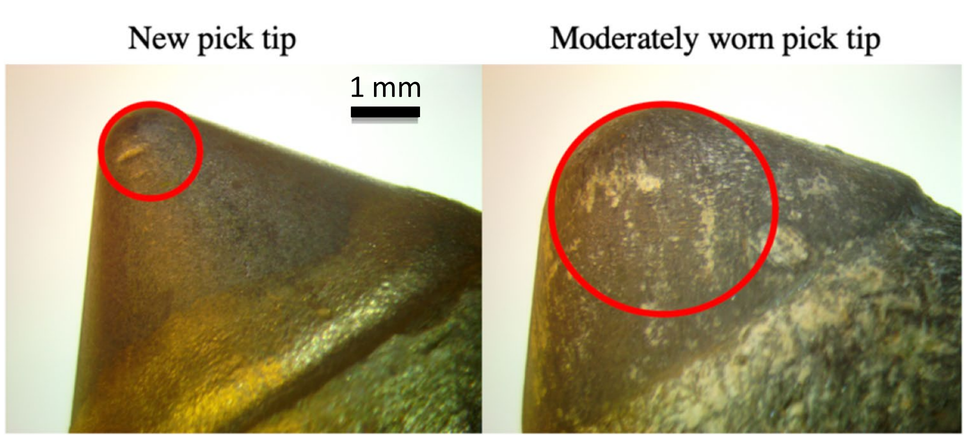


Fig. 3 Comparison of a new pick tip to a moderately worn pick tip with 0.7 × magnification for both pick tips with circle superimposed to show larger radius for moderately worn pick

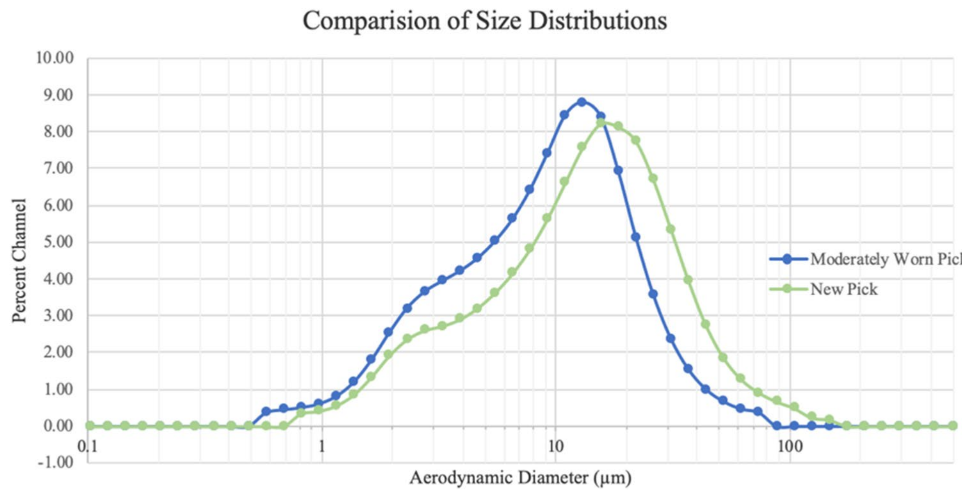


Fig. 4 Size distributions of particles generated from the new and moderately worn pick

3.3 Optical Imaging

A Nikon optical microscope paired with the Clemex image analysis package was used at 500 × magnification to analyze the dust collected on the surface of the PC filters. PC filters were also 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 [33].

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 measure particle geometries. 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 comprised of multiple focus layers. Then, with these captured photos, gray thresholding separated the particles from the background substrate of the PC filter 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 as seen in Fig. 5. Finally, 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 Eq. 1 below.

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

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

With the program, over 90 particles were identified on the filter with dust that was generated from the new pick and over 100 particles were identified on the filter with dust that was generated from the moderately worn pick. The graphical data is presented in Fig. 6 as histograms to visualize the number of particles with specific values for the aspect ratios and roundness.

The most frequent particle aspect ratio was 1.2 obtained from particles generated from the new pick and 1.1 for particles generated from the moderately worn pick. The new pick generated particles with aspect ratios as high as 2.9 and the moderately worn pick generated particles with aspect ratios up to 2.1. Both picks generated particles with the highest frequency of roughness measure at 0.7. There was also no deviation between the smallest and largest roundness values as both the new and the moderately worn pick ranged from 0.35 to 1.

Table 1 Results from NMAM 0600 and 7500 lab tests

Analysis	Result	New pick	Moderately worn pick
NMAM 0600	Concentration	mg/m^3 71	mg/m^3 147
NMAM 7500	Concentration: Cristobalite	mg/m^3 0.43	mg/m^3 0.98
	Quartz	6.98	15.69
	Tridymite	0	0

4 Discussion and Analysis

4.1 Size Distribution

The graphical representation of the particle size distributions generated from the new and moderately work pick

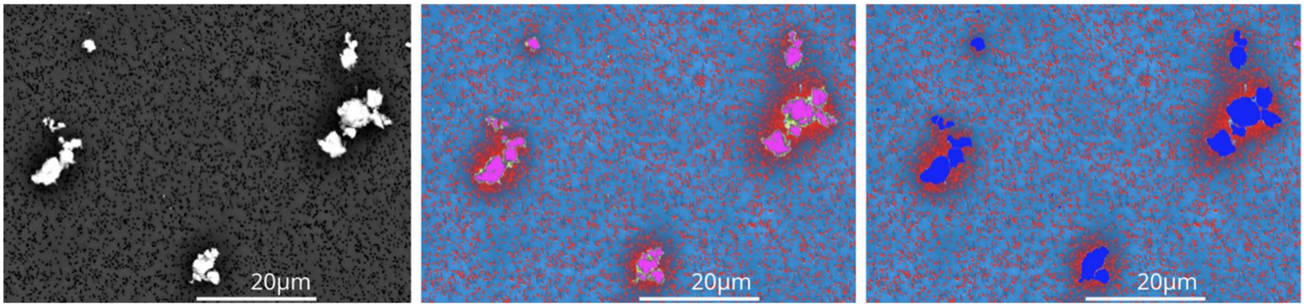
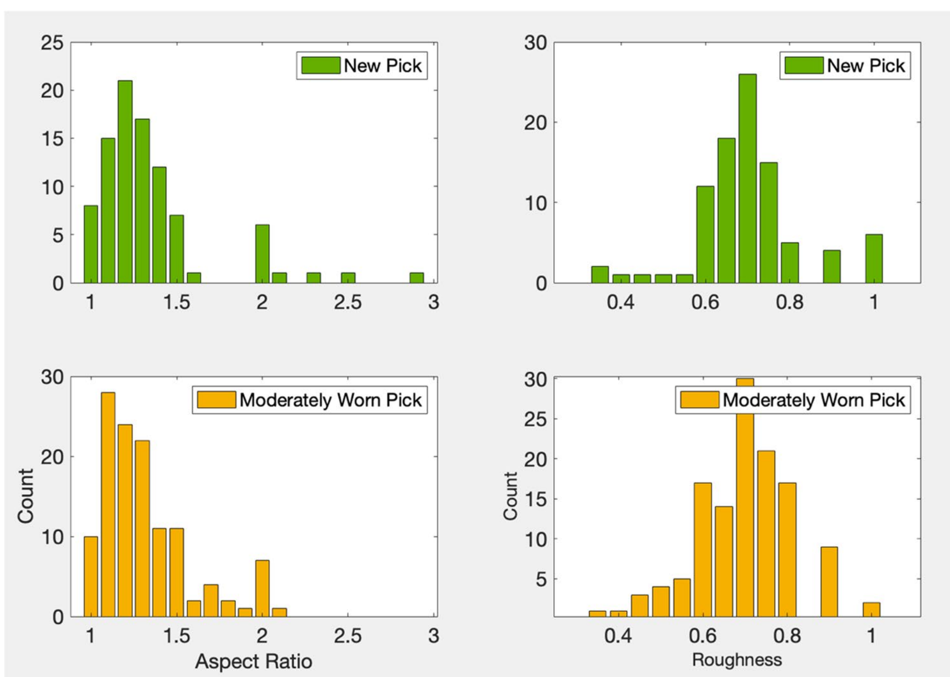


Fig. 5 Raw image (left), the image under gray thresholding (middle), and the program identifying and highlighting individual particles in blue (right) that will then be analyzed for shape features

shows a shift in particle sizes. In other words, the new pick generates slightly larger particle sizes compared to the moderately worn pick. This is noted where the most frequent particle size diameter generated by the new pick is 15.55 μm and the most frequent particle size diameter generated by the moderately worn pick is 13.08 μm. As seen in Fig. 4, there is a similar size distribution shape of particles with a single modal peak; however, there is a shift in the curve where the moderately worn pick seems to generate smaller particles. Additionally, the moderately worn pick generated particles that are as small as 0.578 μm in aerodynamic diameter and the new pick only generated particles that are as small as 0.817 μm in aerodynamic diameter. With this, it can be seen that the moderately worn pick generates slightly smaller particle sizes than the new pick.

Smaller particle sizes generated from the moderately worn pick could possibly be attributed to the higher forces that occur during rock cutting with moderately worn picks [42–45]. With this, higher stresses at the contact point can lead 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 generate smaller particles. However, there is some uncertainty in the shift of particle size distribution in these preliminary experiments. There was only an average of two samples collected with the new pick and only one sample collected with the moderately worn pick. Therefore, while the general trend is intuitive, the quantitative results and conclusions drawn need to be confirmed with repeated tests with more duplicate samples including additional tests with bits at various wear level in different rock types. It would also be critical to test a fully worn pick tip wear to

Fig. 6 Particle counts of the aspect ratios in the left column and roundness values in the right column for dust particles deposited on PC filters from full-scale rock cutting test



observe any possible trends of dust size distributions from new to fully worn picks.

4.2 NMAM Standards

The results obtained by the NMAM 0600 reveals a significant difference in concentration of airborne dust particles. The standard revealed that the moderately worn pick generated 147 mg/m^3 of dust while the new pick generated 71 mg/m^3 of dust. The concentration of dust from the moderately worn pick is twice the dust concentration compared to the new pick. Given the limited testing, this ratio is anticipated to change but the trend appears to be logical.

With this, the dust concentration results from these full-scale rock cutting tests support previous findings and experiments. Previous studies have found that as a conical pick tip becomes more dull, more dust will be generated as a result [14, 16, 20], which is confirmed in these preliminary experiments. Therefore, if further testing with duplicate and repeated samples follows this same trend, then 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. For practical reasons, proper engineering solutions should be used to mitigate dust generated in the working area using scrubbers or spray water curtains when a machine is operating with moderately work picks.

The NMAM 7500 standard reveals that both the new pick and moderately worn pick generate rock dusts that contain hazardous minerals. Both quartz and a fraction of cristobalite were detected in the samples. However, the quantitative differences in mineral concentrations could result from the nature of different layers in the igneous rock block. For example, it could then be alterations or changes in the rock itself that caused the difference in amount of quartz and cristobalite, instead of the wear of the pick. Additionally, the quantitative differences in mineral concentrations could be caused by an overall higher concentration or amount of dust that was generated from different samples. It is inconclusive whether the slight increase in quartz from the new pick to moderately worn pick is due to the rock, dust amount collected, or 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 confirm the 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. The Kolmogorov–Smirnov statistical test (KS test) was performed between the two data sets to test the hypothesis that the distributions of particle shapes generated from the new pick is the same as the shape distributions generated from the moderately worn pick. A significance level of 0.05 was used in the statistical analysis. Therefore, p-values below 0.05 provide strong statistical evidence to reject the hypothesis test.

The KS test provides evidence that there is a difference between the moderate pick distribution when compared to the new pick for aspect ratio and roundness parameters. The p-value obtained for the aspect ratio distribution was 0.51 and for roundness was 0.67, which are both above the 0.05 threshold. Therefore, there is statistical evidence that the new and moderately worn picks generate particles of similar shape characteristics. However, further testing needs to be completed where more duplicates are obtained to confirm this finding.

In order to supplement the limited study on particle shape, it would be necessary to use a field emission scanning electron microscope (FE-SEM) for analysis. Other researchers have utilized FE-SEM to look at particles to determine shapes [35, 43, 46, 47], which would complement the current research. The initial analysis indicates that there are some uncertainties 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 and clusters of particles. Meanwhile, other properties for particle shapes are under consideration, such as roughness measurements.

5 Conclusions

Preliminary full-scale cutting tests of an igneous rock sample with a new and moderately worn conical pick were completed in order to generate dust for analysis. Characterization of the dust from both wear conditions resulted in particle size distribution, concentration, mineral presence, and particle shape data with comparisons. The moderately worn pick generated a size distribution that favored smaller particle sizes compared to the new pick. The moderately worn pick also generated more overall dust, as the concentration level in mg/m^3 was over double the amount of the new pick. Lastly, both picks generated particles that had similar aspect ratios and roundness measures. Although these tests are preliminary and there are plans to expand the testing to include more duplicates and additional pick wears, the data in these experiments supports previous findings that the concentration of dust increases as the wear of the pick increases [14–16, 48].

The results of the preliminary analysis of the dust particles indicate that there is a need for further experiments to determine a trend in dust characteristics as the pick wear changes. Limitations of this experiment include the nature of performing a single test on a single rock type and additional tests are underway to repeat this experiment to obtain more data from multiple tests and include a fully worn pick. Although no concrete solutions can yet be drawn as to which pick generates the most hazardous dust particles to miners in the underground work environment, there is an understanding that both picks generated dust containing hazardous quartz minerals (as the rock type being cut contained such minerals) and that the moderately worn pick generated more overall dust and slightly smaller dust particle sizes. Therefore, when excavating in rocks containing quartz or silica such as the igneous rock in this experiment, it is possible that mining with moderately worn picks generates more hazardous particles and more dusts that workers can be exposed to. In the end, appropriate engineered dust mitigation measures should be considered to protect workers with all levels of pick wear; however, there is some preliminary evidence to suggest moderately worn picks generate more hazardous dusts compared to dusts generated from new picks.

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Declarations

Conflict of Interest The authors declare no competing interests.

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