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Experimental study on effects of drilling parameters on respirable dust production during roof bolting operations

Hua Jiang[a,c], Yi Luo[a], and Joe McQuerrey[b]

[a]Department of Mining Engineering, West Virginia University, Morgantown, WV; [b]Department of Research & Development, J. H. Fletcher & Co., Huntington, WV; [c]College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi, China

ABSTRACT

Underground coalmine roof bolting operators exhibit a continued risk for overexposure to airborne levels of respirable coal and crystalline silica dust from the roof drilling operation. Inhaling these dusts can cause coal worker's pneumoconiosis and silicosis. This research explores the effect of drilling control parameters, specifically drilling bite depth, on the reduction of respirable dust generated during the drilling process. Laboratory drilling experiments were conducted and results demonstrated the feasibility of this dust control approach. Both the weight and size distribution of the dust particles collected from drilling tests with different bite depths were analyzed. The results showed that the amount of total inhalable and respirable dust was inversely proportional to the drilling bite depth. Therefore, control of the drilling process to achieve proper high-bite depth for the rock can be an important approach to reducing the generation of harmful dust. Different from conventional passive engineering controls, such as mist drilling and ventilation approaches, this approach is proactive and can cut down the generation of respirable dust from the source. These findings can be used to develop an integrated drilling control algorithm to achieve the best drilling efficiency as well as reducing respirable dust and noise.

KEYWORDS

Drilling bite depth; dust collection system; dust size distribution; respirable dust; roof bolt drilling

Introduction

Underground mine roof bolter operators are very likely to experience overexposure to inhalable and respirable coal and crystalline silica dust produced from drilling roof boltholes.[1–3] Inhalable particles, smaller than 100 µm, can be drawn into the respiratory tract through inhalation; however, most of these particles are removed in the upper-respiratory tract and fail to reach deep into the lungs. However, a portion of inhalable dust is respirable (less than 10 µm) and can penetrate into the gas-exchange region of the lung. Exposure to an excessive amount of respirable coal and crystalline silica dust can cause coal mine dust lung diseases. The National Institute for Occupational Safety and Health (NIOSH) has shown that the quartz content in the total roof bolting dust can be as high as 58%, with 80% below 100 µm in diameter, 20% below 5 µm.[4] Because silica dust is about 20 times more toxic to the lung than coal dust, a roof bolter operator exposed to high level of crystalline silica dust could develop silicosis in as little as three years.[5]

Dry vacuum dust collectors are commonly used as a control method on roof bolting machines in U.S. underground coal mines. A vacuum fan draws drill cuttings from the drill hole through of the drill bit and the hollow drill into a dust collection system. The most common dust collection system currently used on bolting machine is composed of an initial cyclone called the precleaner, followed by three subsequent dust collection steps in a dust box shown in Figure 1. The precleaner cyclone is intended to remove the large noninhalable dust particles (> 100 µm) and discharge this fraction onto the mine floor so that the materials to be captured by the dust box can be minimized. Dust captured by the dust box, is sequentially transferred to a dust-bag, and a small cyclone with a cartridge filter before the cleaned airstream is exhausted into the environment. While the precleaner is intended to remove the inhalable dust from the discharged particles, it is found that the discharged drilling cuttings still contains a substantial amount of inhalable and respirable dust that could be re-suspended under certain conditions.[6]

CONTACT Hua Jiang hujiang@mix.wvu.edu Department of Mining Engineering, West Virginia University, Morgantown, WV, 26505.
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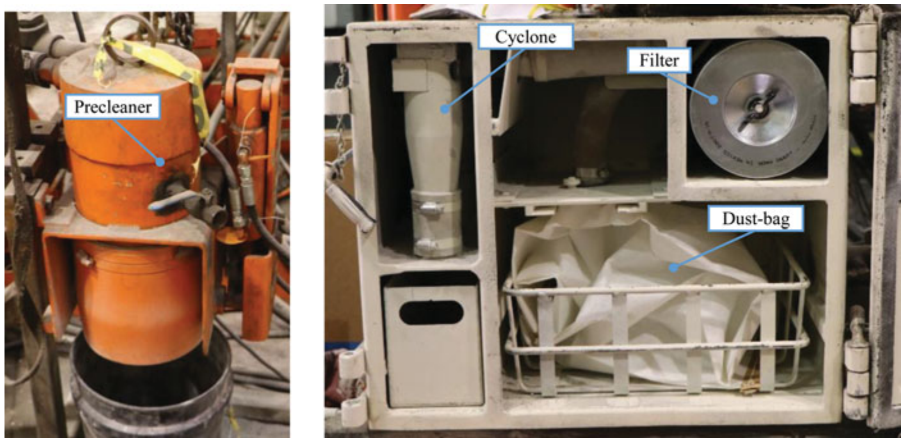

Figure 1. Typical dust collection system composition.

NIOSH researchers have also found that the operation of the roof bolter downwind from an operating continuous mining machine is the predominant source of airborne dust for bolter operators and infrequent maintenance and cleaning of the collector box are the main causes for roof bolter personnel overexposure to crystalline silica dust in underground coalmines.[7] In addition, the dust-bag has been shown to be useful in reducing the overexposure while maintenance and cleaning the collector box.[8]

There are many variables in drilling roof bolt holes in an underground mine that can affect both drilling efficiency and dust generation. Some of these variables are uncontrollable while the other variables (e.g., drill steel, drill bit, drilling parameters such as applied thrust and torque, achieved penetration, and rotational rates) can be controlled by the bolter operator. Previous research conducted with roof geology mapping and drilling noise reduction has shown that control proper of drilling to achieve a reasonably higher bite depth (penetration per rotation of drill bit) is most desirable. These results are shown an inverse relationship between specific energy (the required energy to break one unit volume of rock) and bite depth.[9,10] The same relationship was found between noise dose (measured sound exposure level normalized to an 8-hr working period) and bite depth as well.[11] Since less specific energy represents higher drilling efficiency, and the generation of fine dust consumes additional energy which will lower down the efficiency. Therefore, at a higher bite depth with higher drilling efficiency, it is reasonable to assume that less energy will be wasted on overbreaking the rock. Consequently, the purpose of reducing quartz-rich respirable dust from its generation source, bolt-hole drilling can be achieved by controlling the drilling parameters.

In this research, drilling experiments with different penetration and rotation rates to achieve different bite depths were conducted. The purpose was to demonstrate the feasibility of using proper drilling control to reduce overbreakage of rock and, consequently, achieve a reduction in the amount of respirable dust generated. Samples from each of the dust collection units (i.e., precleaner, dust-bag, cyclone, and filter) have been collected after the drilling of each hole. The sample weight and size distribution were measured. This information was used to analyze the dust generation characteristics under different drilling parameters and evaluate the performance of the current dust collection system.

Laboratory experiments

In order to understand how drilling parameters will impact the generation of dust and the size distribution of the dust, drilling tests were conducted in a laboratory setting. The test setup is shown in Figure 2 and the dust collection system used on this test-drilling machine is the same as those equipped on underground roof bolter machinery. The dust collection system was cleaned before conducting experiment. After drilling each hole, the particles from the precleaner were discharged directly to a container. A new dust-bag was used for drilling each hole

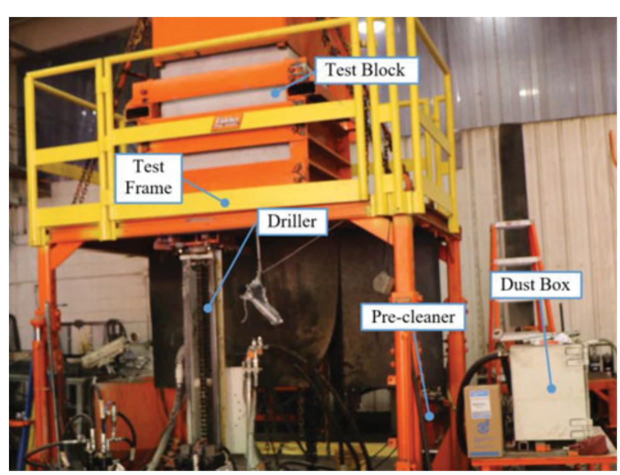

Figure 2. Experiment setup of the drilling dust study.

Table 1. Drilling parameters and sample collecting conditions for each drill hole.

Test No.	Penetration Rate, cm/s	Applied Thrust, psi	Rotational Rate, rev/min	Bite Depth, cm/rev.	Dust Sample Size Distribution obtained			
					Precleaner	Dust-bag	Cyclone	Filter
1	0.41	792.9	450	0.053	Y	Y	Y	Y
2	0.64	827.7	500	0.076	Y	Y	Y	Y
3	0.79	896.4	500	0.094	Y	Y	Y	Y
4	0.58	807.9	300	0.114	Y	Y	Y	Y
5	0.97	924.1	500	0.114	Y	Y	Y	Y
6	1.02	962.3	500	0.124	Y	Y	Y	Y
7	1.17	938.1	500	0.140	Y	Y	Y	N
8	1.40	939.2	500	0.168	Y	Y	Y	Y
9	1.45	982.2	500	0.173	Y	Y	Y	N
10	1.47	979.2	500	0.178	Y	Y	Y	Y
11	0.97	985.3	300	0.193	Y	Y	Y	Y
12	1.63	963.4	500	0.196	Y	Y	Y	N
13	1.68	996.2	500	0.201	Y	Y	Y	N
14	1.83	956.1	500	0.221	Y	Y	Y	N
15	2.08	1005.3	500	0.251	Y	Y	Y	Y
16	3.10	1173.5	450	0.371	Y	Y	Y	N
17	2.79	1009.8	500	0.373	Y	Y	Y	N

Note: Y-dust sample collected and measured; N = dust sample collected is inadequate to perform the size distribution measurement.

Table 2. Summary of sample weight and distribution.

Test No.	Actual Bite Depth, cm/rev	Dust Sample Weight, g							
		Precleaner Sample				Dust-bag Sample			
		Total Weight, g	PCT, %	Above-850 um, g	Sub-850 um, g	Weight, g	PCT, %	Cyclone Dust Weight, g	Filter Dust Weight, g
1	0.053	2412.9	76.6	266.8	2146.1	736.6	23.4	0.21	0.99
6	0.124	2460.0	78.2	338.5	2121.5	685.3	21.8	0.63	0.36
9	0.173	2303.2	81.2	313.3	1989.9	531.7	18.8	0.45	0.01
15	0.251	2706.0	84.2	618.4	2087.6	505.5	15.7	0.69	0.26
17	0.373	2940.0	86.9	1002.4	1937.6	441.3	13.0	0.82	0.21
Overall PCT		81.43%				18.54%		0.02%	0.01%

and the used bag was collected for measuring the dust weight and analyzing dust size distribution. Dust samples from the cyclone and filter inside the dust box were also collected separately and analyzed after completing each bolt-hole.

The drilling tests were conducted on a reinforced concrete block with a uniaxial compressive strength of 4,000 psi to represent the hard roof encountered in underground roof-bolting where dust issue is more concerning compare to soft roof condition.[12] All of the drilling tests

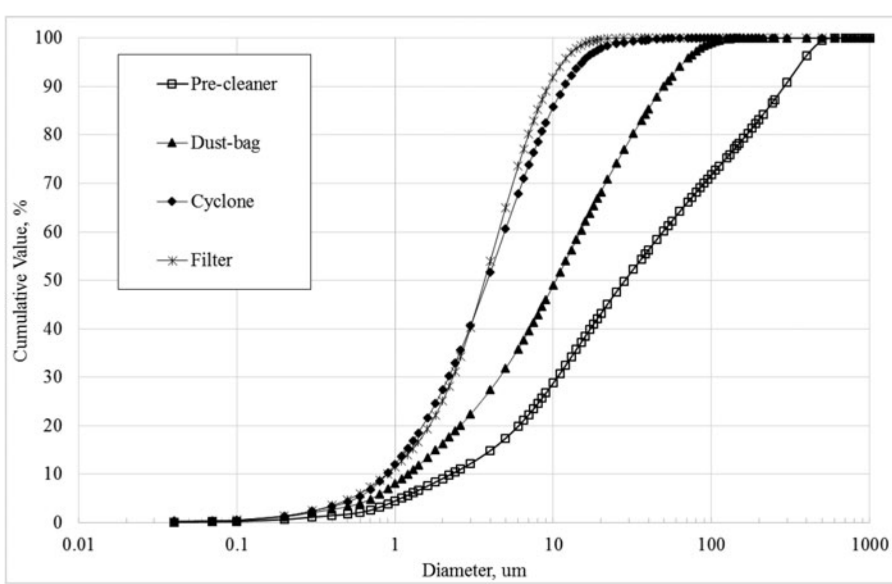

Figure 3. Average dust size cumulative distributions for different dust collection stages.

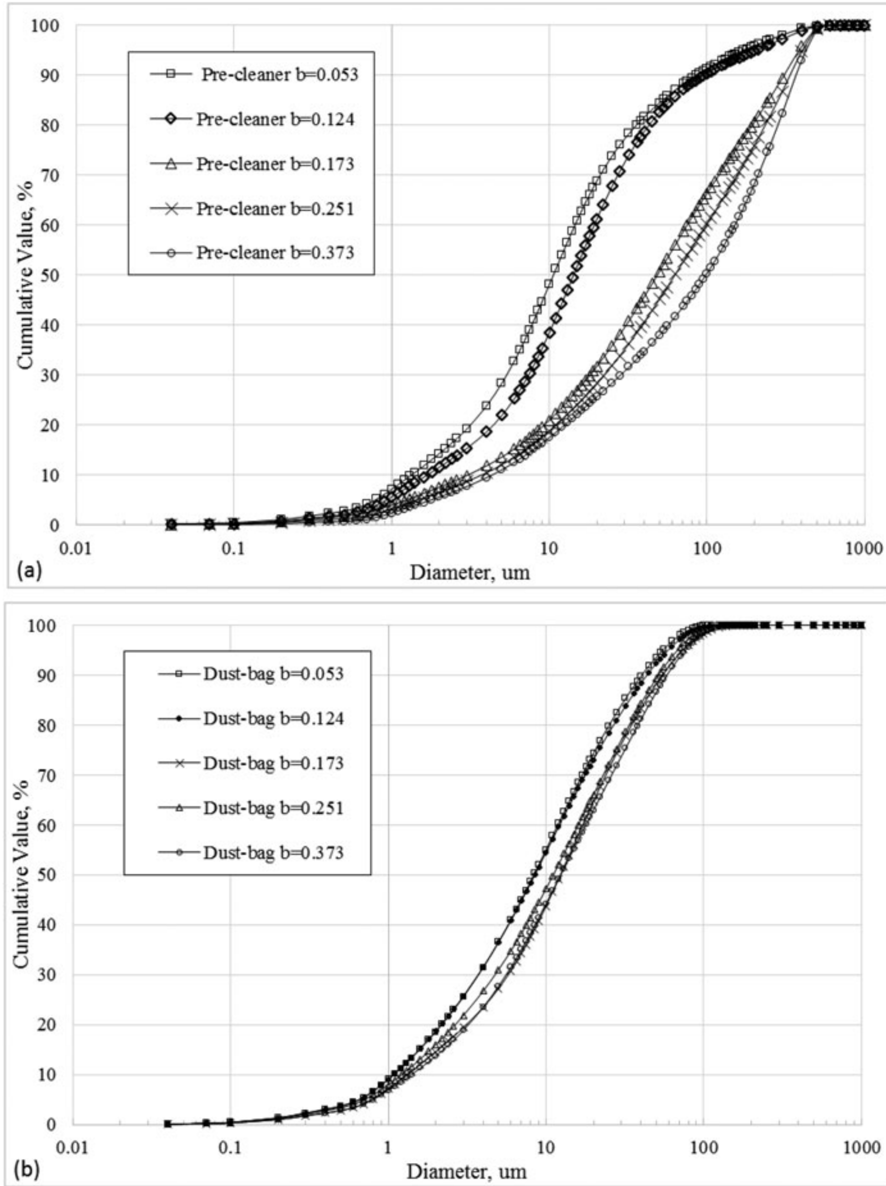

Figure 4. Dust size cumulative distributions for (a) sub-850 µm precleaner and (b) dust-bag dust samples.

were conducted using a 3.493 centimeter (cm) tungsten carbide drill bit and 2.858 cm hexagon drill steel. A new drill bit was replaced for each drilling tests. The diameter of the boltholes produced by this combination was approximately 4.445 cm.

Table 1 shows the drilling parameters and sample collecting conditions for all 17 of the tests. The rotational rates were 300-, 450-, and 500-revolutions/min while the penetration rates varied from 0.41 to 3.10 cm/sec. Consequently, the bite depths achieved ranged from a minimum of 0.053 to a maximum of 0.373 cm/revolution. The selection of these test parameters was based on previous research to avoid drilling be conducted resulting in low energy efficiency and high noise.[10,11] All the dust samples for each test were collected and measured using CILAS model 1190 particle size analyzer, except for several high-bite depth test samples collected from the filter. Those sample size distributions were not obtained due to inadequate sample quantity for the instrument to take.

Experiment results and data analysis

Due to the large number of test data obtained, for a clearer visualization of data and plots, five sets of test data were selected as representative for different bite depth levels. The results from test number 1, 6, 9, 15, and 17 (bite depths of 0.053, 0.124, 0.173, 0.251, and 0.373 cm/sec, respectively) were selected for analysis in this section. The results from other tests were consistent with presented data sets.

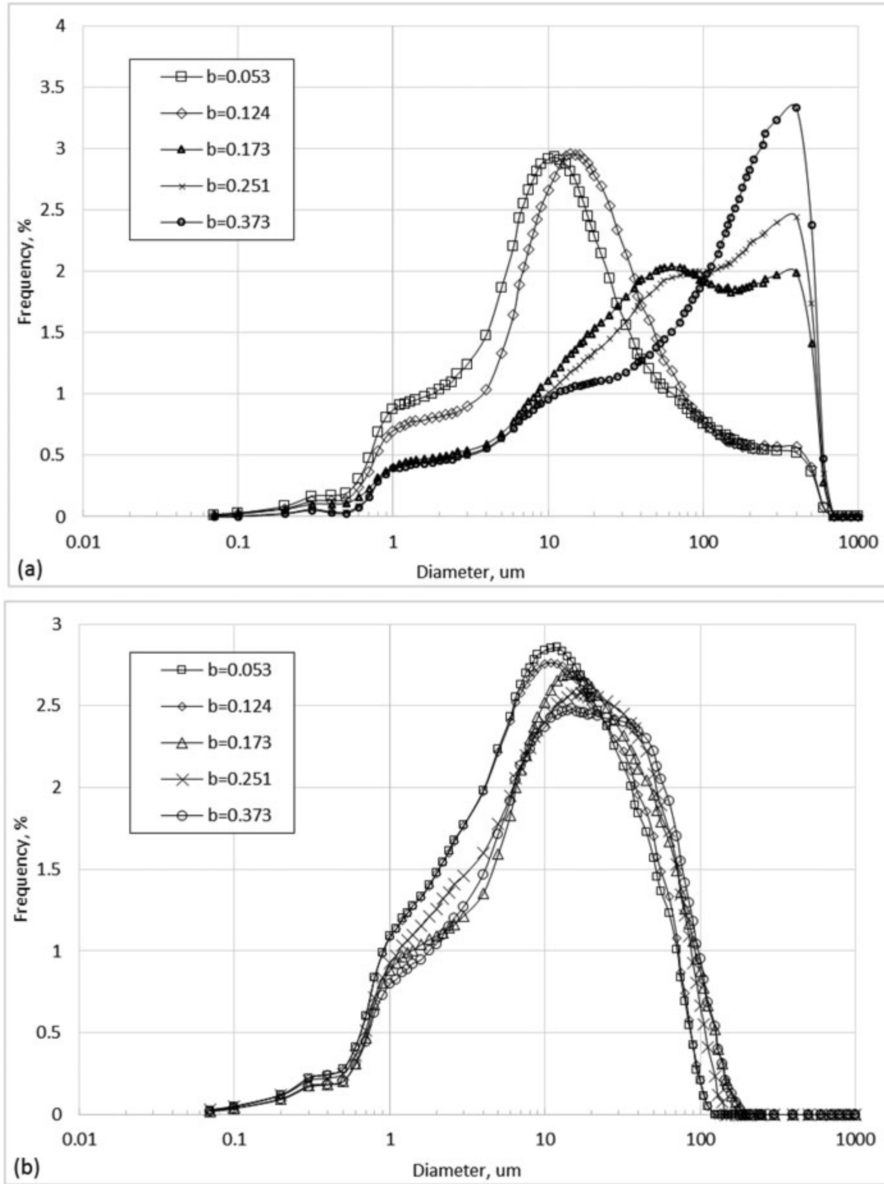

Figure 5. Dust size frequency distributions for (a) precleaner and (b) dust-bag dust samples

The weights for all five-dust samples were measured for the four dust cleaning stages and the results are shown in Table 2. The dust samples for precleaner have also been sieved by No. 20 sieve and split into above-850 and below-850 µm size ranges in order to meet the particle size analyzer's requirement. On average, approximately 81.4% of drilling cuttings were collected by the precleaner, 18.5% by dust-bag and less than 0.1% by cyclone and filter. The total sample weight from the precleaner increased with increasing the drilling bite depth. The quantity of above-850 µm cuttings from the precleaner was significantly larger for higher bite depths. Conversely, less dust gathers in the dust-bag when drilling to higher bite depth. In general, from the perspective of sample weight, more large particles are produced as drilling is conducted at a higher bite depth.

Size distribution (on a volume basis) analyses were performed for the dust samples from sub-850 µm precleaner, dust-bag, cyclone, and filter using a particle size analyzer. The average size distribution results for four cleaning stages in cumulative values are plotted in Figure 3 and the individual distributions for all the samples were plotted and discussed separately in the following sections. It is clear that particles become finer after every cleaning stage. However, there is an overlay area for cyclone and filter dust sample when the size goes below 3 µm.

For the size cumulative distributions of samples from precleaner and dust-bag as shown in Figure 4, it was as expected that for the drilling tests with larger bite depth, the size distribution curves are gentler indicating less fine dust. Figure 4a also shows that the efficiency for precleaner to collect large cuttings were satisfied, the

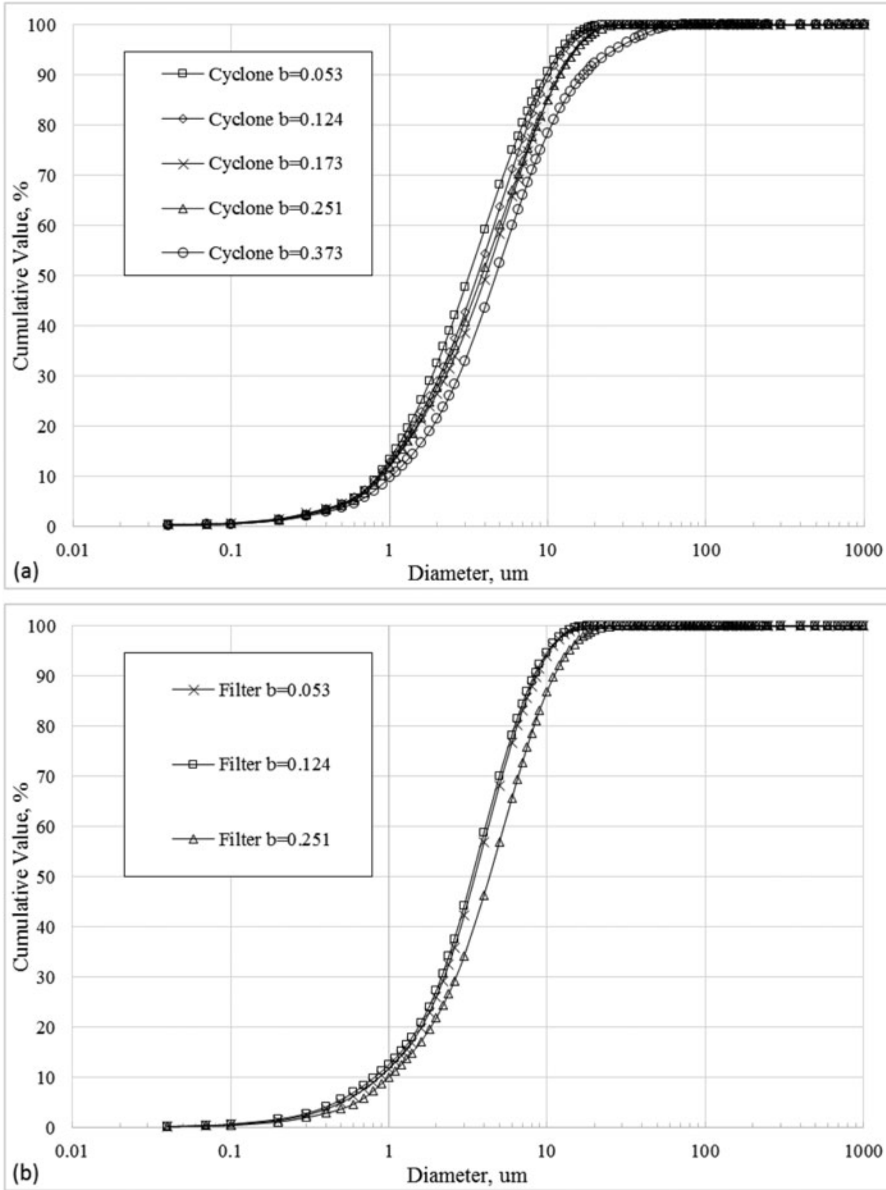

Figure 6. Dust size cumulative distributions for (a) cyclone and (b) filter dust samples.

majority of cuttings larger than 100 μm were collected by precleaner, of which about 3% of the dust entering the dust box is greater than 100 μm in size. However, unexpectedly between 49 and 92% of the below-850 μm precleaner particles were still in the inhalable range (<100 μm) and between 17 and 48% of them are in the respirable range (<10 μm).

The size frequency distributions for sub-850 μm precleaner and dust-bag samples are shown in Figure 5. The peak value indicates the dominant particle size and its percentage. Among the size frequency distribution curves of the precleaner samples, the dominant particle size for low bite depth drilling (0.053 and 0.124 cm/revolution) was between 10 to 15 μm and its peak frequency is around 2.9%. Two peaks were found for the test drilling at bite depth of 0.173 cm/revolution, the dominant particle size for these two bite depths are 55 and 400 μm for the percentage of around 2.0%. The dominant particle size for high-bite depths drilling (0.251 and 0.373 cm/revolution) were also shown to be around 400 μm. The peak frequency at this size is increased from 2.4 to 3.3% when drilling is conducted from 0.251 to 0.373 cm/revolution. These analyses indicate that while increasing the drilling bite depth, the dominant dust size for precleaner has increased from almost respirable (10 μm) to noninhalable (400 μm) range. For the dust-bag, the peak position varies from 12 to 17 μm as the bite depth increases. At the same time, the frequency dropped from 2.8 to 2.5%.

The size cumulative distributions for the cyclone and filter samples are shown in Figure 6, the quantity of two

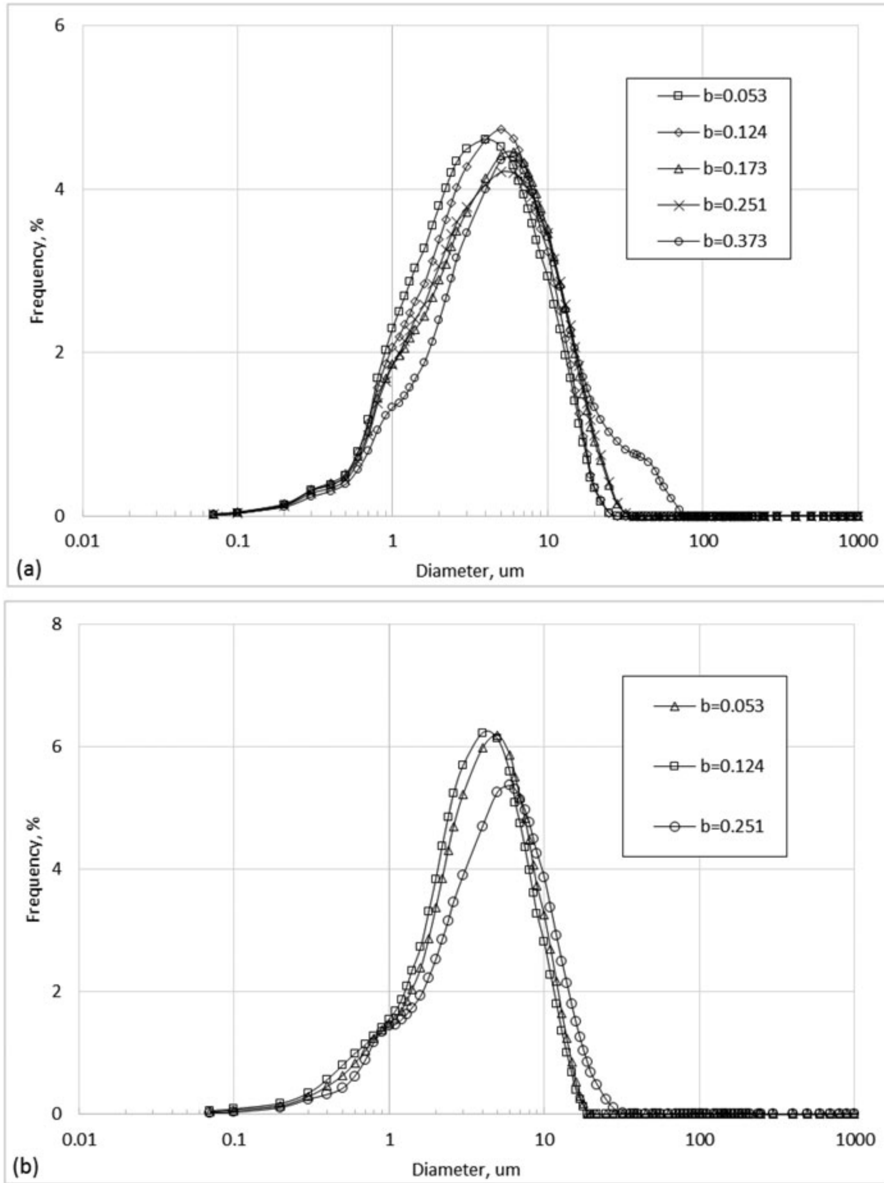

Figure 7. Dust size frequency distributions for (a) cyclone and (b) filter dust samples.

samples (Test No. 9 & 17) collected from filter are less than the amount required by the instrument as shown in Table 1, so only three results are plotted for filter sample size distribution. For both plots, after previous cleaning stages, the size distribution differences caused by different drilling bite depths become less significant, but the trends still follow that higher bite depth generate less fine dust. The maximum dust size for cyclone and filter sample is 60 and 30 µm, respectively. These values are significantly smaller compared with dust-bag results. Consider the enormous sample weight drop from dust-bag to cyclone and filter in Table 2, these results indicate an excellent cleaning efficiency for the dust-bag. The respirable dust content for cyclone samples was from 78 to 92%, while it was from 87 to 97% for the filter samples. This considerable high respirable dust content requires that the operator use extreme caution to avoid exposure when maintaining and cleaning the dust box.

Figure 7 represents the size frequency distributions for the cyclone and filter samples. The distributions are very similar for these two stages. The dominant size is between 4 to 6 µm, the frequency value for filter samples are slightly larger than those for cyclone samples. Although the samples have already been processed by the precleaner and dust-bag, but as the peak position is moving toward larger particle size from low to high-bite depth, the reduction of fine dust can still be observed.

The results of quantified size analyses of the samples are presented in Table 3. The mean diameters for sub-850 µm dust samples from precleaner range from 33.8 to 146.1 µm, shows an increase with the drilling bite depth. The mean diameters for dust-bag samples were between

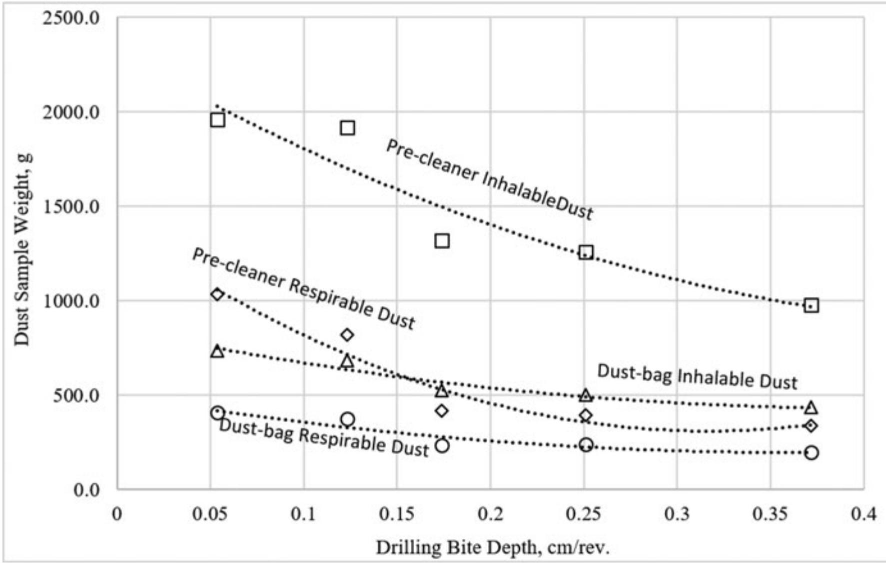

Figure 8. Inhalable and respirable dust weights versus drilling bite depth.

Table 3. Summary statistics for size distribution.

	Precleaner Sub-850 μmv Sample			Dust-bag Sample						
Test No.	Mean Dia., μm	Inhalable Dust Weight, g	Respirable Dust Weight, g	Mean Dia., μm	Inhalable Dust Weight, g	Respirable Dust Weight, g	Cyclone Sample Mean Dia., μm	Filter Sample Mean Dia., μm	Total Inhalable Dust Weight, g	Total Respirable Dust Weight, g
1	33.8	1960.7	1033.1	15.3	735.9	405.5	4.36	4.13	2697.7	1439.8
6	40.0	1918.5	817.0	15.7	682.6	373.6	4.70	4.07	2602.0	1191.5
9	103.9	1320.9	417.7	21.2	523.1	232.6	5.39	—	1844.5	650.6
15	120.6	1257.2	393.1	19.7	501.0	238.6	5.30	5.37	1759.1	632.5
17	146.1	976.2	339.7	22.3	433.6	195.1	7.60	—	1410.8	535.4

15.3 and 22.3 μm and varied with the bite depth. The average mean diameter for cyclone and filter dust samples was 5.47 and 4.52 μm, respectively. The weights of inhalable and respirable dust in the first two dust cleaning stages (precleaner, dust-bag) are plotted against the drilling bite depth in Figure 8, which shows declining trends as bite depth increases. The drop of inhalable and respirable dust amount in precleaner by increasing drilling bite depth is more significant than those for dust-bag samples. This indicates that by employing higher drilling bite depth, not only less fine dust will be produced from the drilling hole, but also a significant reduction of inhalable and respirable dust will be discharged into the mine environment directly by precleaner.

Discussion

The dust sample weight and size distribution results shown significantly less respirable dust was generated while drilling in a reasonably high-bite depth. For dust discharged by the precleaner, the results indicate that by increasing the drilling bite depth, a significant reduction of respirable dust among the sample can be achieved and the dominant dust size has moved from almost respirable range to noninhalable range.

By current dust collection system and laboratory settings used in this test, the substantial amount of respirable dust in the discharged fraction of precleaner is not desirable as a potential inhalation hazard. Other variables may have an impact on the separation efficiency of the precleaner cyclone and should be tested in the future. It is preferable that the precleaner can push more or all of the respirable dust into the dust box and avoid disturbance to the dust deposited to the mine floor. The operator should use extreme caution when maintaining the dust box, because a considerable high respirable dust has been deposited in cyclone and filter.

Conclusion

Drilling tests were conducted under laboratory settings to explore the dust generation characteristics and the dust collection system's performance. The dust weights and size distributions are employed to analyze the effect of drilling parameters on dust generation of bolt drilling process.

The results showed that the amount of total inhalable and respirable dust was inversely proportional to the drilling bite depth and significantly less respirable dust was generated while drilling in a reasonably high-bite depth. Combined with the author's previous study conclusions, total inhalable and respirable dust weights, noise dose, and specific energy are inversely proportional to the drilling bite depth.

This research demonstrated a proactive approach to reduce the generation of respirable dust local to the roof-bolting machine as one possible source of dust exposure. By employing a higher bite depth, when drilling with a roof-bolting machine, can reduce the amount of respirable dust introduced to the dust collection system. Meanwhile, by choosing a proper drilling parameter for different rock materials, less drilling noise, larger cutting fragments, a higher drilling efficiency can be achieved. These findings can be used to develop an integrated drilling control algorithm and incorporated with the roof bolter machine to achieve the best drilling efficiency as well as reducing respirable dust and noise.

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