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Laboratory development and pilot-scale deployment of a two-part foamed rock dust

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ABSTRACT

U.S. Code of Federal Regulations 30 CFR 75.402 and 75.403 require 80% total incombustible content to be maintained within 40 feet of the coal mine face via the liberal application of rock dust. Unfortunately, this application of rock dust limits miners' visibility downwind and can increase the miners' exposures to a respirable nuisance dust. Wet rock dust applied as a slurry is, at times, used to negate these negative effects. Although this aids in meeting the total incombustible limits, the slurry forms a hard cake when dried and no longer effectively disperses as needed to suppress a coal dust explosion. As a result, a dry rock dust must be reapplied to maintain a dispersible layer. Therefore, researchers from the National Institute for Occupational Safety and Health (NIOSH) have been working towards finding and testing a foamed rock dust formulation that can be applied wet on mine surfaces and remain dispersible once dried which minimizes the likelihood of mine disasters, including mine explosions. The initial tests were aimed at discerning dispersion characteristics of three different foamed rock dusts via the NIOSH-developed dispersion chamber and led to identification of a two-part foam with adequate dispersion characteristics. The current study was conducted to assess the robustness of the two-part foamed rock dust. Through a series of laboratory-scale experiments using the dispersibility chamber, the effects of testing conditions and product formulations on the foam's dispersibility was determined. Some of the tested variables include: exposing the foam to high humidity, varying the component levels of the foamed rock dust, altering the rock dust size distribution, and varying the rock dust types. Further pilot-scale tests examined the atmospheric concentrations of dust via personal dust monitors downwind of foamed rock dust production and application. Additionally, product consistency was recorded during pilot-scale testing at key points in the formulation and application. The results of these experiments will be discussed in this paper.

1. Introduction

The impetus for developing a dispersible rock dust slurry came from the two requirements placed on underground coal mines. The first requirement defines permissible rock dust and the amounts that are necessary to be compliant (U.S. Code of Federal regulation, 2019a, U.S. Code of Federal regulation, 2019b). The second requirement is the time-weighted average limit of mine workers' exposure to airborne dust (U.S. Code of Federal regulation, 2019c).

Rock dust acts as a physical heat sink during an explosion (Cybulski, 1975; Richmond et al., 1975; Nagy, 1981) and is the primary technique used to suppress the reaction. Therefore, application of rock dust in sufficient quantities is essential to inert coal dust and to prevent continued flame propagation. Current rock dusts are hydrophilic and wick

moisture, forming a nondispersible wet paste that stiffens to a cake when dried, thereby significantly reducing or inhibiting the rock dust's ability to effectively disperse. Coal dust, due to its hydrophobicity, can remain dispersible under these conditions, thereby permitting its involvement in a propagating dust explosion. The presence of moisture in the mine can lead to the condition in which the coal dust can be dispersed and participate in the explosion while the rock dust becomes ineffectual.

Additionally, there have been continuing concerns of respirable diseases among coal miners resulting in another requirement limiting the total respirable dust to which coal miners are exposed. The respirable size fraction of rock dust used to inert a coal dust explosion can contribute to the total dust being measured. As a result, some mines have turned to applying a wet rock dust to minimize the miner's exposure to respirable dust. The wet application of the rock dust allows the mine to

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place dust in key locations, such as the roof and ribs, and cover the exposed coal without exposing the workers to respirable dust. However, a side effect of the wet application of the rock dust is that the rock dust no longer is dispersible due to caking and is subsequently ineffective. Currently, MSHA requires an application of dry rock dust on top of the wet-applied rock dust once the wet rock dust dries (MSHA, 2015) and becomes caked.

A possible solution to this problem is a foamed rock dust (FRD). The hope is that the FRD has the benefits of a normal rock dust slurry while remaining dispersible when dry. Currently, the ability of the FRD to fracture from a passing pressure wave and disperse into individual particles to inert a dust explosion is not known. Prior laboratory testing has, however, led to promising results showing favourable dispersion characteristics with a few specific formulations. Hierarchically, the resulting engineering control of respirable dust through the application of foam dust would foster better health for coal miners, while keeping them safe from coal dust explosions. The FRD also has the potentially additional benefit of better adherence to elevated surfaces in the mine entry leading to increased effectiveness of the inert material. Past studies have shown that rock dust located on the roof, ribs and other elevated surfaces is more readily dispersed than dust on the floor (Hartmann, 1957).

To this end, laboratory experiments were conducted on a previously tested rock dust which incorporated a two-part foam (TPF). Past studies showed promising results when compared to other foam products currently on the market (Brown et al., 2018). However, the unique formulation and application properties of the TPF with rock dust are still not understood. Therefore, NIOSH researchers conducted a series of laboratory-scale experiments using the NIOSH-developed dispersibility chamber to examine the effects of testing conditions and product formulations on foam dispersibility. The insights gained were then applied during the pilot-scale testing in the Bruceton Experimental Mine (BEM) at the Pittsburgh Mining Research Center. Again, a series of tests were conducted to investigate the impact of various factors on the dispersion characteristics of the foam. Additionally, the airborne dust levels were measured during the production and application of the foam dust to confirm the benefits of the wet-applied method.

2. Materials and methods

The test series had two main environments where the samples were prepared—in the laboratory at the benchtop scale and in the BEM at the pilot scale. The bulk of the sample preparations were conducted under laboratory conditions. The main method of discerning the performance of the rock dust was its dispersion performance in the NIOSH dispersion chamber (Perera et al., 2016). The samples were compared on a relative basis to the reference rock dust used by NIOSH at the Lake Lynn Experimental Mine (LLEM) in large-scale explosions testing.

2.1. Experimental materials

This section describes the two experimental materials used in the testing. These materials include the various rock dusts and a foam.

2.1.1. Rock dust

Several rock dusts were used in these series of experiments, including the reference limestone rock dust, a set of classified rock dusts that used the reference rock dust as input, and five other commercially available rock dusts. The reference rock dust has been extensively used in previous experiments at the LLEM, most notably in experiments which lead to the implementation of the 80% incombustible rule in the United States (Cashdollar et al., 2010). The classified rock dust used the same reference rock dust but was sieved through either a 200-mesh or a 400-mesh sieve. The resulting oversized and undersized material was later used in the experiments.

2.1.2. Foam

Previous experiments were conducted with various commercially available foams that could incorporate rock dust. These tests had the similar aim of creating a wet-applied material which when dried was dispersible via a “light blast of air” (30 CFR § 75.2). These experiments showed that the use of a TPF in this application provided a promising solution. The TPF used in this series of tests consisted of water, a foaming agent, and a stabilizing agent (Brown et al., 2018).

2.2. Experimental apparatuses

This section describes three experimental apparatuses used during the testing. These apparatuses allowed researchers to measure the dispersion characteristics, size distribution and airborne dust concentrations.

2.2.1. Dispersion chamber

The FRD samples produced in the lab or in the BEM were tested in NIOSH’s dispersion chamber. The chamber sends a pulse of air across a sample bed of rock dust, dispersing a quantity of the dust and sending it across a dust probe as seen in Fig. 1.

Passage of the dust across the probe causes the obscuration of a light beam which is measured and recorded (Cashdollar et al., 1981). The obscuration caused by these entrained particles is used as a means of assessing the dispersibility of the sample. The pulse of air used to initiate the test was based on the dynamic pressure measurements of a near-limit propagating coal dust explosion conducted at LLEM, as shown in Fig. 1 and, as such, provides the reproducible “light blast of air” described in 30 CFR § 75.2.

The test procedure, notably, does not simulate a shockwave but, rather, creates a similar pressure history per the rapid release of the air pulse. Use of this method is described in greater detail by Perera et al. (2016).

As shown from the aforementioned large-scale testing at LLEM in Fig. 2, vertical or static forces are created due to the passing of a shock wave. The static pressure in Fig. 2 is about three times greater than the dynamic pressure. It is reasonable to assume that the overpressure may destroy the cohesive foam matrix, freeing individual particles or particle agglomerations for dispersion. Computational models have observed these vertical forces in addition to reflected compaction waves in the dust layer just behind the shockwave (Lai et al., 2018). As a result of these findings, samples were tested using the additional 45° nozzle orientation (Fig. 3). The change in orientation allowed the researchers to add a vertical force component.

2.2.2. Particle size

The particle size distributions of rock dusts were determined using a Beckman-Coulter LS 13 320 laser scattering size analyser. The Beckman-Coulter instrument measures the scattering of a 780-nm laser beam by the entrained dust at various angles with respect to the beam direction. The instrument returns the particle size distribution in terms of the spherical equivalent via Mie scattering.

2.2.3. Dust concentration monitor

Dust concentrations were monitored and measured during the production and application of the foam rock dust in the BEM. The gravimetric samples were collected on pre-weighed filters using the standard Zefon Escort ELF personal air sampling pumps after the respirable size fraction was separated from the oversized dust by a 10-mm Dorr-Oliver cyclone. Additionally, a continuous personal dust monitor from Thermo Scientific, the PDM 3600, was used to monitor dust concentrations during the test via a tapered element oscillating microbalance (Page et al., 2008).

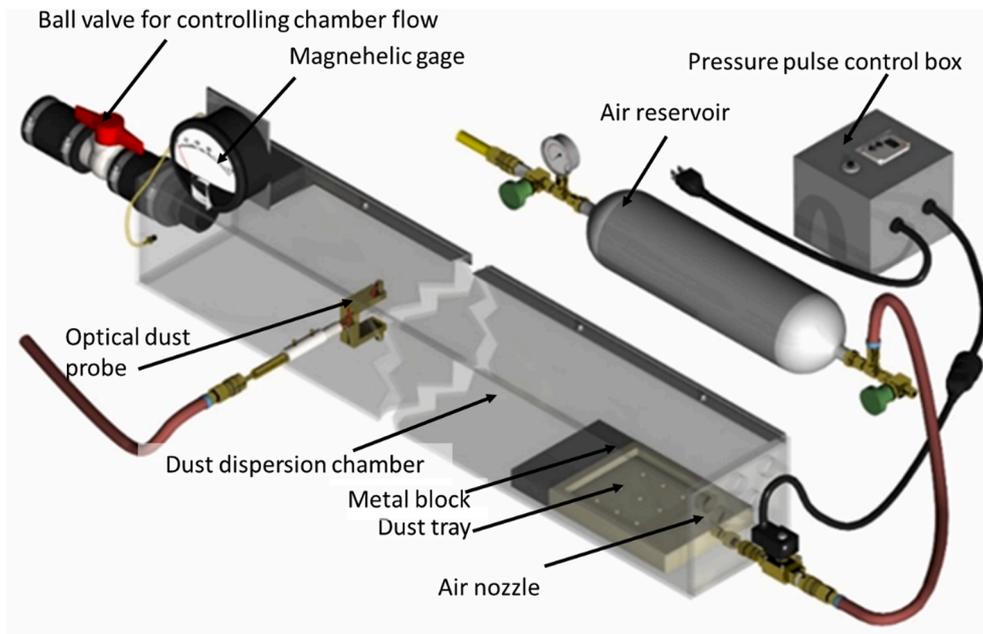


Fig. 1. Dispersion chamber schematic (Perera et al., 2016).

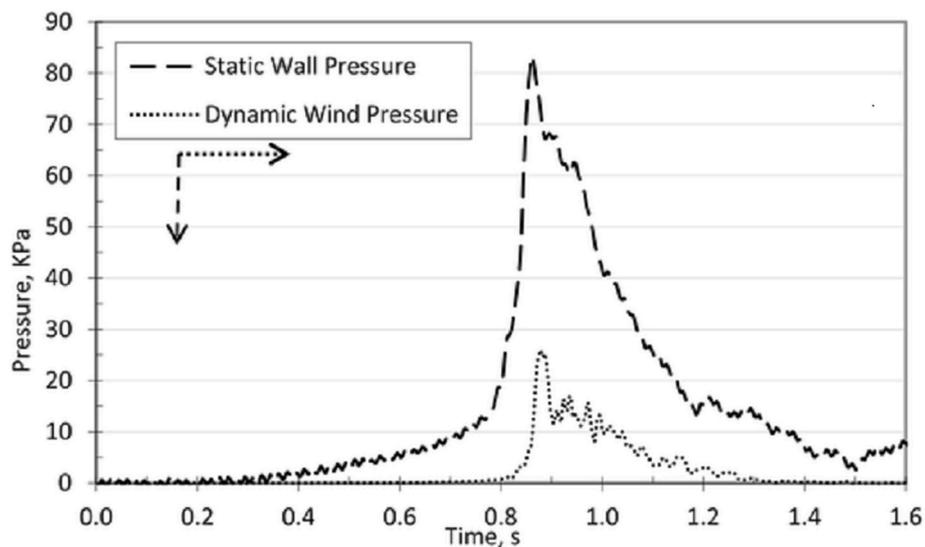


Fig. 2. Horizontal and vertical components of dust explosion pressures measured during LLEM shot #517.

2.3. Experimental sample preparation

This section describes the process of sample preparation in the lab and in the pilot-scale test facility. In addition this section details the changes made to the sample variables.

2.3.1. Laboratory sample preparation

The dry rock dust samples, used for the relative comparison, were prepared in accordance with the standard operation procedures of the NIOSH-developed dispersion chamber (Perera et al., 2016). To prepare the FRD samples, the TPF was prepared first by combining 300 g of water and 15 g of the foaming agent. This solution was whipped with a mixer until a consistent foam matrix was established. A stabilizing agent was then slowly added to the foam matrix. Once blended, the stabilized TPF was combined with the rock dust. The samples were then placed under two drying conditions. The fast-drying condition was the ambient lab environment. The slow-drying condition placed the samples in

sealed chambers with high humidity and no airflow. After a week in the chamber, the samples were taken out and allowed to dry under ambient lab conditions. All samples were dispersed using a 45-degree nozzle.

Initial rounds of testing examined the effects of changing the amount of stabilizer and the amount of rock dust used in the formulation. The amounts of stabilizer tested were 10 g and 21 g. The amounts of rock dust tested were 600 g, 900 g, and 1500 g.

Other FRD samples were made by adding water to the rock dust prior to being mixed with a different blend of foam. The TPF in these cases kept the ratio of stabilizer and foaming agent at 1:1. The stabilizer levels were 6.5 g, 5 g, and 3.5 g per batch while keeping the rock dust mass at 1500 g and the additional water at 400 g. The amount of pre-wet rock dust also varied, but the ratios of rock dust to water and the amounts of stabilizer and foaming agent (5 g) remain the same.

Five total sample sets were run with different commercially available rock dusts using the same FRD formulation. The formulation consisted of 300 g of water, 5 g of foaming agent, 5 g of stabilizer, 1500 g of rock

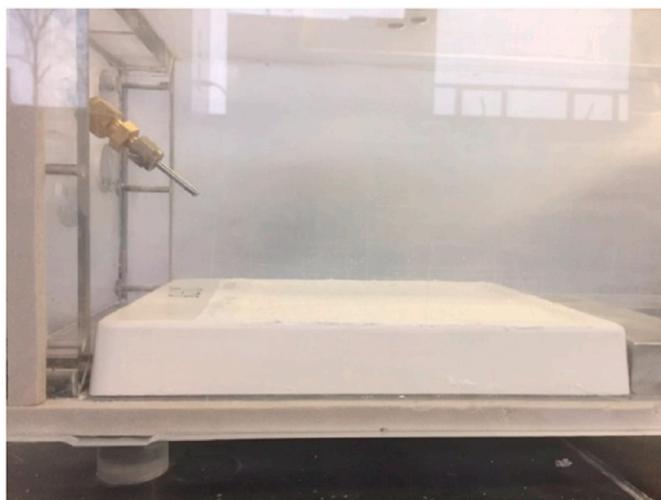


Fig. 3. 45° nozzle orientation.

dust, and 400 g of water to pre-wet the rock dust.

The final sample set produced in the lab used the same previous formulation except with four classified batches of the reference rock dust. The reference rock dust was sieved through either a 200-mesh or a 400-mesh sieve. In both cases, 1500 g of the oversized or undersized material was used in the FRD, keeping all other ingredients the same. Each combination of drying condition and formulation tested a total of five samples. A tabulation of the various sample sets is shown in Table 1 below.

2.3.2. BEM sample preparation

Anemometers were placed upwind and downwind of the test area (Fig. 4) to monitor airflow velocities. Additionally, the dust sampling equipment was placed 100 ft downwind of the test area. The mortar mixer used to blend and apply the FRD was turned on and allowed to run to collect a baseline level of diesel particulate matter (DPM). The test matrix is tabulated in Table 2.

All the tests used the reference rock dust as the base inert material. The first three tests were a set of triplicates that emulated the laboratory formulations. The following four tests looked at variations of the formulation to see how the foam would be impacted if a mine worker would improperly mix the inputs to the system. The first two tests

changed the amount of rock dust by $\pm 15\%$, and the other two tests varied the water used to pre-wet the rock dust by $\pm 15\%$. The parameters for the foam generator would be initially set and not altered by the machine operator. Once the instrumentation was in place, a premeasured amount of dust was placed into the mixing hopper of the mortar mixer. The premeasured amount of water was then added to the rock dust and allowed to mix. At this point, the calibrated foam generator was turned on, and a foam was added to the slurry for a predetermined amount of time. This was mixed until the mixture was homogenous. When the mixer was stopped, a sample was taken with a 1-qt container and weighed to get a density measurement. Additional material was taken from the mixer and used to fill trays for later testing in the dispersion chamber. The initial weight of the trays with the fresh samples was taken at this point for use in later calculations to determine the FRD density and measured water content. Once the samples were taken out of the mixer, the rest of the material was dumped into the hopper and the auger pump was turned on. A 1-qt sample was then taken as the material left the application nozzle. This was then weighed for a density measurement. Additional material was also taken from the end of the nozzle for the dispersion trays. These trays also had their mass recorded. Once the last sample of material was taken, the FRD was applied to the roof and ribs of the mine. This continued until there was no more FRD left for the pump to move. The area was then marked with spray paint to denote the test number, and the application equipment and dust monitoring equipment were then moved to the next testing location. The tray samples were kept in the mine under the same drying conditions until the sample weights stabilized, just over one week. The dispersion testing in the lab began about 2 weeks after the application.

3. Results and discussion

3.1. Lab results

3.1.1. Dispersibility of the reference rock dust (dry powder)

The relative dispersibility of the dry reference rock dust was tested using the 45° nozzle instead of the horizontal nozzle. The resulting average (Fig. 5) was used as a benchmark to compare the relative dispersibilities of the foamed dusts. The average integral optical densities (IOD) of the FRD is compared to that of the dry rock dust powder. After all data was normalized, the relative IOD for the reference rock dust was 1 ± 0.11 .

Table 1

Laboratory tests examining the impact of various components on the dispersibility of foamed rock dust.

Sample set	FOAM			ROCK DUST			Drying Conditions
	Water (g)	Foaming Agent (g)	Stabilizer (g)	Base rock dust	Amount (g)	Water (g)	
1	300	15	10	Reference	600	–	Fast & Slow
2	300	15	21	Reference	600	–	Fast & Slow
3	300	15	10	Reference	900	–	Fast & Slow
4	300	15	21	Reference	900	–	Fast & Slow
5	300	15	10	Reference	1500	–	Fast & Slow
6	300	15	21	Reference	1500	–	Fast & Slow
7	300	6.5	6.5	Reference	1500	400	Fast & Slow
8	300	5	5	Reference	1500	400	Fast & Slow
9	300	3.5	3.5	Reference	1500	400	Fast & Slow
10	300	5	5	Reference	1275	340	Fast & Slow
11	300	5	5	Reference	1725	460	Fast & Slow
12	300	5	5	Commercial RD 1	1500	400	Fast
13	300	5	5	Commercial RD 2	1500	400	Fast
14	300	5	5	Commercial RD 3	1500	400	Fast
15	300	5	5	Commercial RD 4	1500	400	Fast
16	300	5	5	Commercial RD 5	1500	400	Fast
17	300	5	5	- 400 mesh Reference	1500	400	Fast
18	300	5	5	- 200 mesh Reference	1500	400	Fast
19	300	5	5	+400 mesh Reference	1500	400	Fast
20	300	5	5	+200 mesh Reference	1500	400	Fast

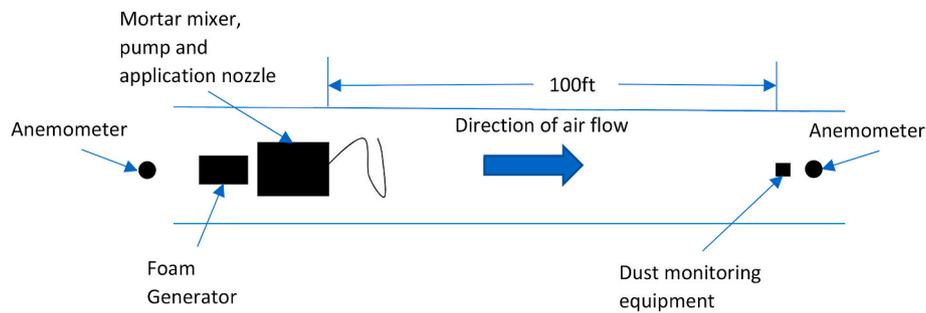


Fig. 4. Schematic of BEM pilot scale testing.

Table 2

Test matrix for pilot-scale testing two-part foamed rock dust in the BEM.

Test Conditions	Test Number	Dust, kg	Water, l	Amount of foam
Triplicate	1	45.4	11.4	40 s of foam
Triplicate	2	45.4	11.4	40 s of foam
Triplicate	3	45.4	11.4	40 s of foam
+15% rock dust	4	52.2	11.4	40 s of foam
-15% rock dust	5	38.6	11.4	40 s of foam
-15% water	6	45.4	9.7	40 s of foam
+15% water	7	45.4	13.1	40 s of foam

3.1.2. Environmental/testing conditions of the foam

The effects of high humidity exposure did show a marked negative difference in the dispersibility of the foams when comparing the combined averages from sample sets 1 through 11 (Fig. 6). Although a number of samples did disperse after being placed in the humidity cabinets, it was to a lesser extent than when the samples were dried quickly in the laboratory environment.

In some cases, the bubbles in the slow-drying foams began to agglomerate, which stiffened its lattice. These resulting agglomerations remained cohesive enough that when the bulk material broke, the agglomerations fell out of suspension very quickly and did not reach the dust probe, resulting in poorer performance.

3.1.3. Variation in formulation

Using sample sets 1 through 6, researchers found that the increased amount of stabilizer, while aiding in the foam's rigidity during longer periods of high humidity, negatively affected the dispersion

characteristics by reinforcing the cohesive characteristics of the dust. Conversely, the lower levels of stabilizer allowed for a rigid yet friable structure which more readily dispersed. Another important note was that few samples collapsed due to insufficient amounts of material being present as the samples dried. Conversely, better dispersion characteristics were seen with samples containing 900 g or 1500 g of rock dust per batch. These results may be due to the changing ratio of water to rock dust, which, could be affecting the rate of drying per unit volume. The additional material also could be simply translating to more material being entrained and, therefore, more obscuration at the dust probe. Lastly, the formulations which used higher amounts of rock dust had a decreased ratio of stabilizer in the formulation. All these factors may have led to the increases in performance. The results of these variations to the formulation under the fast- and slow-drying conditions can be seen in Fig. 7 and Fig. 8, respectively.

The performance of the foam seemed to be most sensitive to levels of stabilizer in the formulation when considering variations to the components of the FRD. Additional efforts were made to keep the amount of rock dust high while decreasing the levels of stabilizer further without causing adverse effects to the foam. To achieve these aims, water was added to the rock dust before being blended into the foam. This practice prevented the rock dust from absorbing too much water out of the foams' lattice, which could have produced negative effects. The results from sample sets 7 through 11 can be seen in Fig. 9 for fast-drying samples and Fig. 10 for slow-drying samples.

The most consistent formulation that performed well in both the fast- and slow-drying conditions used 1500 g of rock dust with 400 g of water, while the stabilizer and foaming agent were held at 5 g per batch. This formulation was then compared to the original dry reference rock dust.

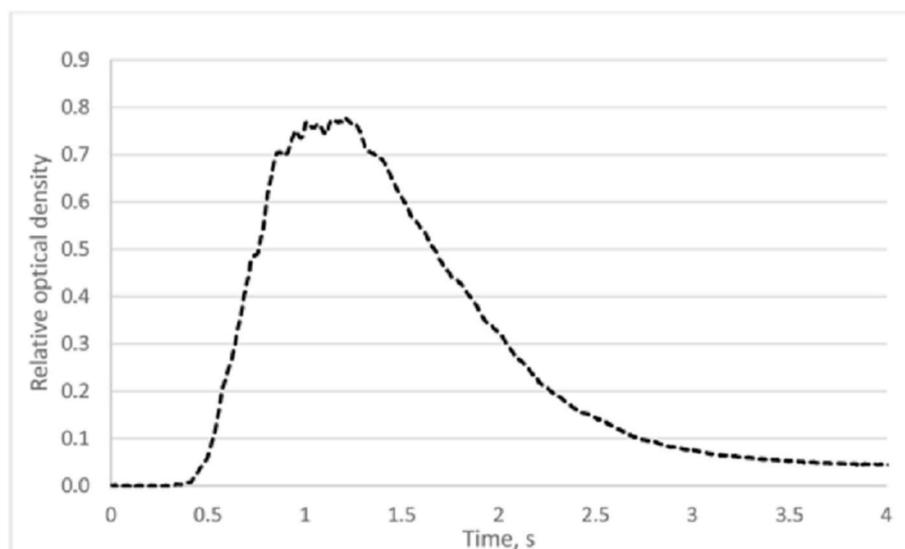


Fig. 5. Relative average IOD for reference rock dust dispersed at 45° - 1.00 ± 0.11 .

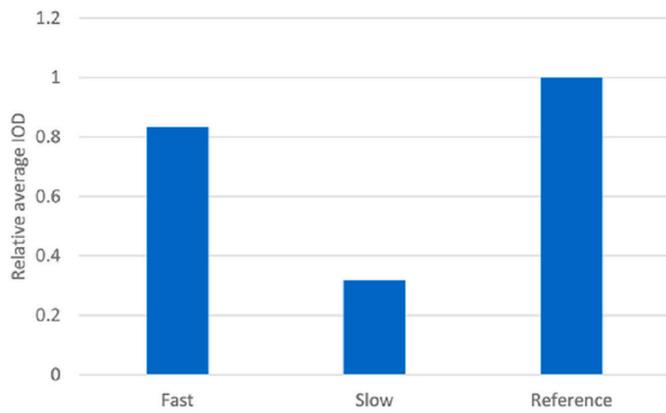


Fig. 6. Relative average IOD of fast and slow-drying FRDs compared to the reference rock dust.

The obscuration traces are shown in Fig. 11.

The robustness of the foam was then tested using samples sets 12 through 16 where the formulations were held the same, but the rock dust was replaced using other commercially available rock dusts. These tests were conducted to ensure the FRD formulation was applicable with various dusts and that the formulation was not over-optimized for the

reference rock dust. The test results are shown in Fig. 12 where the relative average IODs are plotted against their respective specific surface areas (SSA).

When compared to the reference rock dust, the FRD that used a coarser commercial rock dust, commercial rock dusts 1 and 2, did not perform as well as the other rock dusts that had a similar SSA to the reference rock dust. It should also be noted that the coarser dusts also have a larger fraction of particles that fall out of suspension sooner, leading to a drop in performance. To test this, the reference rock dust was classified using a 200- and 400-mesh sieve resulting in the sample sets 17 through 20. The formula ratios were kept the same for all tests, and the results were plotted in Fig. 13 along with the data from sample sets 12 through 16.

The coarser rock dust size fractions performed as expected with less relative average obscuration at the dust probe. The fine size fraction (–200 mesh) closest to the reference rock dust was found to show good performance. The poor results for the –400 mesh material was, however, unexpected. The initial thought was that the finer size fraction would allow for more particles to be entrained and obscure the dust probe. From this initial data set, it looks like the range of SSA for utilizing this formulation is about 2500–3500 cm²/g. The lack of performance from the –400 mesh FRD does not suggest the avoidance of fine material in the mixture but, rather, suggests that the formulation should be altered to better incorporate the ultra-fine dust. The larger surface area allows the ultra-fine material to adsorb more water. This could be

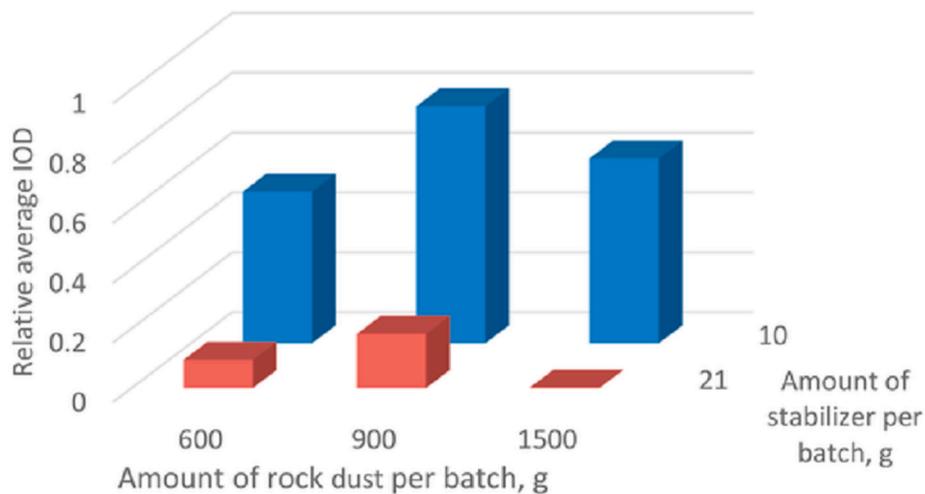


Fig. 7. Relative average IOD for fast-drying foam formulations from samples 1-6.

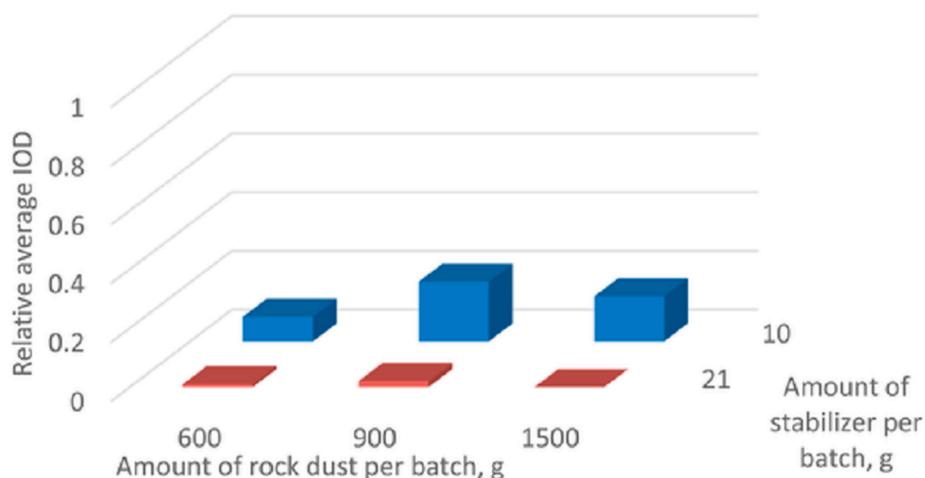


Fig. 8. Relative average IOD for slow-drying foam formulations from samples 1-6.

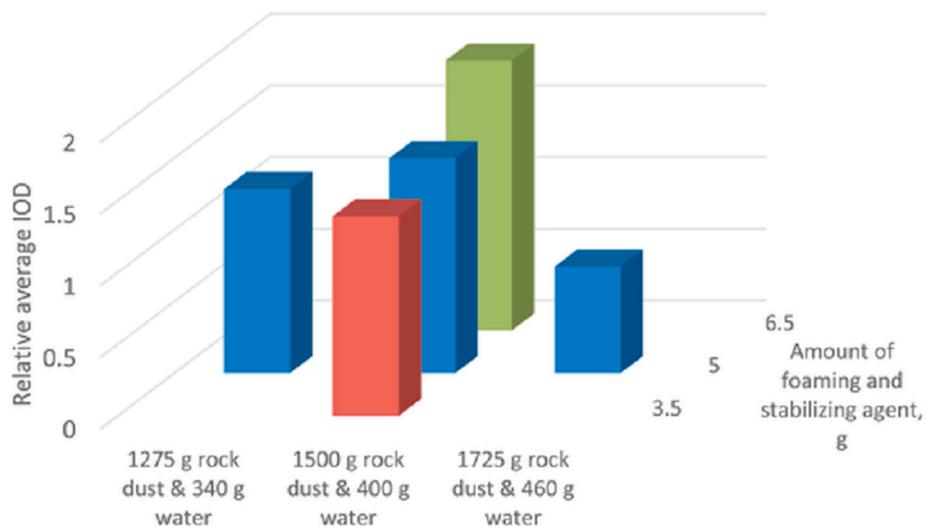


Fig. 9. Relative average IOD for fast-drying foam formulations from samples 7-11.

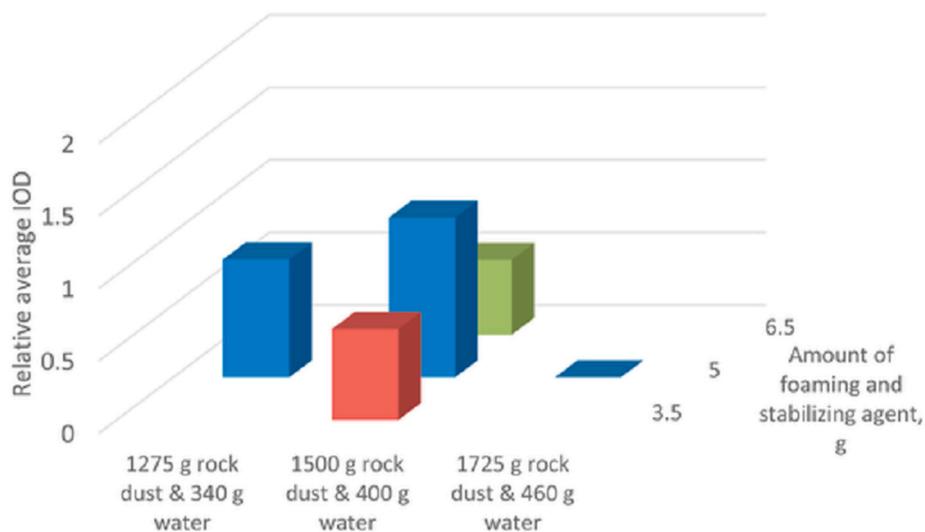


Fig. 10. Relative average IOD for slow-drying foam formulations from samples 7-11.

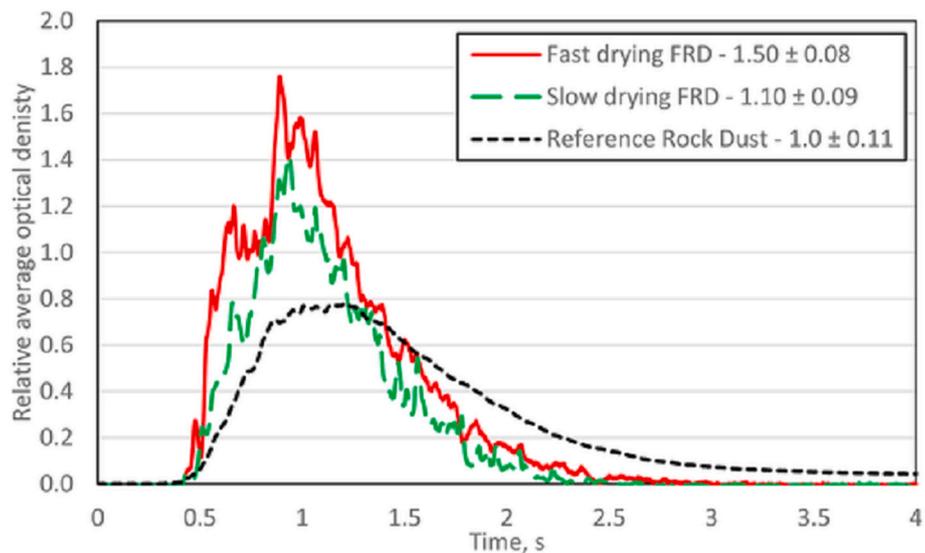


Fig. 11. Impacts of environmental conditions on the formulation from sample set 8 compared to the dry reference rock dust when dispersed with a 45° nozzle.

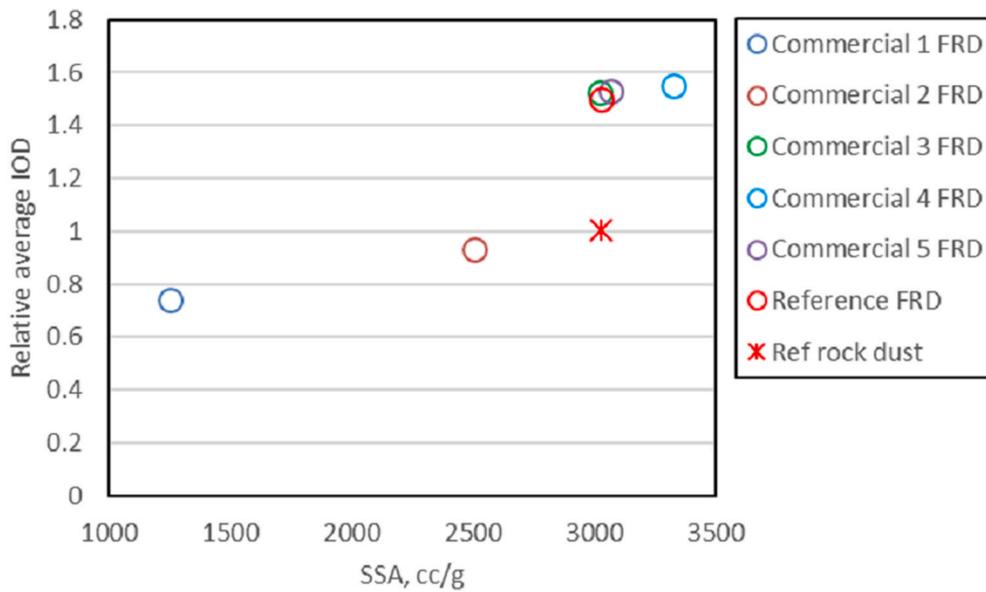


Fig. 12. The impact of various commercial rock dusts on the foam formulation and the relationship with the rock dusts' SSA.

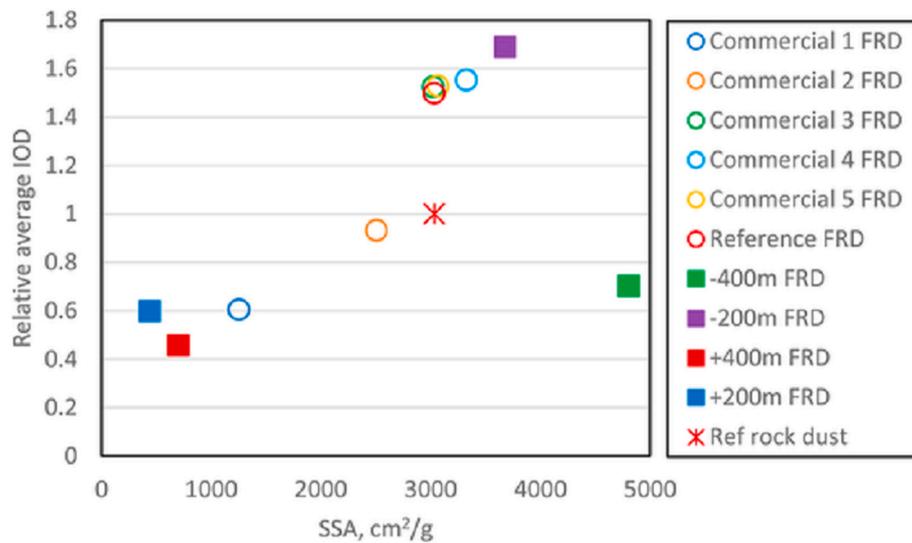


Fig. 13. The impact of classified rock dusts on the foam formulation and the relationship with the rock dusts' SSA.

alleviated by increasing the amount of water in the formulation that is added to the rock dust before the foam is added so that the rock dust does not draw water out of the foam matrix. It is, however, unlikely that mine operators would choose to use a cut of dust with such a high respirable dust fraction.

3.2. BEM results

3.2.1. Respirable content

During the application of the FRD, the respirable dust content was being recorded. The dust levels were so low that the DPM and gravimetric samples were found to be below the limit of detection. This can sometimes result in negative dust totals, and therefore the gravimetric samples were excluded. The results shown in Table 3 depict the levels during the testing using the personal dust monitors (PDMs). The levels ranged from 0.1 to 0.5 mg/m³. These levels include the DPM and could be deemed negligible during the production and application of the FRD.

The PDM, located 100 ft from the FRD application area, shows higher start and stop concentrations compared to the totals for each test. This is

Table 3

Dust concentrations during the production and application of the FRD 100 ft from the test location in the BEM using PDMs.

	Dust Conc. Total, mg/m ³
Test #1	0.473
Test #2	0.485
Test #3	0.366
Test #4	0.100
Test #5	0.319
Test #6	0.398
Test #7	0.386

due to the PDM's continuous sampling. These levels accumulated and account for dust that was re-entrained into the mine atmosphere during the activities and movement of personnel and equipment, and not during the production and application of the foam.

3.2.2. Tray samples

During the application process, tray samples were collected and allowed to dry in the same mine environment as the material on the mine roof and ribs. The resulting stabilized weights were used to calculate the dry bulk density of the foam samples. The dry samples were dispersed in the same manner as the lab samples and compared to the reference rock dust. The results are shown in Table 4.

A discernible trend appears when comparing the dry bulk density of the foam as it moves from the hopper to the nozzle. The increase in density is likely due to the shearing effect of the auger pump, which would cause the matrix to degrade. The only case where there is no difference in the bulk density is the instance where an additional 15% water was added to the rock dust before adding the foam. Similar results would have been expected from the samples that received 15% less rock dust, but the cause of the improved foam stability in this case is not known.

When examining the IOD of the foam samples, no discernible trend is evident. Although the resulting average of all hopper or nozzle samples outperform the reference rock dust, the distribution of the data is too large to make any conclusions. This is clearly seen in the wide variation of the triplicate results. More consideration should be given to selecting the pilot-scale mixing and pumping equipment with an emphasis on the repeatability of foam characteristics.

4. Conclusions

The series of laboratory-produced foamed rock dust (FRD) yielded a wet-applied formulation that performed as well as the dry reference rock dust in the dispersion chamber. The foam's dispersion characteristics were satisfactory under both fast- and slow-drying conditions. The formulation yielded acceptable results when commercially available rock dusts were used in lieu of the reference rock dust. These successes were, however, restricted to rock dusts with a similar specific surface area (2500–3500 cm²/g) of the reference rock dust. The pilot-scale testing yielded mixed results with the largest concern being the repeatability of the foams' performances. Future work should focus on selecting more appropriate pumps and mixers to decrease the degradation of the foam during application. Additional testing should focus on producing consistent results from the foam before variations to the formulation are made. Additional research should be conducted with regards to the longevity of the foam. This testing series has shown that degradation occurs in an atmosphere with high humidity, but it is unknown how fast the degradation occurs or how long the foam can be left before a new application is necessary. Lastly, extensive full-scale testing needs to occur to determine the capability of foamed rock dust to suppress a propagating coal dust flame front. Current and future tests are aimed at fulfilling these research needs in conjunction with NIOSH's overarching research aims of minimize the likelihood of mine disasters, including mine explosions.

Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

Author contribution

Connor B. Brown: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Inoka E. Perera:

Table 4

Bulk density and relative average IOD of samples collected during the pilot-scale testing of FRD in the BEM.

Test	Sample location	Bulk Density, g/cm ³		Relative Average IOD	
		\bar{X}	σ	\bar{X}	σ
1	Hopper	0.31	0.01	0.82	0.18
	Nozzle	0.46	0.02	0.34	0.07
2	Hopper	0.28	0.03	0.52	0.09
	Nozzle	0.36	0.04	1.20	0.10
3	Hopper	0.23	0.00	1.88	0.10
	Nozzle	0.36	0.02	1.52	0.13
4	Hopper	0.32	0.03	0.86	0.24
	Nozzle	0.44	0.03	0.91	0.21
5	Hopper	0.26	0.01	1.29	0.18
	Nozzle	0.40	0.02	0.75	0.26
6	Hopper	0.28	0.01	1.38	0.48
	Nozzle	0.42	0.02	1.23	0.24
7	Hopper	0.24	0.00	1.31	0.21
	Nozzle	0.24	0.01	1.45	0.17

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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