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Participation of large particles in coal dust explosions

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ABSTRACT

Float coal dust is produced during the coal mining process in underground mines. If it is entrained, the float coal dust presents a dangerous explosion hazard to miners when it reaches the minimum explosible concentration and is ignited. However, coal dust can be inerted if properly mixed with generous amounts of pulverized rock dust such as limestone to result in a homogeneous dust mixture with a total incombustible content (TIC) ≥80%. In the United States, it is mandatory for the rock dust to be 100% passing through a 20 mesh (841 μm) sieve and 70% or more passing through a 200 mesh (75 μm) sieve. Laboratory experiments have been conducted using the National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) 20-L and the Fike Corporation 1-m^3 explosion chambers. Coal and rock dust samples were prepared by sieving and were used to investigate the effect of particle size on explosibility and inerting effectiveness.

The results from both chambers show that large coal particles >60 mesh (>250 μm) do not explode/ignite at dust concentrations up to 600 g/m^3, and limestone rock dust particles >200 mesh (>75 μm) require a significantly higher TIC of 90% to inert Pittsburgh pulverized coal (PPC). This data illustrates the significance of particle size for preventing coal dust explosions and the importance of measuring particle size as well as TIC (which includes moisture as well as incombustibles) to determine the true explosibility of a dust sample.

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1. Introduction

Float coal dust presents a major explosion hazard in underground coal mines. Modern mining methods have been shown to produce finer coal dust than in the 1920s (Sapko, Cashdollar, & Green, 2007). In order to mitigate this risk, pulverized rock dust is required to be applied generously to the intake, return, and belt airways/entries. Federal safety regulations (30 CFR 75.403) require rock dust to be applied so that the incombustible content is not less than 80 percent.

Federal safety regulation (30 CFR 75.2) also defines and requires rock dust to be pulverized such that 100 percent passes through a 20 mesh (841 μm) screen and 70 percent or more passes through a 200 mesh (75 μm) screen. Federal safety regulation (30 CFR 75.400-1) also defines coal dust as 100 percent passes through a 20 mesh (841 μm) screen. Therefore, in order to determine that a mine is meeting the 80% incombustible content requirement, MSHA inspectors collect numerous dust samples from the mine roof, rib, and floor on a quarterly basis. These samples, consisting of mixtures of rock dust, coal dust, and other dusts, are screened through a 10 mesh (2 mm or 2000 μm) sieve upon collection within the mine and then through a 20 mesh (841 μm) sieve upon delivery to the MSHA National Air and Dust Laboratory, Mt. Hope, WV. The samples are subsequently analyzed for total incombustible content using a low temperature ashing procedure (Cashdollar, Weiss, Montgomery, & Going, 2007; Sapko et al. 2007).

The current safety regulations were based upon data generated by the U.S. Bureau of Mines from 1913 to 1918 which suggested that the largest sized particle that participated in explosions was 841 μm from Bruceton Experimental Mine (BEM) explosion tests of segregated dusts initiated with 2.5 lb of black powder (Rice, Jones, Egy, & Greenwald, 1922). At that time, Rice stated that the following may prevent 20-mesh dust from propagating:

1. The 20-mesh dust would not mix readily and thoroughly with air due to the weight of the coarser particles,
2. The surface area of the coarse particles is less than that of the same weight of fine particles, resulting in less surface for instantaneous oxidation, and
3. The number of the coarse particles is less than that of the same weight of fine particles making it probable that the distance between the particles would be greater and thus prevent propagation of the flame from particle to particle.

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One hundred years later, there are other methods that can test and determine whether particles of this size participate in an explosion. One of these methods is the use of the 20-L chamber to test explosibilities of dust mixtures. Previous data from the OMSHR 20-L chamber has shown that it requires 76% of limestone rock dust to inert PPC which contains 80% minus 200-mesh particles (Cashdollar and Hertzberg 1989). Dastidar, Amyotte, Going, and Chatrathi (2001) also tested PPC in another 20-L chamber and reported a slightly lower value of 74% rock dust to inert the NIOSH Pittsburgh pulverized coal (PPC) dust at a dispersed coal concentration of 500 g/m^3. In an earlier study, Dastidar, Amyotte, and Pegg (1997) had published an inerting value of 77% limestone rock dust associated with a 300-g/m^3 PPC concentration. The differences were described by the authors as "due to the nature of flame propagation, which is probabilistic at limit conditions." It is important to note that the 20-L chamber results indicate trends and cannot be directly scaled to full-scale explosion experiment results such as at the Lake Lynn Experimental Mine (LLEM) (Sapko, Weiss, Cashdollar, & Zlochower, 2000). The differences between the laboratory chamber results and the LLEM full-scale results include but are not limited to differences between the geometry of the mine and the laboratory chambers, variations in the ignition source, and how the dust is introduced and dispersed (the chamber criteria is based on the measured overpressure rise whereas the LLEM is based on self-sustained flame propagation beyond the influence of the ignition source).

The main focus of this paper is to re-examine the role of large particles in a coal dust/rock dust explosion using the 20-L chamber. This will be investigated from both the explosive dust and inerting material aspects, i.e., the effect of coal and rock dust particle size. Unlike other recent studies which examine the fineness of dusts, this paper focuses on the fundamental properties of large particles by investigating the effect of particle size using well-segregated size fractions. Predictions on full-scale inerting explosions from laboratory-scale experiments will not be made.

2. Experimental

2.1. Dust samples

The Pittsburgh coal dusts used for this study were produced at NIOSH OMSHR. The coal was mined from the Safety Research Coal Mine (SRCM), ground, and pulverized on-site to produce the pulverized Pittsburgh coal. Various amounts of coarse ground coal were added to PPC (80% < 75 μm) to generate the coarse (20% < 75 μm) and medium (40% < 75 μm) ground fractions. This is similar to the coal used in the LLEM study (NIOSH, 2010, p. 48). Separately, some of the coarse coal was manually sieved to produce a 60-20 mesh (250–841 μm) size fraction. The particle size distributions are summarized in Table 1.

Table 1
Particle size distribution of the coal and limestone rock dust samples, dry sieve analyses.

Particle size (μm)	Coarse Pittsburgh coal, wt%	Medium Pittsburgh coal, wt%	Pulverized Pittsburgh coal, wt%	Limestone rock dust, wt%
212–850	57.2	28.8	0.2	1.0
150–212	9.0	7.7	0.8	3.2
106–150	8.2	10.7	5.9	12.2
75–106	5.7	13.6	13.5	12.4
53–75	5.9	14.2	22.8	12.6
38–53	3.7	7.5	17.2	9.2
<38	10.3	17.5	39.6	49.4

A small amount of carefully sieved coal was also prepared for use in the 20-L chamber. These size fractions were 106–150 μm, 150–212 μm, 212–250 μm, and 250–841 μm.

Commercial pulverized limestone rock dust was used as the explosion inhibitor. In addition to the whole (unsieved) pulverized dust, a number of size fractions were created. Particle sizes <38 μm, 38–75 μm, and >75 μm were produced by manually sieving the original as-received rock dust. A coarse rock dust sample (60-20 mesh or 250–841 μm) was prepared by manually crushing and sieving 50-mm lumps of quarry limestone sourced from the same manufacturer as the pulverized rock dust to minimize any chemical variability.

All classified dusts (coal dust and rock dust) were verified using a sonic sieve (dry) method and laser diffraction.

2.2. Explosion test chambers

The NIOSH OMSHR 20-L (Fig. 1) and Fike Corporation 1-m^3 (Fig. 2) explosion chambers were used in this study. Detailed descriptions of these chambers have been previously published (Cashdollar, 1996, Cashdollar, 2000; Cashdollar et al. 2007; Dastidar et al. 2001; Going, Chatrathi, & Cashdollar, 2000).

For the 20-L chamber experiments in this paper, 2500 J (MEC of coal dust) and 5000 J (explosibilities of mixed dusts) electrically activated pyrotechnic ignitors were used as the ignition source. A pressure rise of 1 bar or greater was used as the criterion for determining an explosion or a pressure ratio of 2. The pressure ratio would account for the variations in atmospheric pressure. This is in accordance with the ASTM test for measuring the explosibility of dust clouds (ASTM, 2010). A series of three shots were performed to confirm a non-explosion at each coal dust concentration.

The Fike Corporation 1-m^3 explosion chamber has an external dust reservoir (Fig. 3). During the experiment, a weighed sample of dust of pre-determined composition (for mixtures) was injected into the chamber and dispersed via a small rebound nozzle. The chemical ignitor positioned at the center of the chamber and

Fig. 1. The NIOSH 20-L chamber with the lid open.

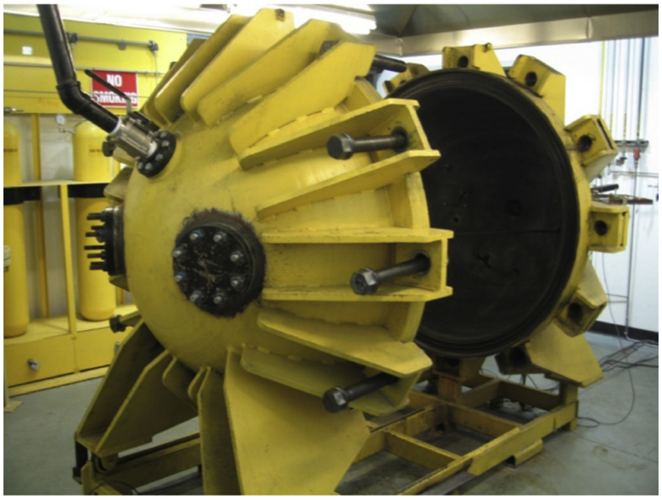

Fig. 2. The 1-m^{3}explosion chamber.

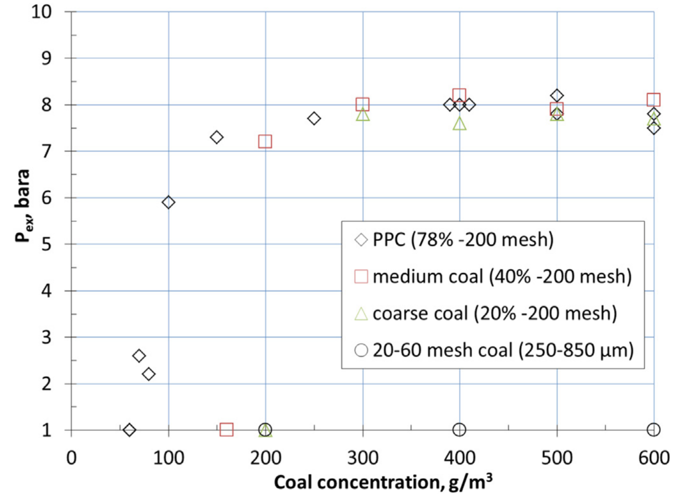

Fig. 4. The effect of coal particle size on explosion pressure, P_{max} in the 1-m^3 chamber.

pointed down toward the bottom of the 1-m^3 chamber was ignited after 0.6 s. Explosion data was captured by a commercial high-speed PC-based data acquisition system operating at 1 kHz. Chemical ignitors used are 5 kJ (for PPC and medium coal dusts), 10 kJ (for coarse coal dusts), and 20 kJ (or 2·10-kJ ignitors for 60-20 mesh coal dust size fractions).

3. Results and discussion

The effect of particle size on the maximum explosion pressure of a series, P_{max}, was investigated for each of the coal samples without any rock dust addition. The dust was tested over a wide range of concentrations from 60 g/m^3 up to 600 g/m^3. While it is important to try to ignite the coal, it is also important not to 'overdrive' the reaction (Going et al. 2000). Therefore, 5 kJ ignitors were used for PPC and the medium coal dust, and 10 kJ ignitors were used with the coarse coal dust. The results from the Fike1-m^3 chamber are shown in Fig. 4 with the single explosion pressures (P_{ex}). The data shows a trend where the minimum explosible concentration (MEC) increases with increase in particle size. Taking the midpoint between the 'no-go' and first 'go' explosion, the MEC for PPC, medium, and coarse coals are 65 g/m^3, 180 g/m^3, and 250 g/m^3 respectively. There is a relatively wide margin of uncertainty for the coarse coal, but nevertheless it illustrates the trend very well. The large 250–841 µm (60-20 mesh) coal was tested at 200 g/m^3, 400 g/m^3, and 600 g/m^3 with 20 kJ ignitors but did not explode at any of these concentrations. This suggests that only the relatively small particles are indeed explosible. If this is the case, then the medium- and large-size particles (>60 mesh or 250 µm) should not be included for MEC testing. This leads to the proposed postulation that the 'real' MEC value is in fact lower than observed experimentally if only the fine particles are considered.

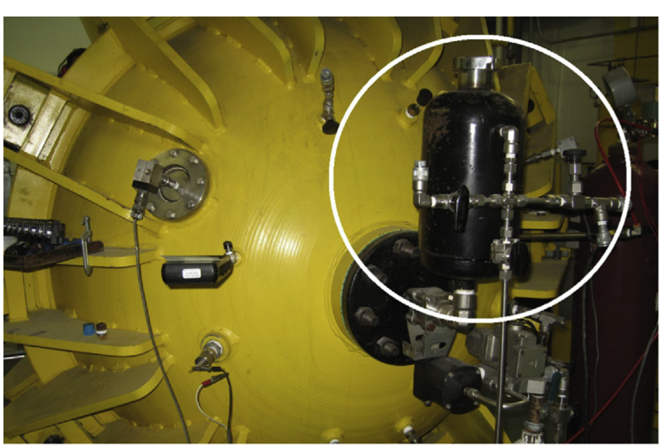

Fig. 3. The 1-m^3 explosion chamber dust reservoir (circled).

To demonstrate, if only particles <150 µm are included, then the revised MEC values can be calculated by simply multiplying the cumulative percentage fraction of small particles (<150 µm) by the measured MEC. In this case, the revised MEC values for PPC, medium, and coarse coals would then be 64 g/m^3, 102 g/m^3, and 68 g/m^3. This is much closer in range than the initially observed data described above. In other words, the relatively high MEC value for the coarse coal is masked by the large number of relatively large particles, which, if removed, results in an MEC value similar to the pulverized coal which only contains about 1% > 150 µm. Interestingly, Chawla, Amyotte, and Pegg (1996) reported MEC values of 80 g/m^3 for PPC in both the 20-L and 1-m^3 chambers using 2.5 kJ and 10 kJ ignitors respectively. This number is almost identical to the mean MEC value of 78 g/m^3 derived from this current study.

The MEC results from the NIOSH 20-L chamber are shown in Fig. 5. The ignition sources in these MEC experiments were 2.5-kJ chemical ignitors made by the same company as those used in the 1-m^3 chamber. It was possible to test a larger selection of particle sizes with narrower size bands in the 20-L chamber, because the amount of dust required for these experiments was much lower than for those tests carried out in the 1-m^3 chamber. The trends from the NIOSH chamber follow a similar pattern observed in the much larger 1-m^3 chamber. From Fig. 5, the MEC for 106–150 µm coal is about 110 g/m^3. By definition, the coal is not explosible below the MEC value. As with the 1-m^3 chamber findings, this value increases with increase in particle size such that the MEC for 150–212 µm is around 160 g/m^3. For this size fraction, the MEC is quite broad, as even at 200 g/m^3 there are both explosions and non-explosions. This was also observed at 450 g/m^3 where there was an unexpected non-explosion which may be due to ignitor variability or dust dispersion unevenness. This emphasizes the need to perform more than one experiment at any concentration to get a clear indication of the overall trend. In general, the larger particles gave few explosions using the pressure ratio of 2 as the criterion for a deflagration. For example, the 212–250 µm did not explode. The

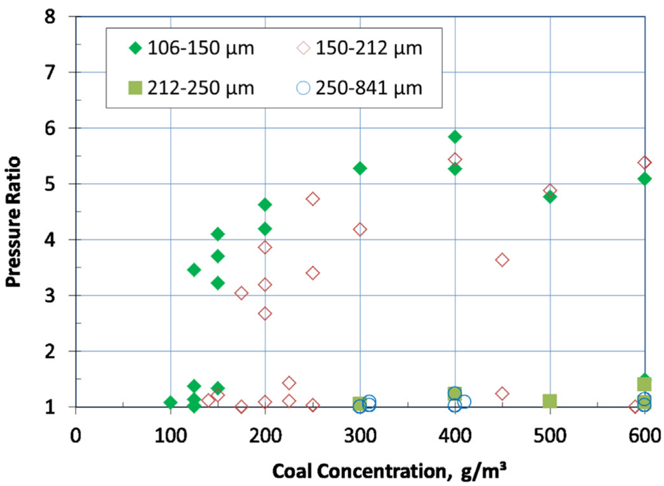

Fig. 5. The effect of coal particle size on explosion pressure in the NIOSH 20-L chamber.

coal sample sieved to 250–841 μm (60-20 mesh) also did not explode with repeated experiments at 300 g/m^3, 400 g/m^3, and 600 g/m^3. This illustrates the progressive difficulty of exploding larger and larger coal particles, especially those >212 μm. There is strong laboratory evidence that these large particles (212 μm and above) are very difficult to ignite and generally do not deflagrate in laboratory-scale explosion vessels up to 1 m^3.

Results from the explosion inerting experiments using limestone as the inhibitor in the Fike 1-m^3 chamber are shown in Fig. 6. The criterion of two non-explosions was used as the extinction limit for all coal dusts. The data shows that 63% regular limestone rock dust did inert PPC at all coal dust concentrations tested. This is similar to previous reports (Dastidar, Amyotte, Going, & Chatrathi, 1999) of a 60% rock dust requirement to inert. Previous researchers reported a lower inerting value of 34% from the 1-m^3 chamber using dolomitic rock dust (Dastidar et al. 2001). However, that value was based on coarse 'mine-size' coal which only contained 15% < 75 μm; therefore, a direct comparison between the two is unjustified. Nevertheless, this example emphasizes the fact that large particles are less explosive and easier to inert, i.e., they require less rock dust for these laboratory test conditions.

The results from Fig. 6 also indicate that rock dust at high levels (60% rock dust) but below the extinction level (63% rock dust) offers little or no protection since the explosion pressures from marginally under-rock dusted mixtures are almost the same as those with no rock dust at all.

The results from the inerting experiments with limestone rock dust on medium and coarse coal are shown in Figs. 7 and 8 respectively. As observed with the PPC, there is a common trend where insufficiently rock dusted coal explodes with a similar pressure rise as pure coal and the coal is inerted only when the extinction limit is reached. This implies that a slightly under-rock dusted area of coal dust in a mine can explode with about the same severity as a non-rock dusted area. This rapid fall in explosibility at the extinction level is consistent with data published by Amyotte, Mintz, and Pegg (1995) using a 26-L explosion chamber. It should be emphasized that the data presented in this paper indicates that rock dust-coal dust mixtures that are below the inerting level, even if it is only slightly, may or may not be explosive. Only those mixtures which are at (or above) the inerting limit do not explode, e.g., PPC and 63% limestone rock dust in Fig. 6. This is similar to findings by Dastidar et al. (1999) in which approximately 60% rock dust was required to inert PPC in a 1-m^3 chamber. Consequently, it is not recommended to only test at one dust concentration. For example, in Fig. 7, at 600 g/m^3 the coal with 48% limestone exploded but the one with only 40% limestone did not. It is important to examine a much wider range of dust concentrations and look at all the data collectively in order to establish the true inerting limit.

The medium-size coal, which contains about 40% < 75 μm, is inerted with 50% regular rock dust. The coarse coal, which only contains about 20% < 75 μm, is inerted with 40% rock dust. This latter value is quite close to the 34% reported by other researchers using the Fike 1-m^3 chamber (Dastidar et al. 2001). The difference can be attributed to the small variance in the amount of fine dust (<75 μm) used in the current study, which is about 5% higher than the value reported by the previous researchers.

The amounts of rock dust required to inert the coarse, medium, and pulverized coals in the 1-m^3 chamber are all significantly lower than the values published by NIOSH (2010, p. 48) using the LLEM. It should be noted that although the trends are similar, there is no direct correlation between laboratory-scale and full-scale inerting levels.

The results from the NIOSH 20-L chamber inerting experiments using PPC and limestone are summarized in Fig. 9. Only the 400 g/m^3 data is shown graphically, since coal is most explosive around this dust concentration (as shown in Fig. 4) and it reaches an

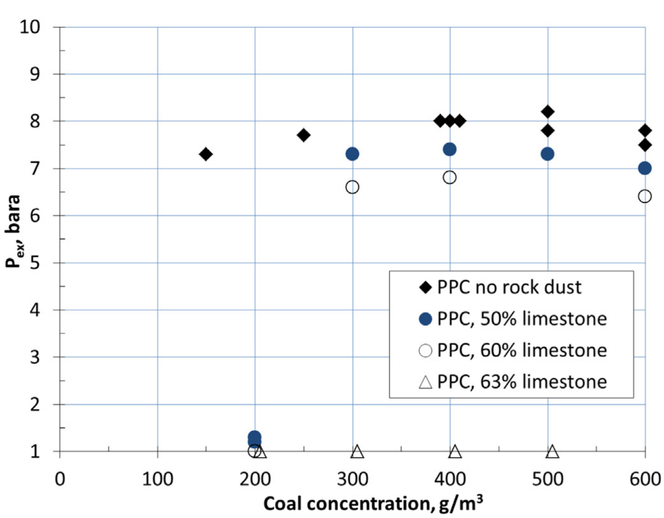

Fig. 6. Inerting PPC with limestone rock dust in the 1-m^3 chamber.

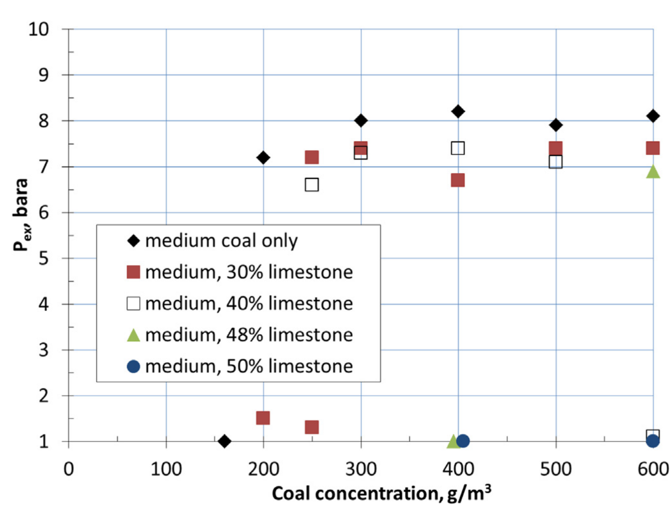

Fig. 7. Inerting medium-size coal with limestone rock dust in the 1-m^3 chamber.

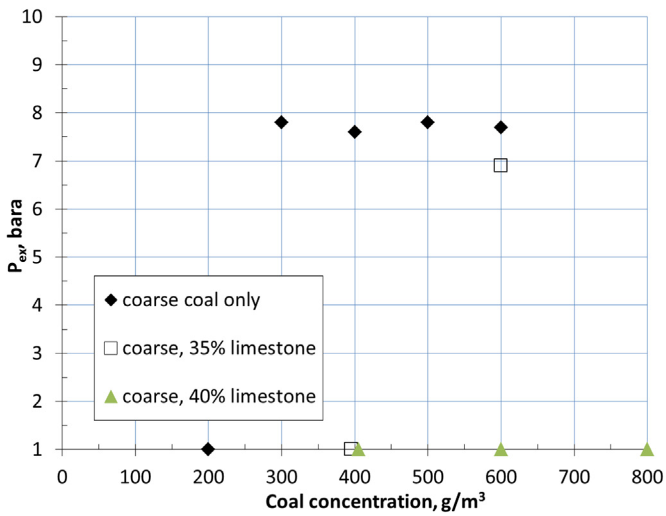

Fig. 8. Inerting coarse-size coal with limestone rock dust in the 1-m^3 chamber.

asymptote beyond this level as previously published (Cashdollar, 2000; Dastidar et al. 1997). More recently and by using a 20-L chamber, Kuai et al. (2011) explained why coal dust at concentrations of 200–400 g/m^3 is the most reactive region because it is where the volatiles reach near-stoichiometric concentration.

The 20-L data from this study (Fig. 9) shows that PPC requires about 72% of regular limestone rock dust to inert. This is the same value as reported by other OMSHR researchers using the same chamber (Cashdollar and Hertzberg 1989). Other investigators using 20-L chambers have published slightly higher values. For example, Sapko et al. (2000) required 74% limestone rock dust to inert PPC, and Dastidar et al. (1997) required 75–80% limestone rock dust to inert PPC in their 'Siwek' 20-L chamber. The differences may be attributed to the variability of the 20-L chamber, the slight variabilility of fine particles of coal dusts from lot to lot, as well as the variability of the chemical ignitors used. It should also be noted that the LLEM required 79% TIC to inert the pulverized coal (NIOSH, 2010, p. 48).

As expected, the medium and coarse coals required lesser amounts of rock dust to inert. This is consistent with the trend reported by Amyotte et al. (1995), who compared fine and coarse coal particle size for inerting requirements with limestone rock dust. Fig. 9 shows the inerting requirements for medium and coarse coals to be about 60% and 50% respectively.

Fig. 10 shows the effect of rock dust particle size on inerting PPC in the 20-L chamber. As mentioned earlier, PPC required about 72% of the unsieved "whole" limestone rock dust to inert in the 20-L chamber. However, different particle size rock dust has varying effects on its inerting ability. In general, a decrease in limestone particle size improves its performance as an inhibitor and results in a decrease in the inerting levels. Fig. 10 also shows that only two of the particle size ranges tested appears to be more effective than the whole rock dust. These are the <38 μm and <75 μm fractions which both required about 70% to inert PPC. Conversely, the larger particles (38–75 μm and >75 μm) required 85% and 95%, respectively, and the 250–841 μm size rock dust failed to inert even at 90%. This suggests that the explosion inerting process is mostly effected by the small particles or those <75 μm. This outcome is favorable, as the regulations (30 CFR 75.2) require rock dust used in coal mines to contain a minimum of 70% < 75 μm (or −200 mesh). However, the results from Fig. 10 indicate that it may be better to have 100% < 75 μm since this size fraction is significantly more effective than the >75 μm component at inhibiting coal dust explosions. Since the regulation (30 CFR 75.403) is primarily concerned with the % TIC value, samples containing high amounts of >75 μm material will nevertheless be regarded as compliant in meeting the 80% TIC requirement. From the results shown in Fig. 10, this determination where % TIC is the only variable measured and other rock dust qualities such as particle size are not, the current low temperature ashing method of only measuring the % TIC may be insufficient in identifying an explosion hazard.

Some of the sieved limestone rock dust was also tested in the 1-m^3 chamber for its inerting ability with PPC. The results are summarized in Fig. 11. As before, two non-explosions at any rock dust concentration was considered to be the inerting limit. These often appear superimposed in the graph—e.g., there are multiple data points for the <38 μm rock dust at 52%. In general, the results show very similar trends to those obtained using the 20-L chamber. Notice the abrupt change from explosive to non-explosive in each of the dusts. Again, the finest rock dust particle size requires the least amount of rock dust to inert the coal, but this value is lower than observed in the 20-L chamber. Both of the coarse size fractions (the >75 μm sieved from rock dust and the 60-20 mesh (250–841 μm) ground from lumps taken from the same quarry as the commercial rock dust) require about 90% to inert the coal dust.

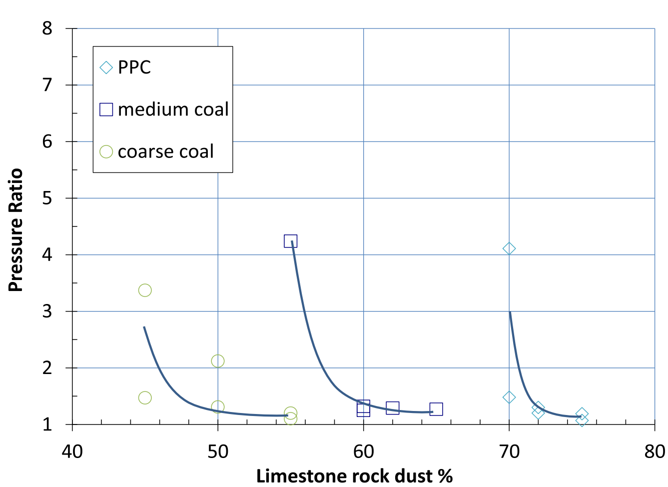

Fig. 9. Inerting PPC, medium, and coarse coal samples with regular limestone rock dust in the NIOSH 20-L chamber. All experiments were carried out with 400 g/m^3 coal concentrations.

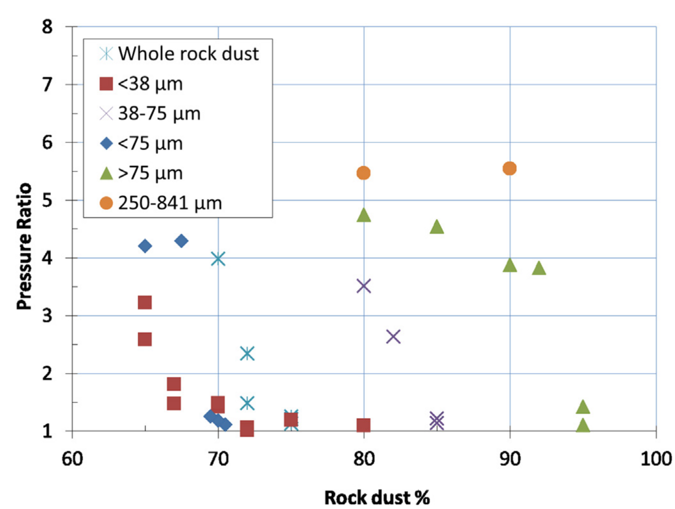

Fig. 10. Inerting PPC with limestone rock dust and 250–840 μm (60-20 mesh) limestone particles in the 20-L chamber.

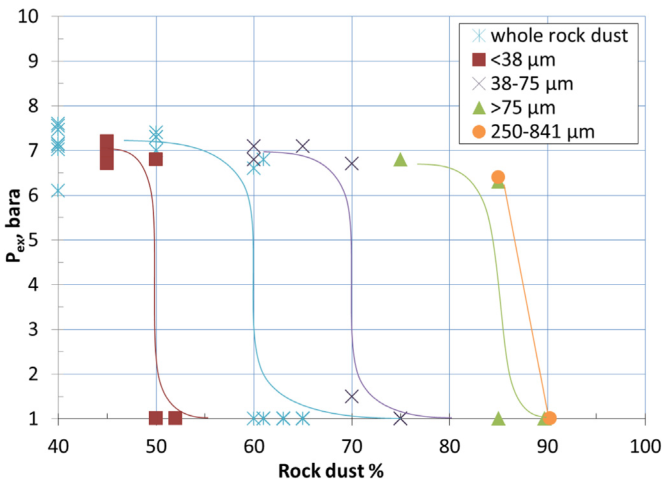

Fig. 11. Inerting PPC with limestone rock dust including sieved size fractions and 250–840 μm (60-20 mesh) particles in the 1-m^{3}chamber.

This outcome indicates very little inertization effect from the laboratory-scale experiments, which raises the question as to whether these particles should be included in commercial rock dust or in the laboratory incombustible analysis. It should be noted again that mixtures of coal and rock dust in the laboratory near to the inerting limit may or may not explode as observed in Fig. 11 with the >75 μm rock dust at 85% inerting.

4. Conclusions

Coarse, medium, and pulverized Pittsburgh coals each have similar P_{max} values but the MEC increases with increasing particle size. This suggests the explosion is largely controlled by the amount of the finer-size component, probably 150 μm or smaller. If the particles >150 μm are excluded, the calculated MEC values become quite similar to each other.

The large coal dust particles, 250–841 μm (60-20 mesh), did not explode in the 1-m^3 chamber over the range of 200–600 g/m^3, even when 'overdriven' by strong 20 kJ chemical ignitors. This observation has ramifications for the sampling and analysis of coal dust in mines. If coal particles of this magnitude do not explode, then the justification for including those sizes in the dust sampling and laboratory analysis should be questioned.

The results suggest that the current definition of rock dust (30 CFR 75.2) to include particles up to 841 μm (20 mesh) is inappropriate from an explosibility perspective. Large limestone rock dust particles both >75 μm (>200 mesh) and 250–841 μm (60-20 mesh) offer almost no protection as an inhibitor against coal dust explosions according to these laboratory results.

It should be noted that although the trends observed in these laboratory experiments compare favorably with full-scale LLEM data (NIOSH, 2010, p. 48), the absolute inerting percentages differ with the laboratory chambers and require less rock dust than the LLEM. This is due to the different geometries of the chambers, dust dispersion techniques, and the ignition sources utilized. LLEM uses a turbulent methane flame to initiate the coal dust explosion (the chamber criterion is based on the measured pressure rise whereas the LLEM is based on self-sustained flame propagation beyond the influence of the ignition source). Laboratory-scale explosion vessels such as the 20-L and the 1-m^3 chambers have been demonstrated to give consistent trends and are a useful exploratory method for preliminary investigations (Cashdollar and Hertzberg 1989).

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