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Effects of proper drilling control to reduce respirable dust during roof bolting operations

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Abstract Dust generated from bolt hole drilling in roof bolting operation could have high quartz content. As a dust control measure, vacuum drilling is employed on most of the roof bolters in US underground mines. However, fine rock particulates from drilling could escape from the dust collection system and become airborne under some circumstances causing the roof bolter operators expose to quartz-rich respirable dust. A previous research shows that drilling can be controlled through properly selected penetration and rotational rates to reduce the specific energy of drilling. Less specific energy means less energy is wasted on generating noise, heat and over-breakage of rock. It implies that proper control of drilling has a great potential to generate significantly less fine rock dust during drilling. The drilling experiments have been conducted to study the effect of controlling drilling on reducing respirable dust. The preliminary results show that the size distributions of respirable dust were different when controlling drilling in different bite depths. This paper presents the findings from laboratory experimental studies.

Keywords Drilling control · Roof bolting · Bite depth · Respirable dust · Size distribution

1 Introduction

Roof bolting is the primary roof support system in US underground mines. Roof bolting usually consists two major processes: drilling and bolting. In the drilling process, a hole is drilled to the desired length into the mine roof at the required location. In the bolting process, bolts, either conventional bolts, cable bolts or resin roof bolts are inserted into the drilled hole for roof support. The fundamental problem of rock drilling is the breakage of fragments out of the face of a solid wall of rock (Teale 1965). The breakage of fragments generates particles of a wide size range out of the face of the rock surface.

MSHA studies have shown that roof bolting is one of the sources of high respirable quartz dust in underground coal mines (Schultz and Haney 2002). Over-exposure to quartz-rich dust could cause pneumoconiosis, silicosis, and chronic obstructive pulmonary diseases (COPD) for underground coal miners (NIOSH 2011). To reduce the miners' exposure to respirable dust, MSHA sets a dust standard to reduce the overall dust concentration limit from 2.0 to 1.5 mg/m^3 in the coal mine atmosphere during a working shift. This new standard will be effective on August 1, 2016. Between 2012 and 2014, MSHA collected 341,788 miners' dust samples both by mine operators and by inspectors (MSHA 2015). The analysis of the data shows that among all the samples 9060 are above the limit of 2.0 mg/m^3 while 18,668 are above the 1.5 mg/m^3 new standard. It also shows that among the 23,416 dust samples of roof bolter operators, 381 and 983 of them are above the 2.0 and 1.5 mg/m^3 standards, respectively.

Most roof bolting machines used in the US underground mines are equipped with vacuum dust collection system to remove the drilling dust from mine environment. Some new dust control measures for roof bolters are canopy air curtain and air tubing (Goodman and Organiscak 2002;

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Goodman et al. 2006), wet exhaust conditioner (Beck 2012). However, the MSHA dust sample data still show that roof bolter operators are experiencing the similar level of dust overexposure as the other miners but potentially to dust with much high silica contents. This indicates that the drilling dust could still escape from the bolter's collection systems in some circumstances.

The object of this research is to control the drilling dust from its source by reducing the respirable portion of the dust. The findings from our previous researches "to drill at an allowable high bite depth for reducing specific energy and noise" are applied to reduce respirable drilling dust (Luo et al. 2013, 2014). The analyses are concentrated on the size distributions of the drilling dust in relation to the drilling bite depth. This paper presents the findings from a preliminary research to show the feasibility of the proposed dust control approach.

2 Drilling mechanism

Drilling of bolt holes is a rock penetration process in which the rotary drug bit breaks and fragments the rocks to form the desired path. The rock penetration can be considered as a combination of two actions applied on the rock by the drill bit: the compression and shearing. The compression action continuously pushes the bit tip into the rock while the shearing action uses the bit tip and edge to scrap off the rock. A drill bit-rock interaction model was developed by Luo et al. (2004) to estimate the mechanical properties of the roof strata utilizing the acquired drilling parameters. The model determines the rock uniaxial compressive and shear strengths, the presence of fractures and voids, and the minimum drilling energy required. It was found that the drilling energy efficiency (the ratio of the energy for rock breakage to the total input energy) is strongly related to how the drill is operated. The model shows that a significant amount of drilling energy is wasted in excessive rubbing actions between the drill bits and the rocks. Such rubbing action could limit the drilling energy efficiency to less than 20%. The wasted energy not only causes excessive heat and wear of the drill bits, but could also produce noise and fine dust. If drilling is not properly controlled, the noise, fine dust and bit wear problems can become very serious in drilling hard rock. An important finding from that research was that the specific energy of drilling (i.e., energy required to break a unit volume of rock) decreases as the bite depth increases. Figure 1 shows one of the specific energy—bite depth relationships derived from experimental data (Luo et al. 2004). The bite depth (b) is defined as the penetration depth per drill rotation and is related to penetration rate (v) and rotational rate (ω) by Eq. 1.

$$b = 60v/\omega \tag{1}$$

Based on the definition of Teale (1965), the specific energy of drilling consists of two parts, the part consumed by thrust (e_F) and the part by torque (e_T). In the developed drill bit-rock interaction model, the applied torque is divided into the torque to overcome the shear strength (T_1) and the torque to overcome the frictional resistance (T_2). The specific energy of drilling can be determined as Eq. (2) (Luo et al. 2004).

$$e = e_F + e_T = \frac{F}{A} + \frac{2\pi \times 60 \times (T_1 + T_2)}{Ab} \tag{2}$$

In Eq. (2), F is the applied thrust and A is the cross-section area of the bolt hole. Since the specific energy used to overcome the frictional resistance is wasted in the drilling. The efficiency of the drilling energy (η) can be obtained as Eq. (3):

$$\eta = 1 - \frac{2\pi \times 60 \times T_2}{eAb} \tag{3}$$

A research was also conducted to study the drilling control technology for the reduction of drilling noise during roof bolting operation (Luo et al. 2014). It is found that the noise dose generated during drilling one bolt hole decreases at higher bite depth as shown in Fig. 2. Since noise dose accounts for both the sound level and exposure time, it is considered as a better way to assess the effects of drilling noise to the bolter operators. The noise dose for drilling a bolt hole is relative to the MSHA 100% noise dose standard (i.e., 90 dBA criterion level, 5-dB exchange rate, and an 8-h working shift). The noise dose to bite depth relationships are very similar to the relationship of specific energy and bite depth (Fig. 1). The research shows that by properly controlling the drilling operation, less specific energy is spent and less energy was spared to generate drilling noise. These theoretical and experimental studies imply that it also is feasible to control the drilling for the purpose of reducing the fine dust generated in roof bolting operation.

3 Experiment design and setup

In order to demonstrate the dust control feasibility, drilling experiments were conducted in the drilling laboratory of the J.H. Fletcher & Company in Huntington, WV (Fig. 3). The Fletcher drilling experiment system consists of a set of sensors, a drill control unit, drill and hydraulic power pack. The control unit acquires, in real-time, the drilling parameters such as torque, thrust, rotation rate, rotation pressure, feed pressure, and bit position, etc. The desired drilling penetration and rotational rates can be preset on the control unit for the machine to automatically achieve and maintain during the drilling operation. The tests were

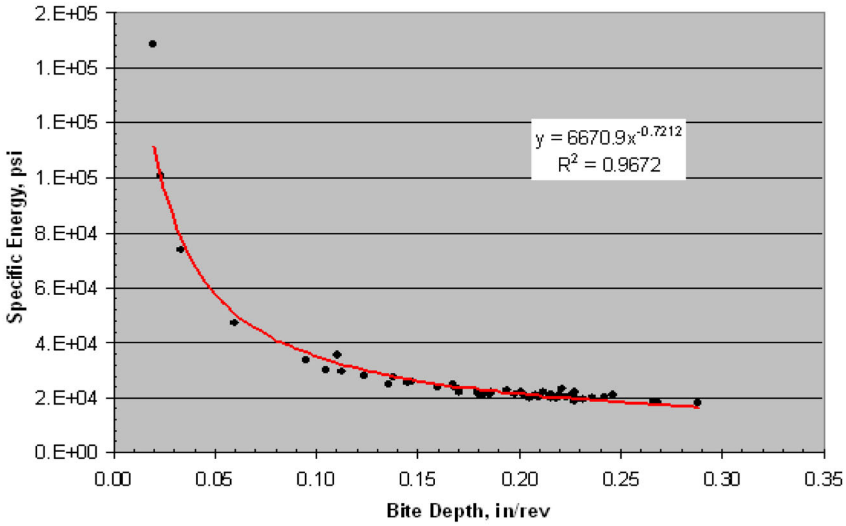


Fig. 1 Specific energy versus bite depth while drilling a cement block (Luo et al. 2014)

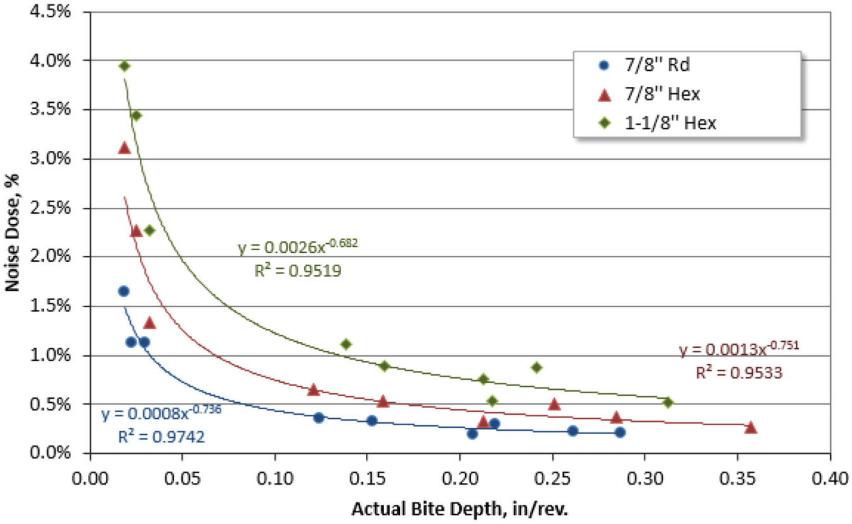


Fig. 2 Noise dose versus bite depth using different drill bit-steel combinations

conducted on a cement block with medium compressive strength (5.5–6.9 kPa or 8000–10,000 psi) of 0.9 m (3 ft) width, 0.9 m (3 ft) length and 1.5 m (5 ft) height. The roof bolter is equipped with a standard vacuum dust collection system in which the large cutting particles are removed with cyclone while the finer particles are collected by the filters. The finer particles are captured and contained by the dust bag which are used for later analysis in this paper.

3.1 Drill steels and bits

The standard drill steels and bits for underground coal mines were used in the tests. Three different types of drill steels used in the tests are 22-mm (7/8-in) round, 22-mm hexagon, and 29-mm (1–1/8-in) hexagon while the two types of drill bits are 22-mm (7/8-in) and 35-mm (1–3/8-in) as shown in Fig. 4. For the 22-mm (7/8-in) drill bits, 22-mm (7/8-in) round and hexagon steels are alternately used. For the 35-mm (1–3/8-in) bits, only 29-mm (1–1/8-in) hexagon steel is available. The 22-mm (7/8-in) drill bits produce bolt holes of 25 mm (1-in) in diameter while the 35-mm (1–3/8-in) bits result in 44 mm (1–3/4-in) holes. Tungsten carbide tip inserted in the steel bit body is intended for the rock cutting interactions. These bits are widely used in underground coal mining industry.

3.2 Drilling control parameters

The drilling control is realized by varying the penetration and rotational rates to achieve desired bite depths in the

Fig. 3 Experimental setup of the drilling dust study

Fig. 4 Drill bit and steel combinations (L) and drill bit (R) used in the experiments

experiments. The preset penetration rates are 15, 28, 36 and 43 mm/s (0.6, 1.1, 1.4, and 1.7 in/s) while the rotational rates are 350, 400, 500 and 550 rpm. Table 1 shows the controlled drilling rates and the resulting bite depths. The rate combinations that result in bite depths either impractically too low or too high are not tested. For example, when the penetration is preset at 36 mm/s (1.4 in/s), the rotational rates are preset at 400, 500 and 550 rpm. The selection of the test parameters is based on the previous drilling tests on the same experimental setup (Li 2015).

The feasibility to achieve preset controls for previous drilling tests was analyzed and it shows that the preset bite depth can be easily achieved when it is smaller than 4.6 mm/rev (0.18 in/rev). The maximum bite depth is also coincident with the height of the tungsten carbide insert above the steel body of new drill bits. Drilling at a bite depth higher than the maximum bite depth could result in excessive rubbing actions between the bit body and rock, and in low energy efficiency and high noise (Luo et al. 2014). For each drill bit and steel combination, 11 tests

Table 1 Drilling parameters for each drill steel

Bit size—steel type	Rotational rate (rpm)	Penetration rate, mm/s (in./s)			
		15 (0.6)	28 (1.1)	36 (1.4)	43 (1.7)
		Bite depth, mm/rev. (in/rev.)			
22-mm (7/8-in.)—Rd	350	2.61 (0.10)	4.79 (0.19)	–	–
	400	2.29 (0.09)	4.19 (0.17)	5.33 (0.21)	–
	500	–	3.35 (0.13)	4.27 (0.17)	5.18 (0.20)
	550	–	3.05 (0.12)	3.88 (0.15)	4.71 (0.19)
22-mm (7/8-in.)—Hex	350	2.61 (0.10)	4.79 (0.19)	–	–
	400	2.29 (0.09)	4.19 (0.17)	5.33 (0.21)	–
	500	–	3.35 (0.13)	4.27 (0.17)	5.18 (0.20)
	550	–	3.05 (0.12)	3.88 (0.15)	4.71 (0.19)
29-mm (1-1/8-in.)—Hex	350	2.61 (0.10)	4.79 (0.19)	–	–
	400	2.29 (0.09)	4.19 (0.17)	5.33 (0.21)	–
	500	–	3.35 (0.13)	4.27 (0.17)	5.18 (0.20)
	550	–	3.05 (0.12)	3.88 (0.15)	4.71 (0.19)

with different drilling parameters were conducted. Totally, 33 effective holes were drilled for the three different types of drill steels.

3.3 Drilling dust sample collection

For each drill bit and steel combination, the 11 tests were performed in four groups according to their bite depths as shown in Table 2. The average bite depths for the groups are 2.54, 3.30, 4.06, 5.08 mm/rev (0.10, 0.13, 0.16 and 0.20 in/rev). After drilling all the holes in a group, the dust is disposed from the dust collection system to a bucket where the dust samples were collected from. In order to ensure the sample representativeness, a sample is collected from several different locations of the dust mass. The weight of each sample ranges from 200 g to 500 g.

4 Results and analysis

The size distributions of dust samples collected are analyzed to show the feasibility of using proper drilling control for the reduction of respirable portion of the drilling dust. The collected drilling dust samples are first separated using sieve method to coarsely quantify the distributions in the entire size range. Then the laser diffraction method is used to study the size distributions of the drilling dust in the respirable range.

4.1 Sieve analysis

In the sieve analysis, rock dust samples are separated by a series of sieves with progressively smaller openings using a Ro-tap machine as the sieve shaker. It enables the

Table 2 Drilling parameters of dust samples for each drill steel—bit combination

Dust sample no.	Average bite depth, mm/rev. (in/rev.)	Bite depth, mm/rev. (in/rev.)	Penetration rate, mm/sec (in/sec)	Rotational rate (rpm)
1	2.45 (0.10)	2.61 (0.10)	15 (0.6)	350
		2.29 (0.09)	15 (0.6)	400
2	3.20 (0.13)	3.35 (0.13)	28 (1.1)	500
		3.05 (0.12)	28 (1.1)	550
3	4.11 (0.16)	4.19 (0.17)	28 (1.1)	400
		4.27 (0.17)	36 (1.4)	500
		3.88 (0.15)	36 (1.4)	550
4	5.00 (0.20)	4.79 (0.19)	28 (1.1)	350
		5.33 (0.21)	36 (1.4)	400
		5.18 (0.20)	43 (1.7)	500
		4.71 (0.19)	43 (1.7)	550

measurement of cumulative weights of dust particles up to different sieve sizes. The nests of sieves used were as follows: bottom pan, 0.074 mm (200 mesh Tyler), 0.149 mm (100 mesh), 0.250 mm (60 mesh), 0.595 mm (30 mesh), 1.19 mm (16 mesh), 2.38 mm (8 mesh) and the lid as shown in Fig. 5. It results in the following seven size ranges: <0.074 mm, 0.074–0.149 mm, 0.149–0.25 mm, 0.25–0.595 mm, 0.595–1.19 mm, 1.19–2.38 mm and >2.38 mm. The largest particle size of the sample is around 9 mm-10 mm.

The mass of the particles passing through the individual sieve are computed. The obtained cumulative size distribution for each dust sample is shown in Fig. 6. A distribution showing steeper curve in the small size range indicates higher content of fine dust particles. Figure 6a shows the cumulative size distributions of the drilling dust by the 22-mm (7/8-in) round steel-bit combination. Among the four groups, drilling with 2.54 mm/rev (0.10 in/rev) bite depth produces the highest percentage of fine dust particles (<1000 μm) while drilling at 4.11 mm/rev (0.16 in/rev) and 5.00 mm/rev (0.20 in/rev) produce lower percentages of fine dust (<1000 μm). The tests show that the higher the bite depth, the lower percentages of fine dust diameter is produced. The equivalent diameter for 50% cumulative dust mass (D_{50}) is a good measure for particle size distribution. Figure 6a also shows that the equivalent diameters are 270, 325, 465, and 520 μm for drilling at bite depths of 2.54, 3.20, 4.11 and 5.00 mm/rev (0.10, 0.13, 0.16 and 0.20 in/rev), respectively.

The drilling particle size distributions for the 7/8-in bit and hexagon steel combination (Fig. 6b) and 1–1/8-in bit and hexagon steel combination (Fig. 6c) show basically the similar trend as those in Fig. 6a. Drilling at 3.20 m/rev (0.13 in/rev) produces the lowest percentage of fine dust while drilling at highest bite depth of 5.00 mm/rev (0.20 in/rev) produced the highest percentage of fine dust. It should be noted that the heights of the tungsten carbide insert above the bit steel body is between 4.1 and 4.6 mm (0.16 and 0.18 in) at new condition. When a drill bit is operated at a bite depth larger than this height, the bit steel body starts to rub the rock and produces more fine dust. For drilling tests with 7/8-in hexagon (6b) and 1–1/8 hexagon (6c) steel—bit combinations, the equivalent diameter for 50% cumulative dust mass (D_{50}) is the largest for drilling at 3.20 mm/rev (0.13 in/rev) bite depth. The testing results also show smallest D50's for drilling at 5.00 mm/rev (0.20 in/rev) bite depth. The results of drilling at 4.11 mm/rev (0.16 in/rev) using 1–1/8-in hexagon steel—bit combination seem to be abnormal.

4.2 Respirable dust analysis

As discussed before, the sieve method is not suitable for analyzing the particle size distribution in the respirable range. Since the proposed dust control approach is targeted to the reduction of respirable dust, characterization of the particle size distribution of the drilling dust in the respirable range is of high importance. In this step, a newly acquired CILAS 1190 Laser particle size analyzer is used to perform the more detailed size distribution analysis. This laser based particle analyzer can provide a measurement range between 0.04 and 2500 μm via the volume distribution. Measurement were made in liquid mode using water as the medium. The amount of sample placed into the particle size analyzer for analysis should be appropriate since "too much" sample in the system would result in high obscurations and erroneous measurement. Trial tests indicate that a rock dust sample amounting between 300

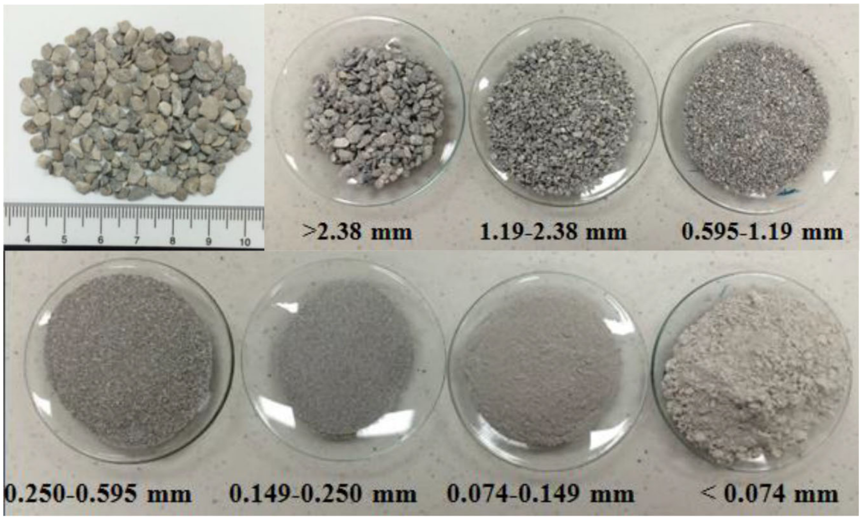
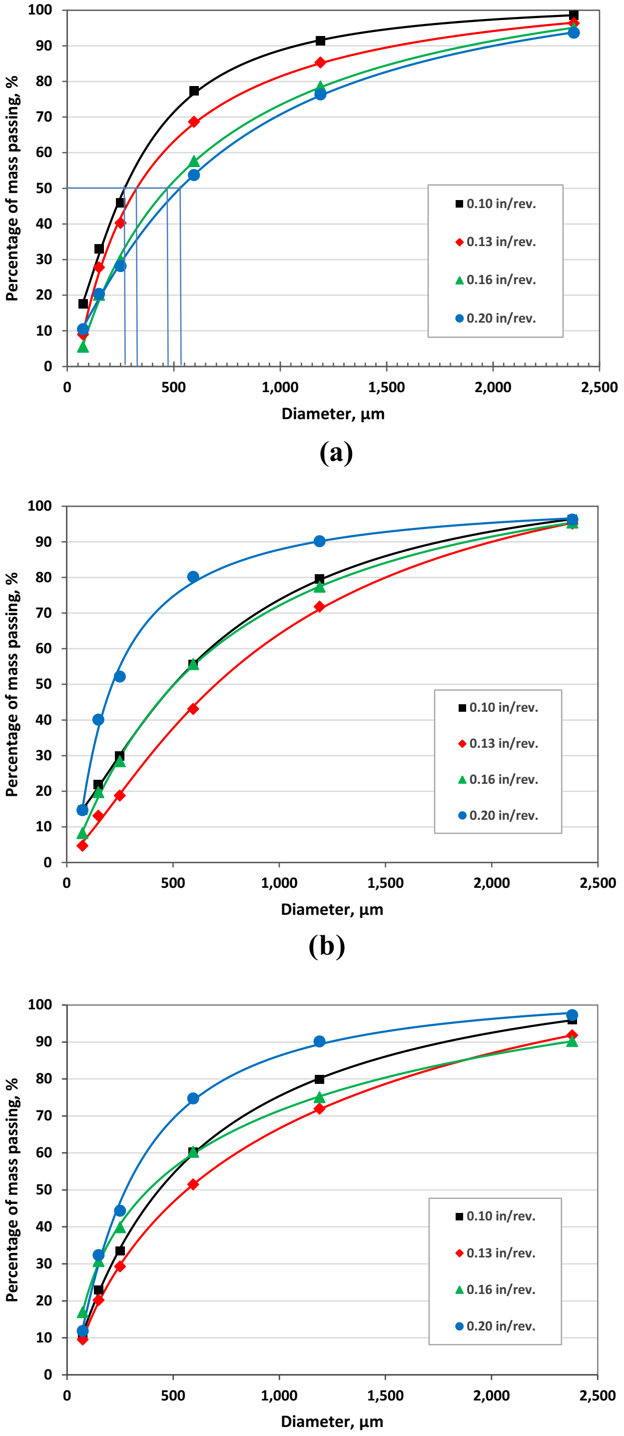


Fig. 5 Dust sample sieved into seven different size ranges



(a)

(b)

(c)

Fig. 6 Cumulative particle size distributions. **a** 22-mm (7/8-in) bit—round steel combination, **b** 22-mm (7/8-in) bit—hexagon steel Combination, **c** 29-mm (1–1/8-in) bit—hexagon steel combination

and 1000 mg is proper considering the particle size range. It is also found that too much coarser particles in the sample would cause inaccurate measurement as it settles quickly in water medium. Attempts were made to use the particle size analyzer to test on the dust samples up to 2500 µm in size but it is hard to obtain representative small sample in such a wide size range. Attempt has also been made to narrow the size range from 0 to 1190 µm but erroneous measurements occurred in a number of such tests as coarser particles were not detected. The particles smaller than 74 µm, obtained from sieve screening, are analyzed with the CILAS 1190 particle size analyzer.

The cumulative volume percentages from 0.04 to 74 µm (i.e., the inspirable particle range) for each sample are computed and plotted in Fig. 7. The size distribution of dust particle less than 5 µm (respirable dust) is of our interest. In this size range, dust particles are small enough to penetrate the nose and upper respiratory system and deep into the lungs. Figure 7a shows the cumulative size distribution of the drilling dust by the 22-mm (7/8-in) round steel-bit combination. Among the four groups, drilling with 5.00 mm/rev (0.20 in/rev) bite depth produces the highest percentage of respirable dust (<5 µm) while drilling at 3.20 mm/rev (0.13 in/rev) produces lowest percentages of respirable dust. However, the differences between the lowest and highest percentages of respirable dust are small (less than 2%) compared to the differences between the lowest and highest percentages of fine dust less than 74 µm (around 12%). Figure 6a shows that the cumulative mass percentages of fine dust (<74 µm) are 17.5%, 8.98%, 5.51% and 10.43% for drilling tests at bite depth of 2.54, 3.20, 4.11, and 5.00 mm/rev (0.10, 0.13, 0.16, and 0.20 in/rev), respectively. Considering the particle size distribution in the whole size range and particle size distribution less than 74 µm, drilling with bite depth 4.11 mm/rev (0.16 in/rev) generates lowest content of respirable dust while drilling with bite depth 2.54 mm/rev (0.10 in/rev) generates highest content of respirable dust.

The similar analysis is applied to drilling dust using 22-mm (7/8-in) hexagon and 29 mm (1–1/8-in) hexagon steel-bit combination. For drilling tests using 22 -mm (7/8-in) hexagon steel-bit combination (Fig. 7b), drilling at 4.11 mm/rev (0.16 in/rev) and 5.00 mm/rev (0.20 in/rev) bite depth produces higher percentages of respirable dust (<5 µm) than drilling at 3.20 mm/rev (0.13 in/rev) and 2.54 mm/rev (0.10 in/rev). In Fig. 6b, the cumulative mass percentages of fine dust (<74 µm) are 14.68%, 4.63%, 8.22% and 14.67% for drilling tests at bite depth of 2.54, 3.20, 4.11 and 5.00 mm/rev (0.10, 0.13, 0.16 and 0.20 in/rev), respectively. Considering the particle size distribution in the whole size range and particle size distribution less than 74 µm, drilling with bite depth 3.20 mm/rev (0.13 in/rev) generates lowest content of respirable dust while drilling with bite depth 2.54 mm/rev (0.10 in/rev) generates highest content of respirable dust.

For drilling tests using 29 mm (1–1/8-in) hexagon steel-bit combination (Figs. 6c, 7c), the content of respirable

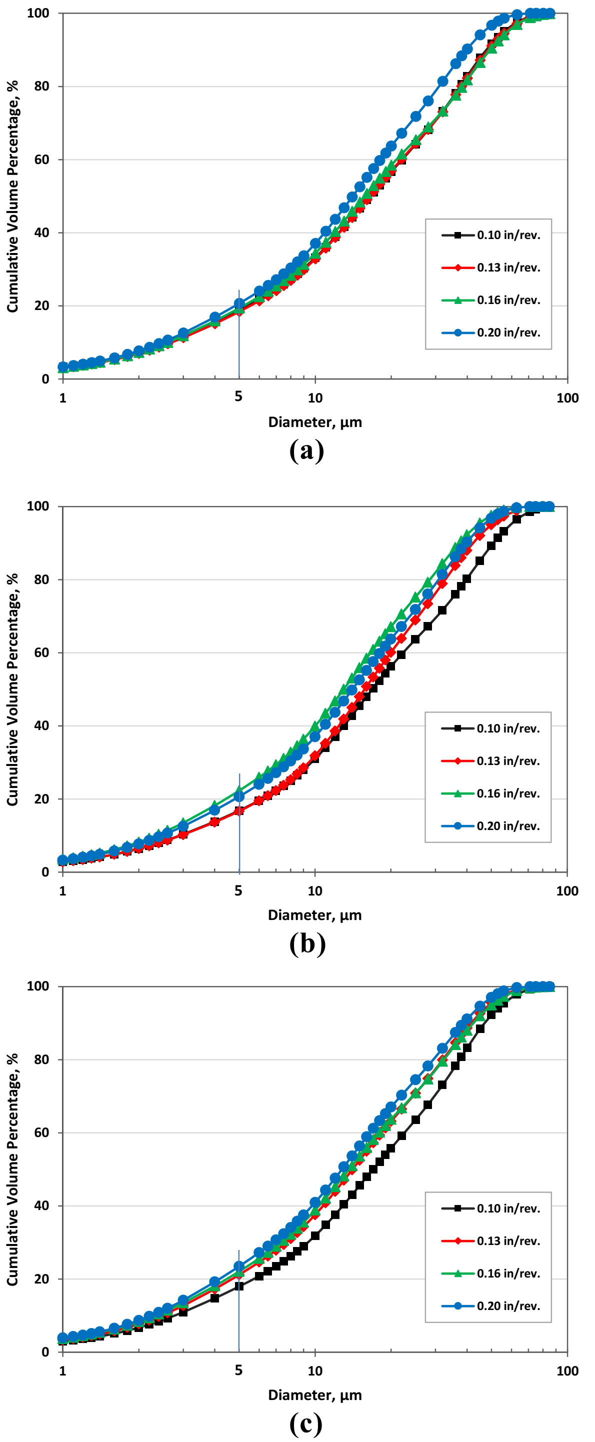


Fig. 7 Cumulative size distribution (<74 µm). **a** 22-mm (7/8-in) bit—round steel combination, **b** 22-mm (7/8-in) bit—hexagon steel combination, **c** 29-mm (1–1/8-in) bit—hexagon steel combination

dust drilling with bite depth 3.20 mm/rev (0.13 in/rev) is the lowest. Drilling with bite depth 4.11 mm/rev (0.16 in/rev) generates highest content of respirable dust as the percentages of fine dust less than 74 µm is higher than drilling with other three bite depths. As mentioned previously, the results of drilling at 4.11 mm/rev (0.16 in/rev) using 1–1/8-in hexagon steel—bit combination seem to be abnormal. That could be caused by a bad sampling.

5 Conclusions

An approach to reduce drilling dust for roof bolting operations through proper drilling control has been pro-posed based on the findings from a previous research. Drilling experiments have been conducted to explore the feasibility of this dust control approach. Through analyzing the size distributions of the drilling dust in relation to the drilling bite depth, it was found that controlling drilling in different bite depths has significant effect on the distributions of respirable dust. The preliminary experimental study shows rationalizing drilling control, to achieve an allowable high bite depth for varying rocks, is promising to reduce fine dust in roof bolting drilling operation. Drilling with bite depth 2.54 mm/rev (0.10 in/rev) generates highest content of respirable dust for both 22-mm (7/8-in) round and hexagon steel-bit combination. Drilling with bite depth 4.11 mm/rev (0.16 in/rev) is promising to generate lowest content of respirable dust when using 22-mm (7/8-in) round steel-bit combination and drilling with bite depth 3.20 mm/rev (0.13 in/rev) generates lowest content of respirable dust for 22-mm (7/8-in) hexagon steel-bit combination. Through proper control of the drilling parameters according to rock types, the dust exposure to the bolter operators can be significantly reduced, while the bolting productivity is not affected or is even improved.

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