How does limestone rock dust prevent coal dust explosions in coal mines?

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Introduction

Methane gas is a colorless, odorless, flammable gas that is liberated naturally from coal seams. Methane is particularly dangerous if it reaches concentrations between approximately 5% and 15% in air where the mixture becomes explosive. Therefore, it is important for mine operators to monitor the level of methane in coal mines. Current federal safety standards require sufficient ventilation to keep methane levels below 1% (Code of Federal Regulations, Title 30, Part75-323).

Explosions in coal mines can be prevented or mitigated by eliminating ignition sources, by minimizing methane concentrations through the entries with adequate ventilation and by using barriers to suppress propagating explosions. Methane explosions can also cause subsequent large explosions of coal dust, which can have devastating consequences.

To prevent the coal dust from taking part in such an explosion, mine operators routinely cover the floor, rib and roof areas of mine entries with a generous application of inert rock dust. Pulverized limestone rock dust is commonly used. The percentage of rock dust is frequently checked by mine inspectors.

Federal law requires that all areas of a coal mine that can be safely traveled must be kept adequately rock dusted to within 12.2 m (40 ft) of all working faces. In the United States, there are regulations for underground coal mines that require mine operators to dust mine corridors liberally with an inert rock dust, such as pulverized limestone, and maintain a total incombustible content of at least 65% in the non-return (intake) and at least 80% in the return areas (Code of Federal Regulations, Title 30, Part 75-403). The regulations also require additional rock dust where methane is present in any ventilating current and involves adding an extra 1% of incombustible material per 0.1% methane for air in intakes and 0.4% incombustible per 0.1% methane in the returns.

Conventionally, it has been accepted that during an explosion, the rock dust disperses, mixes with the coal dust and prevents flame propagation by acting as a thermal inhibitor or heat sink; i.e., the rock dust reduces the flame temperature to the point where devolatilization of the coal particles can no longer occur; thus, the explosion is inhibited. The amount of rock dust required to inert such an explosion will depend on the particle size of the inerting agent as well as the particle size and composition of the coal dust. Pulverized limestone (with a low silica content) is commonly used as the rock dust material because it is inexpensive and widely available around the world. However, other types of minerals such as dolomite and marble dust may also be used.

This study investigates how limestone rock dust prevents the propagation of coal dust explosions by assessing its changes in chemical composition. A number of large scale coal dust explosions have been carried out in an experimental mine. A series of post-explosion floor samples were taken after each experiment and analyzed in the laboratory.

The post-explosion dust sample studies reported here were part of a larger 2008 LLEM research study on the explosibility of various sizes of coal, which was led by K. L. Cashdollar and E. S. Weiss.

Experimental

Pittsburgh coal was used in the explosion tests. The coal was mined, ground and pulverized at the National Institute for Occupational Health (NIOSH) Pittsburgh Research Laboratory (PRL), Pittsburgh, PA.
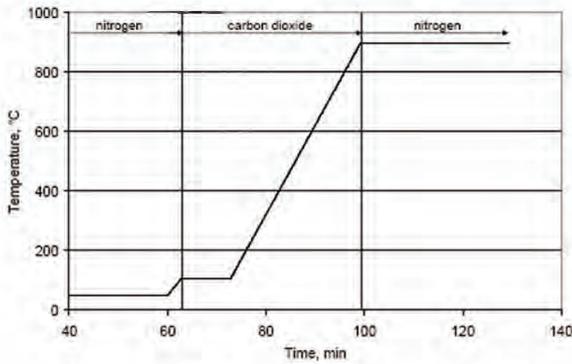
Coal dust explosion tests

The full-scale, single-entry explosion experiments were carried out at the PRL Lake Lynn Experimental Mine (LLEM). Situated about 80 km (50 miles) southeast of the PRL, the mine consists of an underground limestone mine and surface quarry area. The underground mine section of LLEM is a sophisticated underground testing facility for

Abstract

Coal dust explosions in underground coal mines are prevented by a generous application of rock dust (usually limestone). If an explosion should occur, the rock dust disperses, mixes with the coal dust and prevents flame propagation by acting as a thermal inhibitor or heat sink.

To investigate this process in more detail, a number of explosion experiments using various coal dust and limestone rock dust mixes have been carried out at the Lake Lynn Experimental Mine (LLEM). These were conducted in a single entry of about 488 m (1,600 ft) in length and initiated with a methane gas explosion. A consistent set of post-explosion floor dust samples were taken along the entry after each test. These dust samples have been analyzed in the laboratory using thermogravimetric analysis (TGA) and solubility to determine how the limestone rock dust behaved during the coal dust/rock dust explosions. The preliminary results are reported in this paper and indicate that the chemistry of limestone plays an important role in its capacity to inhibit coal dust explosions. The results also show that it may be possible to estimate the intensity of the explosion using these conventional methods of analysis.

FIGURE 1

TGA heating program.

conducting large-scale gas and coal dust explosions as well as other relevant mine research programs. The entries have been designed to physically match those of commercial coal mines, making them authentic and full-scale.

The mine consists of four parallel drifts (A, B, C and D), which are approximately 488 m (1,600 ft) long. In addition, C and D drifts are connected by another entry, E drift, which is only about 152 m (500 ft) long (Weiss et al. 2006; Cashdollar et. al. 2007; Sapko et. al. 2000). There are seven perpendicular crosscuts connecting A, B and C drifts. The entries are about 6-m (20-ft) wide and about 2-m (6.5-ft) high with cross-sectional areas approximately 12 to 13 m² (130 to 140 sq ft).

All of the explosion experiments described in this paper were done as "single-entry" explosions and were carried out in A drift. Prior to these tests, the crosscuts joining A and B drifts were sealed (PRL, 2008). A list of the explosion program parameters including details of the coal and rock dust mixtures have been summarized in Table 1.

In test LLL#511, the coal dust loading was 150 g/m³ (1.2 lbs/linear ft of entry). For all of the other shots, the coal dust loading was 200 g/m³ (1.6 lbs/linear ft of entry). For each experiment, approximately 50% of the coal and rock dust mixture was loaded onto disposable styrofoam shelves, suspended on chains hanging about halfway down from the roof. The remainder was distributed evenly on the mine floor by hand.

Before each explosion test, the area nearest to the face was isolated from the dusted area using a polythene diaphragm. This "ignition zone" was then filled to give a 10% methane/air mixture. Two gas samples were routinely tak-

en from a remote location and saved in vacutainers. These gas samples were analyzed using gas chromatography after the explosion to check the gas content. About 15 m³ (530 cu ft) of natural gas is required for an ignition zone of 12 m (40 ft). To initiate the explosion, the methane/air mixture in the ignition zone was ignited using single point ignition (i.e., two electric matches twisted together and located at a center point of the face at mid-height).

It should be noted that the total incombustible or inert contents (TIC) of the coal/rock dust mixtures are higher than the rock dust content due to the presence of moisture and mineral material in the coal.

After each explosion experiment in the LLEM, dust samples were collected from the mine floor at various distances from the face. The samples were sieved through -20 mesh (850 μm) to remove any debris and contaminants before being stored for later analysis.

Analysis of post-explosion dust samples

Solubility test. In a coal dust explosion, the limestone rock dust may undergo thermal decomposition into calcium oxide and carbon dioxide as shown by Equation 1. However, some of the calcium oxide may react with water vapor to give calcium hydroxide (Equation 2). Therefore, it is important to remove this ambiguity by converting any oxide into the hydroxide before doing the tests.

$$CaCO_3 + heat \rightarrow CaO + CO_2 \qquad (1)$$

$$CaO + H_2O \rightarrow Ca(OH)_2 \qquad (2)$$

To avoid any effect from the coal, the post-explosion dust samples were low temperature ashed (LTA) to remove the combustible material in each of the samples. This was carried out by placing about 2 to 3 g (-20 mesh or 850 μm) of sample into a porcelain crucible and ashing them overnight in an oven at 400° C (752° F) for 20 hours. This was followed by hydrating the residual inorganic material in order to convert any calcium oxide into calcium hydroxide (Equation 2). The hydration process was carried out in a modified laboratory desiccator cabinet containing trays of water in place of desiccant material, for about 24 hours. After the samples were hydrated, they were transferred into stoppered glass vials ready for analysis.

For the solubility experiments, about 0.5 g of a hydrated, ashed sample was mixed with 300 ml of distilled water in a 500-ml beaker to allow as much of the soluble component of the sample to dissolve. This was placed in a water

Table 1

Summary of large-scale explosion test parameters (a and b indicate two adjacent dusted zones of different amounts of rock dust).

Explosion test ID	Ignition zone, ft (m)	Dust zone ft (m)	Coal dust loading, g/m³	Rock dust (wt.%)	Total inert (wt.%)
LLL#511	40 (12)	210[a] (64)	150	[a] 65,	[a] 67.8,
		330[b] (100.5)	150	[b] 80	[b] 81.5
LLL#512	40 (12)	300 (91.4)	200	75	77.0
LLL#513	40 (12)	300 (91.4)	200	80	81.5
LLL#514	40 (12)	300 (91.4)	200	64	67.0
LLL#516	40 (12)	300 (91.4)	200	69	71.5
LLL#517	40 (12)	300 (91.4)	200	71.7	74.0
LLL#518	40 (12)	300 (91.4)	200	74.4	76.4
LLL#520	40 (12)	300 (91.4)	200	68.5	71.0

Table 2

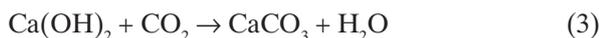**Solubility of low temperature ashed post-explosion dust samples.**

Distance, Ft (m)	#511	#512	#513	#514	#516	#517	#518	#520
				Solubility, wt.%				
108 (32.9)	15.25	7.03	3.34	10.82	5.18	6.93	4.11	5.03
208 (63.4)	15.63	4.19	1.68	6.02	2.79	4.54	1.86	8.69
306 (93.3)	5.59	1.28	0.00	0.93	0.63	0.61	0.69	5.77
404 (123.1)	5.02	0.04	0.00	0.00	0.00	0.64	0.60	7.12
502 (153.0)	3.08	0.00	0.00	0.00	0.13	0.44	0.90	3.69
600 (182.9)	0.42	0.02	N/A	0.00	0.00	0.03	0.00	2.34
699 (213.1)	0.16	0.00	N/A	0.00	N/A	N/A	N/A	1.47
807 (246.0)	0.25	N/A	N/A	0.00	N/A	N/A	N/A	1.59

and ice bath for two hours. Unlike most inorganic salts, the solubility of calcium hydroxide increases with a decrease in temperature (Handbook of Chemistry & Physics, 1976-1977). The mixture was then filtered using a pre-weighed 55-mm (2.16-in.) diameter piece of Whatman binder-free glass microfiber filter (Type GF/F) and a Büchner flask. The sample was left to dry in the laboratory for 48 hours then reweighed. The amount of the LTA "ashed" material dissolved was calculated by difference (divided by the amount tested and multiplied by 100 to give the solubility percentage). A "blank" mixture consisting of 70 wt.% analytical grade "pure" calcium carbonate powder with 30 wt.% PPC was used as a control.

TGA carbonation test

The post-explosion samples that were low temperature ashed and hydrated were also analyzed in a Perkin Elmer TGA7 thermogravimetric analyzer (TGA) with a Perkin Elmer TAC/DX thermal analysis controller interface. The thermobalance is sensitive to 0.1 μg and was calibrated for temperature using the Curie points of nickel and Perkalloy (355.3° C and 596° C or 671.5° F and 1,104° F, respectively).

The carbonation process involved heating about 30 mg of each sample in a platinum crucible in a stream of carbon dioxide (Equation 3) and monitoring the mass as a function of temperature. A simple two-step heating program was used (Fig. 1). The system was initially purged with nitrogen to remove any air in the instrument then heated at 20° C/min to 105° C (36° F/min to 221° F) to remove any moisture. After holding at temperature for 10 minutes, the furnace was ramped at 30° C/min to 900° C (54° F/min to 1,652° F) and held at temperature for 30 minutes. A constant gas flow rate of 55 ml/min was used for throughout each experiment. The gas was switched from nitrogen to carbon dioxide only for the second heating sequence.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (3)$$

Results and discussion

Results from the solubility tests on the ashed post-explosion floor samples obtained from the experimental mine (LLL#511 – LLL#520) are summarized in Table 2. Since the solubility of calcium carbonate is very low, (less than 1/100th compared to the hydroxide) (*Handbook of Chemisty*, 1976-1977) the quantity that did dissolve during the solubility test can be assumed to be calcium hydroxide.

All of the samples gave low solubility values and, as expected, the amount of calcium carbonate converted was highest near to the face; i.e., by the ignition point of the explosion test.

The solubility of the blank mixture (70 wt% calcium carbonate powder plus 30 wt% PPC) was found to be about 1.5 wt% or approximately 0.0018 g/100 ml of water. This is close to the published solubility data where calcium carbonate has a solubility of 0.00153 g/100 ml of water (*Handbook of Chemistr y*, 1976-1977). The slightly higher solubility value observed in the blank sample may be attributed to small losses through the filter during the filtration process.

The post-explosion calcium carbonate rock dust solubility results for explosion test LLL#511 are illustrated in Fig. 2. The data shows a significant amount of the rock dust is soluble in some of the samples. The common trend in all the results shows the amount of soluble material is greatest near the face and falls rapidly along the entry (Table 2).

Since the carbonate form is only slightly soluble, the majority of the dissolved fraction must be calcium hydroxide, although it should be noted that this may have been formed from the oxide during the hydration step in the experimental procedure. Nevertheless, this clearly indicates that the calcium carbonate does not only act as a physical heat sink in the prevention of a coal dust explosion, but also absorbs some of the energy in a calcination process to convert it into calcium oxide, which may be hydrated by any atmospheric moisture into calcium hydroxide. The degree of solubility indicates the extent of

FIGURE 2

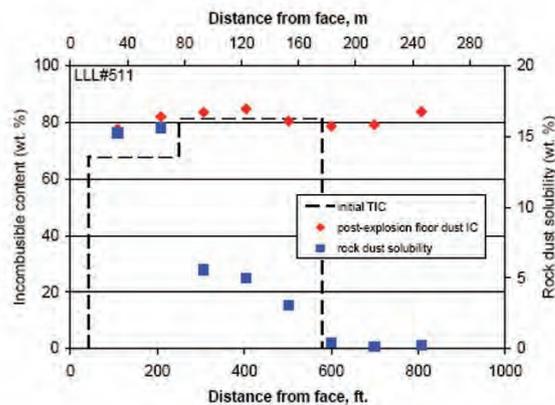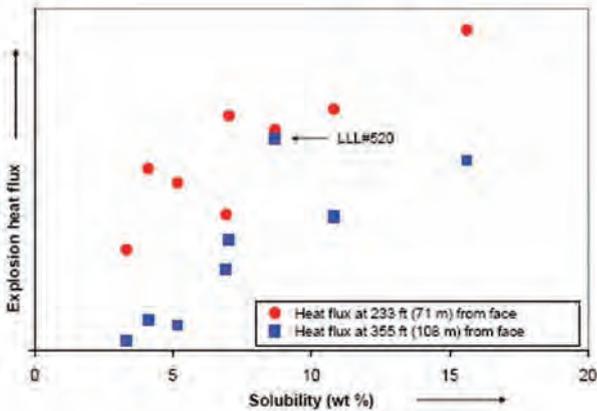**Solubility of post-explosion dust samples LLL#511.**

FIGURE 3

Comparison between heat flux data and rock dust solubility for samples taken at 233 ft (71 m) and 355 ft (108 m).

this calcination process. It appears this value is quite low and only reaches about 15% to 16% (Table 2) for this series of explosion tests. It should be noted that out of all of the samples tested, the ones that exhibited the largest amount of soluble material (more than 10%) were from explosion tests containing the least amount of rock dust, namely, LLL#511 and LLL#514, which had 65 and 64% limestone rock dust, respectively.

The decomposition of the calcium carbonate rock dust into the more water soluble oxide and hydroxide is likely to be dependent on the intensity of the explosion test. Therefore, the solubility data has been plotted against heat flux data obtained during the explosion experiments. Two heat flux gauges were placed at 71 m (233 ft) and 108 m (355 ft) in the entry and were positioned about 0.05 m (2 in.) from the rib. The results are given in Fig. 3. This shows a fairly good correlation between the largest amount of rock dust dissolved (per explosion) against the peak heat flux values measured from the two heat flux gauges. It should be noted that there is one distinct outlier in the 108 m (355 ft) curve, which has been identified as the data from LLL#520.

The TGA apparatus typically produces thermograms. The data for LLL#511 are shown in Fig. 4. This shows the carbonation reaction to occur between approximately 450 to 800° C (842° to 1,472° F) or 85 to 97 minutes in the

FIGURE 4

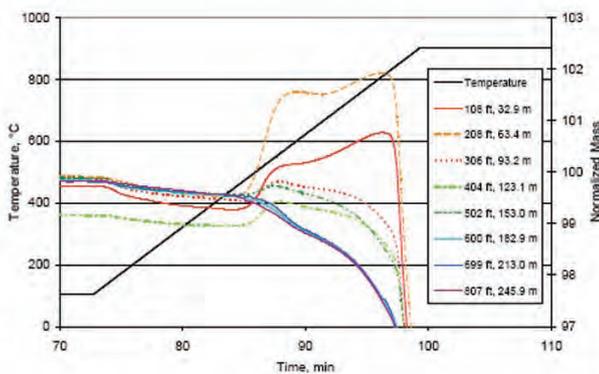TGA thermograms for LLL#511 post-explosion dust samples.

diagram. A further increase in temperature results in the decomposition of the carbonate material via the calcination process.

It is slightly more complicated to calculate the amount of calcium hydroxide present from this set of data than it is to determine those values from simple solubility experiments since molar fractions need to be taken into consideration. If the sample was pure calcium hydroxide and 100% of it was converted into calcium carbonate, the resulting weight gain would only be about 35.1 wt.%.

The results from the heterogeneous carbonation experiments in the TGA are summarized in Table 3. Due to the fact that the TGA tests require a long time to complete, a few repeat experiments were carried out on the first set of samples upon completion of all the tests shown in Table 3 to check that the quality of the samples had not changed with time. The results of the second experiments showed the TGA to give good reproducible data.

Table 3 also shows the calculated amount of calcium hydroxide present in the ashed, hydrated post-explosion dust samples. Many of the samples, especially those furthest from the explosion, did not appear to contain any calcium hydroxide and this is consistent with the solubility data. Conversely, the samples that did react in the TGA were all collected near the face. Interestingly, the correlation between the maximum solubility and the TGA is not 1:1 (Fig. 5) with the relative solubility values roughly double the TGA weight gains. The low TGA values may be due to the competing decomposition reaction, which becomes increasingly significant at high temperatures (Lee et. al. 1993). It has been reported that the heterogeneous carbonation reaction is relatively slow (Sun et. al. 2008; Lee 2004; Murty et. al. 1994; Wang et. al. 2008) but can be accelerated with water vapor which acts as a catalyst (Wang et. al. 2008). These factors may also account for the low conversion values observed. The data given in Fig. 5 suggest that only about 50 percent of the calcium hydroxide has reacted in the TGA. Nevertheless, there appears to be a good correlation to show that the soluble component of the post-explosion limestone rock dust is either calcium oxide or calcium hydroxide and, critically, not the original limestone.

Conclusions

This research has shown that limestone rock dust acts

FIGURE 5

Comparison between post-explosion rock dust solubility and TGA carbonation (only the maximum values of each explosion test is shown).
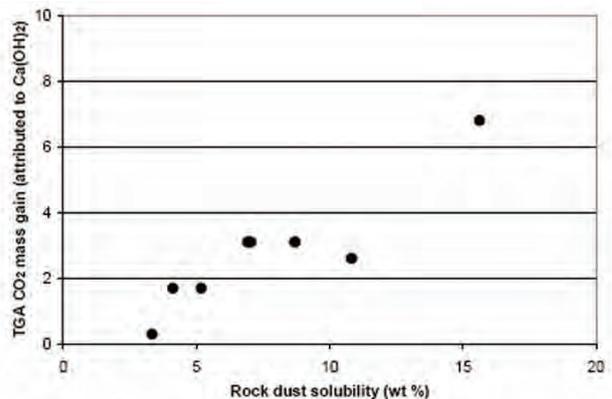
Table 3

Summary of TGA carbonation data on the post-explosion dust samples collected at various distances.

Explosion test ID	Distance, ft (m)	Mass gain (%)	Calculated mass of Ca(OH)$_2$ (%)	Explosion test ID	Distestance ft (m)	Mass gain %	Calculated mass of Ca(OH)$_2$ (%)
LLL#511	108 (32.9)	1.5	4.3	LLL#516	108 (32.9)	0.6	1.7
	208 (63.4)	2.4	6.8		208 (63.4)	0	0
	306 (93.3)	0.4	1.1		306 (93.3)	0	0
	404 (123.1)	0.5	1.4		404 (123.1)	0	0
	502 (153.0)	0.2	0.6		502 (153.0)	0	0
	600 (182.9)	0	0		600 (182.9)	0	0
	699 (213.1)	0	0	LLL#517	108 (32.9)	1.1	3.1
	807 (246.0)	0	0		208 (63.4)	0.5	1.4
LLL#512	108 (32.9)	1.1	3.1		306 (93.3)	0	0
	208 (63.4)	0.1	0.3		404 (123.1)	0	0
	306 (93.3)	0	0		502 (153.0)	0	0
	404 (123.1)	0	0		600 (182.9)	0	0
	502 (153.0)	0	0	LLL#518	108 (32.9)	0.6	1.7
	600 (182.9)	0	0		208 (63.4)	0.1	0.3
	699 (213.1)	0	0		306 (93.3)	0	0
LLL#513	108 (32.9)	0.1	0.3		404 (123.1)	0	0
	208 (63.4)	0.1	0.3		502 (153.0)	0	0
	306 (93.3)	0	0		600 (182.9)	0	0
	404 (123.1)	0	0	LLL#520	108 (32.9)	0.7	2.0
	502 (153.0)	0	0		208 (63.4)	1.1	3.1
LLL#514	108 (32.9)	0.9	2.6		306 (93.3)	0.7	2.0
	208 (63.4)	0	0		404 (123.1)	0.8	2.3
	306 (93.3)	0	0		502 (153.0)	0	0
	404 (123.1)	0	0		600 (182.9)	0	0
	502 (153.0)	0	0		699 (213.1)	0	0
	600 (182.9)	0	0		807 (246.0)	0	0
	699 (213.1)	0	0				
	807 (246.0)	0	0				

more than a simple heat sink when stopping a coal dust explosion. A small fraction of it decomposes during an explosion. From the limited number of tests carried out so far, there appears to be a good correlation between the amount of calcium carbonate, which decomposes, and the magnitude of the explosion.

TGA has been shown to be a useful instrument. The TGA carbonation data supports the solubility data well and gives a similar trend. However, it is a time-consuming test and requires more skill in the interpretation of the data.

Acknowledgments

Disclaimer

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