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LARGE-SCALE EXPLOSION PROPAGATION TESTING OF TREATED AND NON-TREATED ROCK DUST WHEN OVERLAIN BY A THIN LAYER OF COAL DUST

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ABSTRACT

To prevent coal dust explosion propagations, rock dust needs to be lifted and suspended in the air with the coal dust during an explosion. The addition of anti-caking agents prevents caking of rock dust in the presence of water. Mining and rock dusting processes can frequently create alternating layers of rock dust and float coal dust on mine surfaces. For this test series, a thin layer of coal dust was distributed on top of a layer of either treated or non-treated rock dust in the Experimental Mine Barbara, Poland. The experimental results compare the effectiveness of treated and non-treated rock dusts to attenuate a propagating coal dust explosion initiated with either strong or weak methane explosions.

Keywords: Dust Dispersibility, Treated Rock Dust, Coal Mining, Explosion Prevention, Layered Dust

BACKGROUND

One of the goals of the National Institute for Occupational Safety and Health (NIOSH) is to conduct research to reduce the risk of mine disasters and provide workplace solutions to reduce the risks associated with accumulations of combustible and explosible materials, the most common form of which is the generation of coal dust during the mining process and its subsequent distribution downwind. Dispersible rock dust is a primary defense for preventing coal dust explosion propagation in underground coal mines, and its properties are defined in 30 CFR 75.2.

An earlier NIOSH investigation of rock dust revealed two significant concerns with the supply of rock dust for coal mines in the United States: (1) insufficient particles <200 mesh (75 µm) and (2) all rock dusts when wetted and dried formed cakes and were not easily dispersed with a light blast of air [1]. Past research conducted by the U.S. Bureau of Mines and others showed that bituminous coal dust remains relatively dry and dispersible in the presence of moisture. Rock dust must also be dispersible in concert with the coal dust to effectively inert a propagating coal dust explosion [2-5]. Non-treated rock dust, however, readily absorbs moisture, limiting its dispersibility, while a rock dust treated with long-chain fatty acids (such as stearic acid) can remain dry and dispersible. Stearin-treated rock dust has been used in British coal mines [6] and is commonly used in Polish coal mines. Traditionally, testing in large-scale explosion research facilities has been required to validate laboratory-scale explosibility results and to provide supporting data for decision-making regarding explosion safety in underground coal mines. After closure of NIOSH's Lake Lynn Experimental Mine, the Experimental Mine Barbara (EMB) at the Central Mining Institute (CMI) of Poland has been used as an alternate facility to validate laboratory-scale explosibility results through large-scale explosion tests. Fundamental research has been conducted at the EMB on a large-scale basis since 1925 to address the explosive danger of coal dust, firedamp, and flammable fire gases [2]. Such research includes examining main explosion parameters, rock dust suppression effects, initiator effects, accumulations of firedamp, barriers, etc. This renowned facility consists of 200-m and 400-m underground entries having cross-sectional areas of 7.5 m^2 (Figure 1). This paper presents the results from laboratory and large-scale explosion experiments conducted at CMI to help answer the question if treated rock dust is as effective as non-treated rock dust in attenuating or quenching a coal dust explosion when a thin layer of coal dust is present on top of the rock dust.

LARGE-SCALE EXPERIMENTAL CONDITIONS

The Experimental Mine Barbara consists of a network of experimental galleries equipped with a measuring system and utilities to initiate dust explosions. This facility is adapted for the research of fire development, gas and dust explosions, as well as testing of the underground infrastructure in large-scale conditions. The configuration of the galleries can be changed and arranged according to the given tests. An outline of the experimental gallery network is shown in Figure 1.

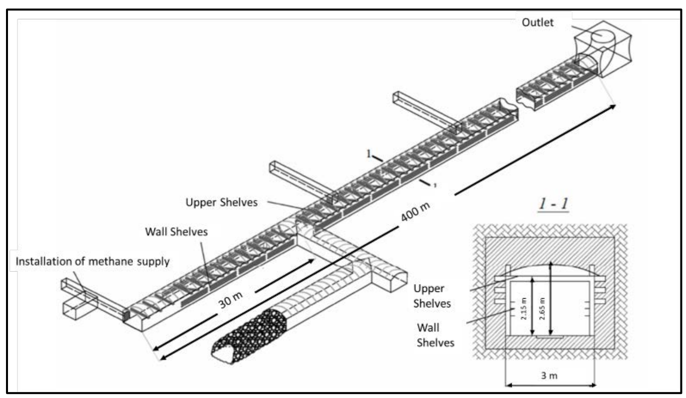

Figure 1. An outline and the basic parameters of the 400-m experimental gallery at the Experimental Mine Barbara, Poland.

Explosions with layered dusts were carried out in the 400-m experimental gallery. The entire gallery is reinforced with a concrete casing, and its walls and ceiling are equipped with steel elements (shelves and ribs). The gallery has an outlet to the surface for the free release of the explosion pressure wave and combustion products. A 30-m-long crosscut, located 30 m from the closed end of the gallery, was isolated with a concrete pillar during NIOSH testing. Methane gas in the required concentration is released into the test gallery from a mixing room located near the closed end. Figure 2 displays the entry of the experimental gallery.

Explosion parameters included flame and pressure readings and were gathered, measured, and transmitted to the surface via a high-speed data collection system installed in the 400-m gallery.

Figure 2. The 400-m experimental gallery.

Three dusts were used in this study including Barbara coal dust (all particles smaller than 75 µm) and two limestone dusts obtained from Labtar (Tarnów Opolski, Poland), which supplies treated and non-treated rock dusts to coal mines in Poland [7,8]. The dust size characteristics were determined using an optical particle size analyzer and are summarized in Table 1.

Table 1. Particle size distributions of coal dust and treated and non-treated Polish rock dust.

Mesh Size	Particle size (µm)	minus 200 mesh coal dust	Non-treated Polish rock dust ($3140\ cm^2/g$)	Treated Polish rock dust ($3291\ cm^2/g$)
		% < particle size	% < particle size	% < particle size
635	**20**	11.2	62.1	60.5
400	**38**	39.2	72.3	69.2
200	**75**	99.1	95.2	88.1
60	**250**	100.0	100.0	100.0
20	**850**	100.0	100.0	100.0

As described by Nagy [9,10], a gas and/or dust explosion in a mine passageway develops two types of destructive pressures—static and dynamic. The hot combustion products expand and exert a force equally in all directions. This is a static overpressure which is the pressure measured in a closed volume. In a mine, the hot gases expand and flow through the mine entries, pushing air ahead. This flow of gas at high speed generates a strong wind wave or dynamic pressure wave. Both the static and dynamic pressure can cause damage during a mine explosion. The static pressure rise can destroy stoppings inside entries perpendicular to the direction of gas flow. The dynamic pressure produces wind forces that can disperse coal dust and move other mine objects. The velocity and duration of the moving air in a mine explosion entrains dust from mine surfaces forming a combustible cloud which, when ignited, causes the most damage in an underground mine environment. The dynamic pressure (wind force) is proportional to the square of the air velocity as shown in the following equation: $P=0.5*\rho*v2$, where ρ is the air density and v is the air velocity.

In this current series of tests (Figure 3), strong gas explosions produce an initial average flame speed of 520 m/s in the first 20-30 m of the gallery, while weaker gas explosions produce an initial average flame speed of 60 m/s. These types of explosions were used to initiate the layered dust explosion propagations. Flame speeds of ~520 m/s are expected to scour and disperse most of the floor dust layer and produce nominal inert concentrations approaching ~80% incombustible content (IC). In contrast, the weaker gas explosion disperses less of the underlying rock dust resulting in nominal dispersed concentrations less than 80% IC, which can support flame propagation over longer distances. In this series of experiments, both weak and strong explosions were examined to assess mitigation effectiveness. From Newton's law, the product of a mass and its change in velocity must equal the impulse, which is the product of the pressure force and time over which it is applied. The explosion impulse is a measure of the magnitude and duration of a blast wave and used as one method to compare the relative effectiveness of a treated rock dust versus a non-treated rock dust under similar test conditions.

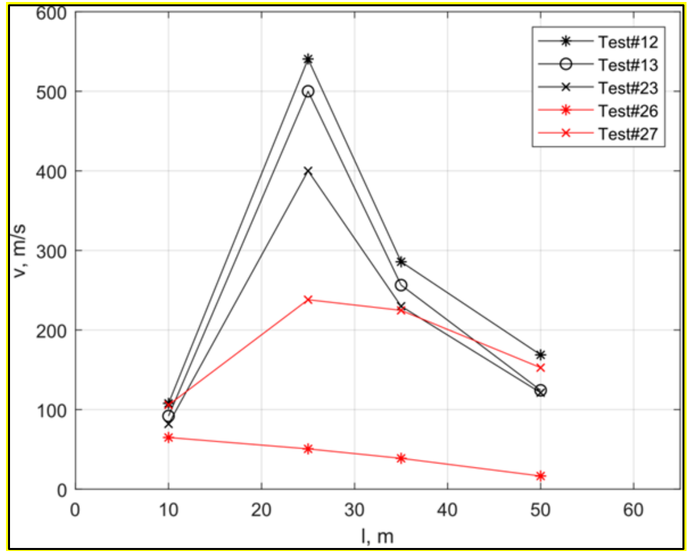

Figure 3. Flame velocity in the explosion of methane/air mixtures (Strong explosion Test # 12,13,23; weak explosion Test #26.

In order to generate strong explosion tests, 100 m^3 of a 9% methane-air mixture was ignited at the blind end of the gallery with a 10 kJ electrical ignitor (1 m from the blind end) (Figure 4). A weak explosion was initiated when the ignition source was positioned closer to the diaphragm (13.2 m away from the blind end) as shown in Figure 5.

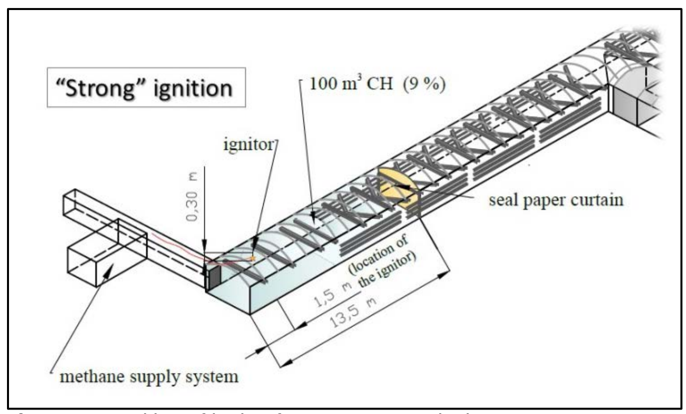

Figure 4. Position of ignitor for a "strong" explosion.

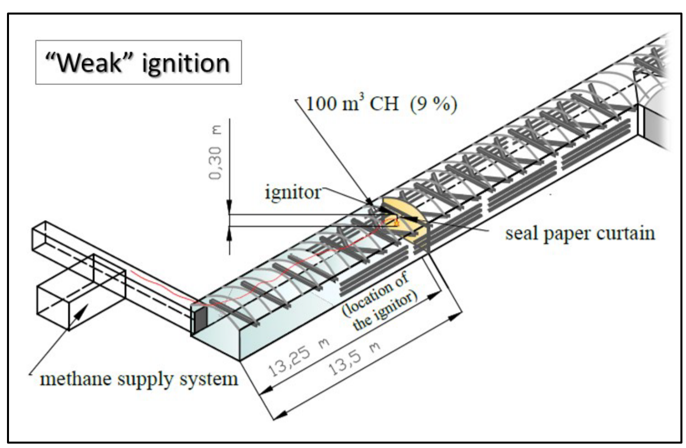

Figure 5. Position of ignitor for a "weak" explosion.

Experiments were conducted with treated rock dust (TRD) and non-treated rock dust (NTRD), both dry and wetted, and with a thin layer of coal dust placed on top of the rock dusts. For testing with dry rock dust, 300 kg of rock dust were uniformly deposited along the floor, on 100-m dust zone (Figure 6A and 6B). Then, 75 kg of Barbara coal dust was deposited on top of the rock dust layer. If all of this dust was dispersed, an average dispersed coal concentration of ~0.1 kg/m^3 and an average dispersed rock dust concentration of 0.4 kg/m^3 would be produced. Since the coal dust contained 8.7% ash and 4.1% moisture, an average IC of 83.6% would be produced if all the dust were suspended at the same time (Figure 7).

Figure 6A. Rock dust distributed on the floor; **6B**: Rock dust topped with coal dust before the explosion.

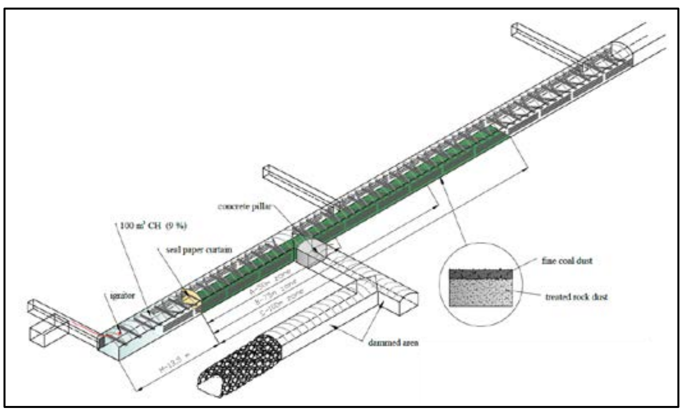

Figure 7. Schematic of the conditions for the dry tests.

The wet test condition was similar to that of the dry test condition except that 25 kg of water was uniformly distributed along the 100-m dust zone before applying the rock dust. After a wait time of 4 hours, 75 kg of coal dust was applied on top of the 300 kg of rock dust.

Dry tests and wet tests were ignited with both strong and weak explosion conditions. Test combinations are tabulated below in Table 2. Methane-only explosions were carried out to obtain the baseline flame characteristics. Dry TRD and NTRD tests were conducted in a previous study and, hence, are not repeated here [11].

Table 2. Test combinations (test number indicated for each condition).

		Dry Rock Dust Tests		Wet Rock Dust Tests	
Explosion Type	**Explosion Only – No Dust**	**TRD**	**NTRD**	**TRD**	**NTRD**
Strong	12, 13, 23, 27	14, 15, 16	17, 18, 19	20, 21, 22	25
Weak	26	NA	NA	30, 32, 34	28, 29, 33

RESULTS AND DISCUSSION

Methane-only Explosion

Comparisons of the results suggest good repeatability of the methane explosions (no dusts). As depicted in Figure 8, all strong explosion tests had very high flame speeds as evidenced by the slope of the plots (Tests 12, 13, 23, and 27). The flame speed (slope) was lower in Test 26. In this weak explosion test, the ignition source was placed closer to the diaphragm, producing a much slower displacement of the flame towards the closed end of the gallery. In this weak explosion, a larger heat loss was observed due to a longer burnout time, which resulted in lower explosion pressures.

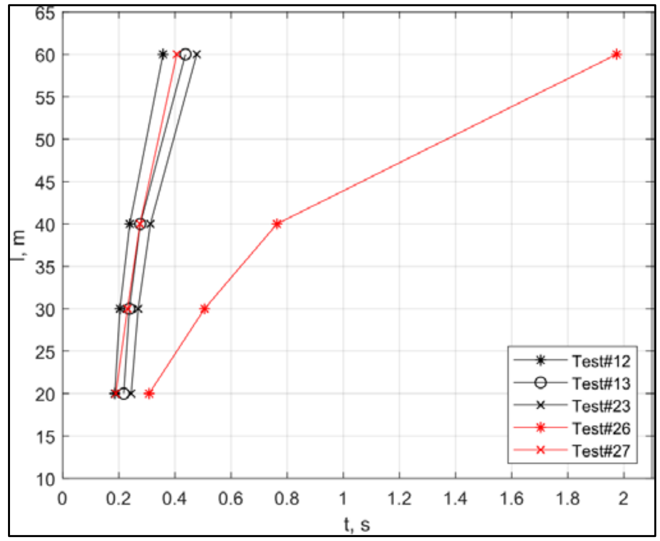

Figure 8. Flame front position as a function of time. Tests #12, 13, 23, 27 – ignition closer to the blind end; Test #26 – ignition closer to the paper diaphragm.

Strong Explosion Tests for Dry TRD and NTRD

The first test series was carried out in dry conditions, without any additional water sprayed on the gallery floor. This test series, identified as "dry tests," was carried out with NTRD (Tests #14, 15, 16) and TRD (Tests #17, 18, 19) using strong explosions. Pressure impulses calculated for each location of the pressure sensor along the gallery are plotted in Figure 9. For comparison, pressure impulses for a methane explosion alone are also included.

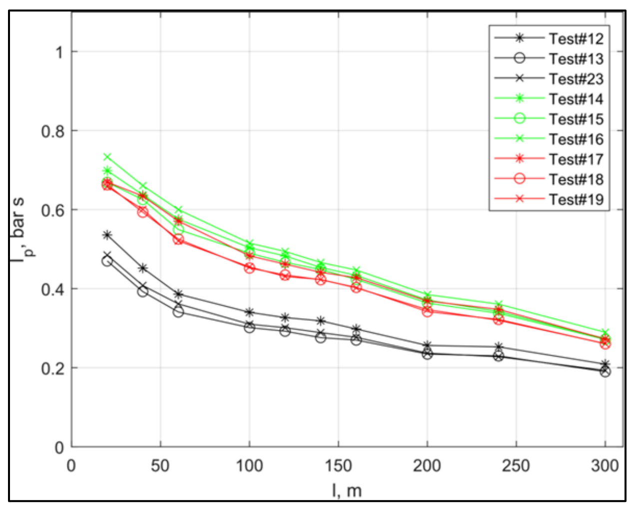

Figure 9. Pressure impulses along the gallery in "dry" tests.

A similar conclusion may be drawn from the plot in Figure 10 where average pressure impulses at each measuring point are directly compared. Although all data points lay below the line representing the perfect agreement, the distances from the line are very small. The slope of the straight line fitted to the experimental points with a zero intercept is b = 0.94 ± 0.05, very close to perfect agreement.

Another measure used frequently to describe the explosion intensity is the explosion flame behavior. Similar to the pressure impulse data, flame positions as functions of time using a strong explosion source showed little variation between TRD and NTRD tests (Figure 11). The flame velocities had similar values (~520 m/s) and gradually decreased as the pressure wave moved down the gallery. In the results presented here, only the moment of flame arrival at a particular location was utilized. The moment was defined as 10% of the sensor measurement range. Times of the flame arrival along the gallery, *t,* are plotted in Figure 11. As in the case of flame position data, the results suggest similar behaviors of TRD and NTRD. In all the tests, flame travel approached or exceeded 100 m, with the exception of Test 19 where the travel was only 80 m. All of the plots have the same shape in the first 60 m, including those for methane-only explosions. This suggests that the flame movement is controlled by the methane explosion. After 60 m, the flame velocity decreases as indicated by the change in slope.

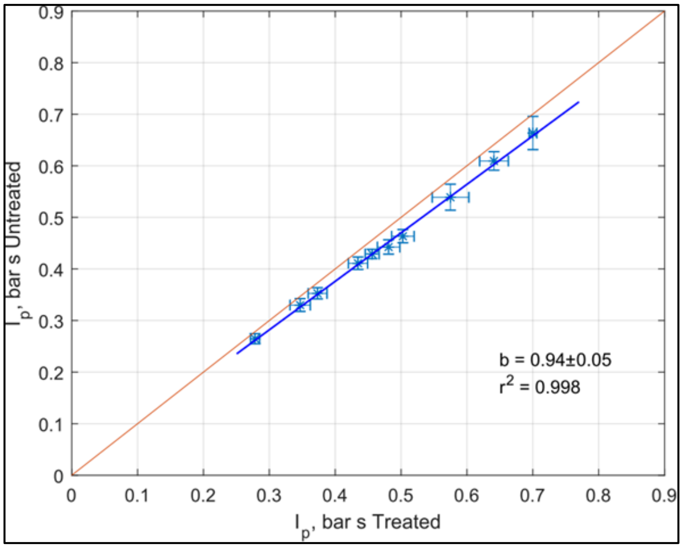

Figure 10. Direct comparison of average pressure impulses along the gallery, in "dry" tests; b is the slope of the linear fit with zero intercept.

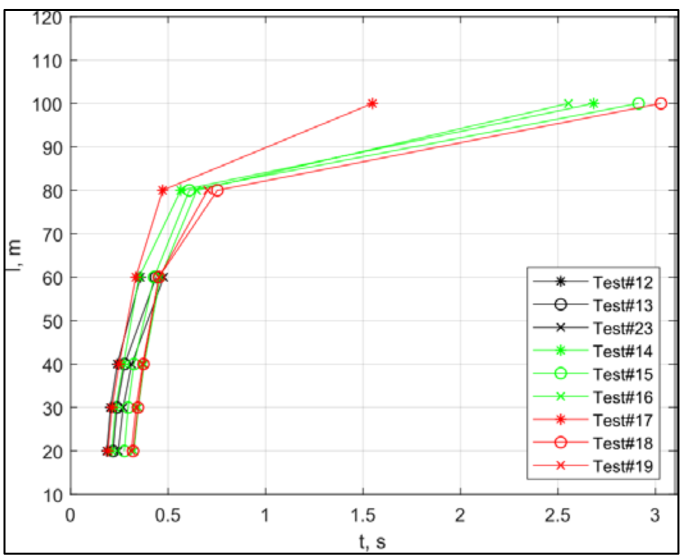

Figure 11. Distance-time plot of flame front in "dry" tests, with TRD (green) and NTRD (red), methane-only explosions (black).

Strong Explosion Tests for Wet TRD and NTRD

The next series of tests assessed the ability of TRD and NTRD to suppress a coal dust explosion in wet conditions using strong explosions. The dust layers were prepared the same way as in dry tests except 25 kg of water was sprayed on the gallery floor (166 ml/m^2), the rock dust was applied as before to the test zone, and after a 4-hour wait the coal dust was applied on top of the rock dust. Three tests were conducted with TRD (Tests #20, 21, 22) and, due to resource constraints, one test was conducted with NTRD (#25). In Figure 12, pressure impulses are presented for the four tests. The strength of the explosion can be examined by considering the pressure impulses at each measurement location. The pressure impulse is the integral from the moment when the explosion pressure exceeds 10% of its maximum value until the time that the pressure drops below 0 bar g. In order to account for the varying ignition strength influences, the pressure impulse at each measurement location is normalized by the ignition pressure impulse. This scaled impulse is equal to the pressure impulse divided by the ignition pressure impulse. The results show no difference between the tests with TRD and NTRD. Furthermore, the impulses are practically the same as those obtained in dry tests (Figure 12).

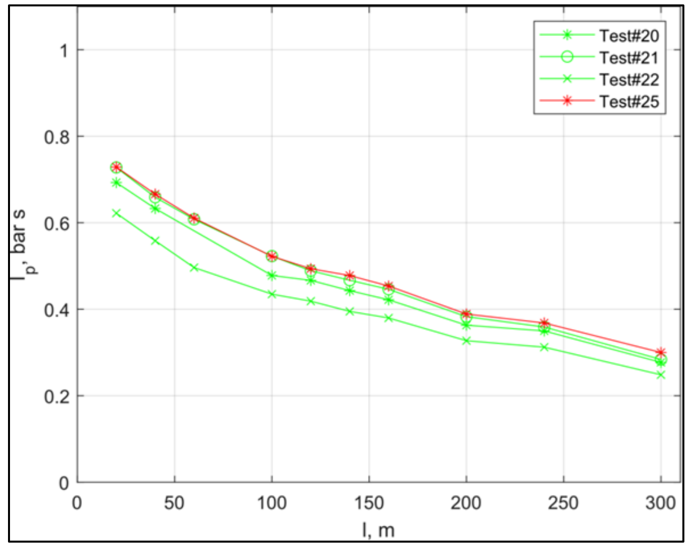

Figure 12. Pressure impulses along the gallery in "wet" tests, with TRD (green) and NTRD (red).

Figure 13 shows that little differences were observed in flame travel for TRD and NTRD tests under wet conditions using strong explosions. As stated previously, a strong explosion produces energy to raise, not only coal dust, but sufficient amounts of rock dust to inert the flame front. The data showed little variation in pressure for TRD and NTRD. A weak explosion, on the other hand, will raise coal dust into suspension, but be unable to raise sufficient rock dust into suspension to inert the coal dust. These strong explosions likely dispersed rock dust in sufficient quantities to produce similar flame travels. Test #21 may be an aberration likely caused by a slow burn of the methane cloud at the closed end of the gallery.

Historical coal mine dust explosion data suggest that weak explosions can often be the most dangerous. As stated previously, early experiments conducted by Nagy and Mitchell in the Bruceton Experimental Mine showed that layered coal on top of rock dust with weak explosions (2.5 psig static pressure) could produce very violent explosions while strong explosions often did not [7,8].

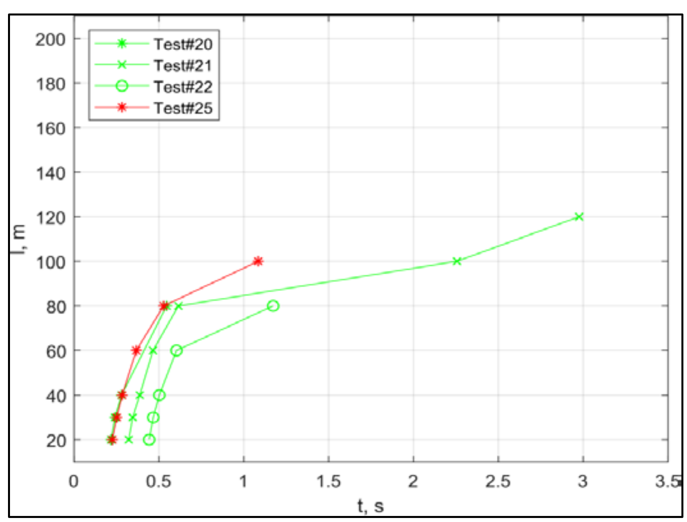

Figure 13. Distance-time plot of flame front in "wet" tests, with TRD (green) and NTRD (red).

Weak Explosion Tests for Wet TRD and NTRD

To further compare inerting properties of the rock dusts, an additional series of tests were conducted to check the performance of the dusts in the case of a weak methane explosion. Weak explosion tests were performed only in "wet conditions," primarily due to time and labor constraints. In addition, previous tests conducted at the CMI facility showed that dry TRD was more effective than NTRD in preventing explosion propagation under weak explosion conditions [11]. Except for using a weak explosion source, all other experimental parameters were kept constant.

Weak explosions are a greater hazard in that they allow the coal dust to be lifted without lifting adequate rock dust. Figure 14 displays the pressure impulses across the gallery for the "weak" methane explosions, where I_p is the calculated pressure impulse and l is the sensor location along the gallery. The differences between the NTRD and TRD results are apparent in that NTRD has a very high-pressure impulse due to non-dispersing rock dust; whereas, the TRD was more efficient, exhibiting lower pressure impulses. Again, the NTRD impulses are quite similar to those in the dry test, while the TRD impulses are much smaller. In the presence of moisture, NTRD may cake and become non- or less- dispersible, whereas TRD does not cake. Thus, improved attenuation of the fire propagation by the TRD can be easily observed.

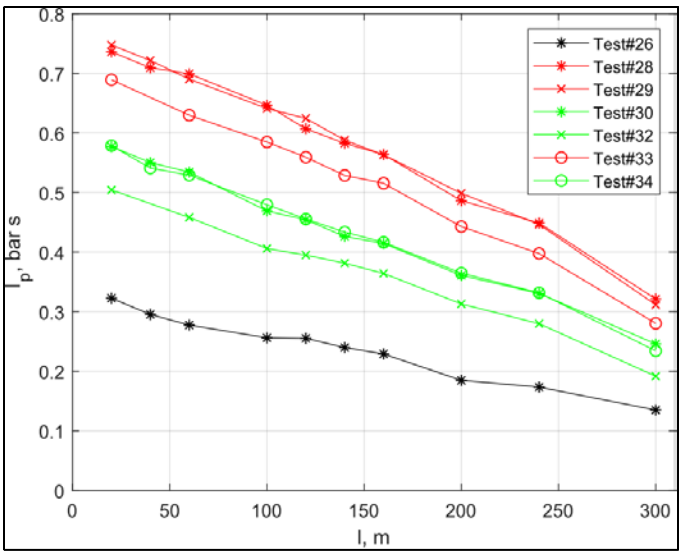

Figure 14. Pressure impulses along the gallery in "weak" tests, with TRD (green) and NTRD (red), "weak" methane explosion only also included (black).

Information provided in Figure 14 is represented in a different manner in Figure 15. Figure 15 shows side-by-side comparisons of the averages of the pressure impulses (I_p values) for TRD and NTRD tests at nine sampling locations. The position of the data with respect to the red line (slope of the liner fit b = 1.32 ± 0.11) indicates the improved performance of the TRD compared to that of the NTRD in suppressing a weakly ignited coal dust explosion.

Flame propagating behavior is analyzed and presented in Figure 16, showing the impulse pressure with respect to the time of the flame travel. As depicted in the graph, the NTRD flame ranges (Tests # 28, 29, 33) are longer (180–200 m), as the flame traveled further than the TRD (Tests # 30, 32, 34) flame ranges (120–140 m) due to the increased dispersibility of the treated rock dust, which would aid in suspending the rock dust in conjunction with the coal dust. Additionally, the flame velocities (the slope of the plots) for TRD tests start to decrease at 100–120 m, while those for the NTRD tests do not decrease.

This tendency is even more apparent in Figure 17 where the average flame arrival times are compared for TRD and NTRD tests. At the beginning when the initial methane explosion controls the propagation, the points (the average flame arrival times) lay on the line of perfect agreement. Beyond the range of influence of the methane explosion, the average times of flame arrival, t_f, in TRD tests are longer than those for NTRD tests, indicating that in the presence of TRD, the flames propagate more slowly than in the presence of NTRD.

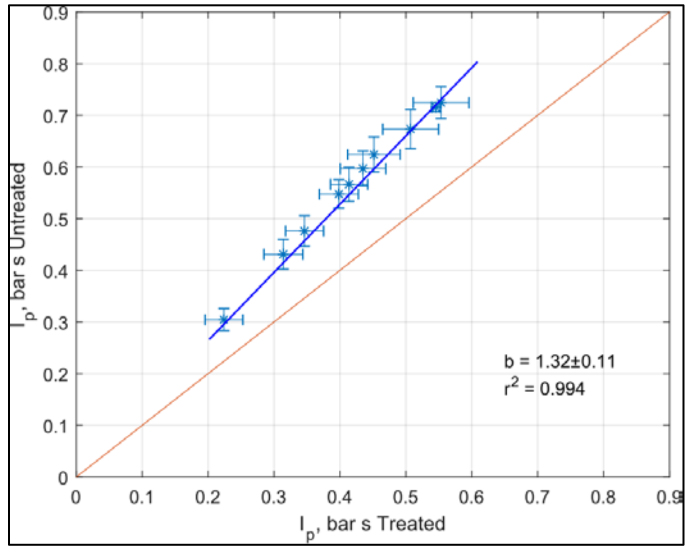

Figure 15. Direct comparison of average pressure impulses along the gallery in "weak" tests; "b" is the slope of the linear fit with zero intercept.

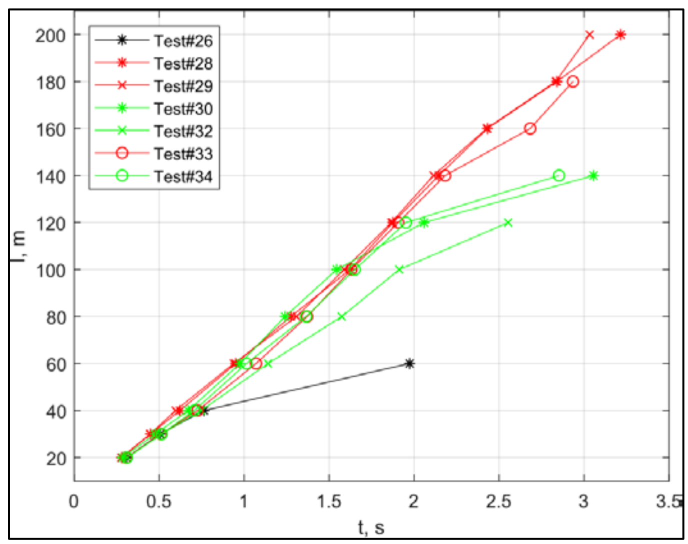

Figure 16. Distance-time plot of flame front in "weak" tests, with TRD (green) and NTRD (red), "weak" methane explosion also included (black).

SUMMARY

All the comparisons presented in this study show that the TRD capability to limit propagation of a coal dust explosion is at least comparable to that of NTRD. The improved performances of the NTRD with no moisture on the gallery floor (dry conditions) are within the uncertainty of the results obtained and are expected. The performance of the NTRD using a strong methane explosion in wet conditions was not significantly different than that of the TRD as the strong explosion entrains practically the whole depth of both dust layers. The coal dust explosion development in wet conditions was very similar to that in dry conditions.

On the other hand, less violent methane explosions exhibited significant differences in the inerting properties of TRD and NTRD in an environment of moisture. All the parameters measured and calculated indicate improved mitigation of the coal dust explosion by the TRD. While an NTRD layer is agglomerated by water on the gallery floor, the TRD layer does not absorb water and remains easily scoured and dispersed, resulting in more efficient suppression.

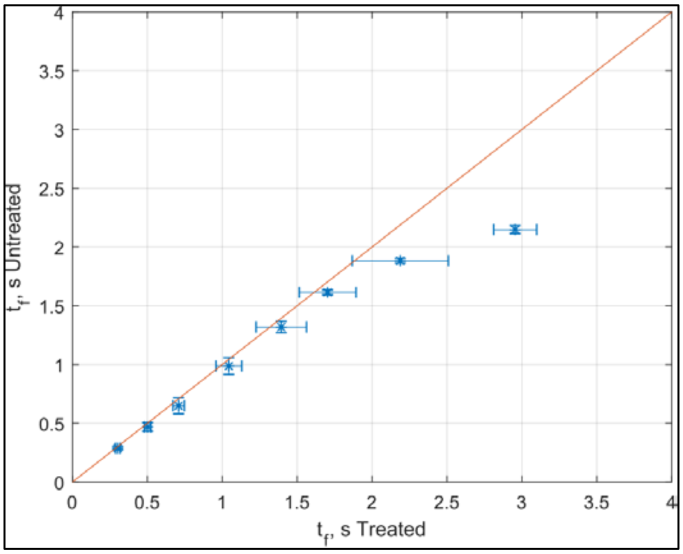

Figure 17. Time of flame arrival at the subsequent measurement panels in "weak" tests.

CONCLUSION

NIOSH conducts research to reduce the risk of mine disasters and provide workplace solutions to reduce the risks associated with accumulations of combustible and explosible materials. To this end, a series of tests was carried out in the 400-m underground experimental gallery of the Experimental Mine Barbara. The explosions developing from a thin layer of standard Barbara coal dust on top of a layer of limestone rock dust were assessed in terms of flame travel and pressure impulse. In the tests, two limestone rock dusts produced by LABTAR and commonly used in Polish coal mines were used: a non-treated rock dust (NTRD) and an anti-caking treated rock dust (TRD). The experimental results gathered using strong methane explosions indicated that the suppression properties of the treated rock dust (TRD) were as good as those of the non-treated rock dust (NTRD). Furthermore, in high moisture conditions and weaker methane explosions, the treated rock dust performed better than the non-treated rock dust.

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, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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