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Ignition and explosion parameters of Colombian coals

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ABSTRACT

The explosivity of coal in Colombia is usually determined by chemical analysis based on the volatile ratio. To improve the assessment of the explosivity of those coals that have led to numerous explosions in Colombian mines, 22 coals from the department of Antioquia were analyzed. Flammability characteristic parameters were determined, such as minimum temperatures and energy for ignition and the lower explosive limit. Also explosion data, ie. Pmax and Kmax values were obtained. In addition, the susceptibility to spontaneous combustion was studied by thermogravimetry and differential scanning calorimetry, together with chemical attack with hydrogen peroxide and also measuring the temperature of ignition of flammable volatiles. Finally the effect of particle size and the percentage range of limestone needed for inerting coal under two different granulometries were determined.

1. Introduction

The southwest area of Antioquia, a Department of Colombia with a long mining tradition, consists of 23 municipalities in four areas: Sinifaná, Penderisco, San Juan and Cartama. The basin area of Sinifaná includes five municipalities in mining area: Angelópolis, Titiribí, Amagá, Venecia and Fredonia. High-quality thermal coal constitutes the main type of mining in the basin of Sinifaná, which brings together a total of 56 mining titles, of which 18 are under exploitation (Molina Escobar, 2010, Molina Escobar et al., 1998).

According to the National Emergency System of Colombia in the last five years there have been 18 explosions in coal mines. On June 16, 2010, there was a major accident that killed 73 workers in a coal mine southeast of Antioquia, in the municipality of Amagá. The final report on the causes of the accident showed that the incident was caused by an explosion of methane and coal dust (Instituto Colombiano de Geología y Minería, 2010).

With the support of the National Agency for Mine Safety in the United States (NIOSH), the explosibility of coal dust samples from 40 underground mines were determined. Mines were selected in the coalfields of Antioquia, Cundinamarca, Boyacá and Norte de Santander, where it is extracted 95% of Colombian coal in underground mining. The result was devastating: all mines, but two in Antioquia, were potentially explosive (Baquero et al., 2012).

The practical procedure followed was based on the so-called volatile ratio, which is a value set by the US Bureau of Mines to assess the explosibility of the coals on the basis of large scale tests in Bruceton Experimental Coal Mine (Department of Health and Human Services, 2010, Harris et al., 2008). To calculate the volatile ratio, proximate analysis should be performed to the coal samples in the laboratory. This analysis determines the content of moisture, ash, volatile matter and fixed carbon of coal. The ratio is defined as volatile matter divided by the sum of volatile matter and fixed carbon in the coal. This method of calculating the volatile ratio produces an independent value of the total amount of non-combustible material in the coal, taking into account the own ashes of coal and also any aggregated non-combustible material. It was determined that coals with a volatile ratio higher than 0.12 represent an explosion hazard. All bituminous and subbituminous coals fall into this category. Anthracites can have a volatile ratio of 0.12 or less, and therefore it is frequently said that they can participate in the fires but they do not present an explosion hazard. However, experimental explosion tests have shown that this statement is incorrect and does not correspond to the observed facts (Cashdollar, 2000) (Stephan, 1998).

Obviously, volatile matter plays a very important role for coal flammability properties (Cybulski, 1975) and for coal dust explosion

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propagation (Lebecki, 1991), so that the higher the volatile content the easier is the ignition of dust and the propagation of the explosion. In the case of anthracites, with few volatiles, explosibility lowers significantly. But a dust explosion is possible even without volatile: this applies to metal products, for example, where the oxidation reaction occurs directly on the solid, without intervening gas phase reaction. Therefore, particles can be ignited and explosion can spread for substances not yielding volatiles. As previously described, two different flame propagation mechanisms were observed in the experiments: kinetics-controlled regime and devolatilization controlled regime (Gao et al., 2014).

There is a correlation between the explosion of different types of coals and its composition (proximate and ultimate analysis) (García Torrent et al., 1988), so that it is possible to classify coals as regards to their flammability as a function of their chemical composition (García Torrent et al., 1991). Furthermore, it is even possible to predict the quantity of inert matter, such as calcium carbonate, that should be added to the coal in order to have a safe mixture (Medic Pejic, 2012). But to assess the risk of explosion due to coal dust, besides coal properties, the characteristics of the operation and the mining method that affect the production of dust accumulations and dispersal ability must be considered (García Torrent et al., 2001; Kennethashdollar o M). Physical and chemical properties of coal can lead to the evaluation of the frequency of explosive atmospheres occurrence and then, an explosion risk index can be estimated taking into account the probability of ignition source occurrence and the severity of consequences, besides that frequency of explosive atmospheres (Medic Pejic et al., 2013).

Another important issue related to safety in coal mines is the risk of spontaneous combustion that can produce significant ignition sources and can lead to mine fires. This risk affects differently to the various types of coals and can be determined by thermal susceptibility tests designed to quantify the tendency of a given coal to undergo self-heating and spontaneous combustion (García Torrent et al., 2004, García Torrent et al., 2012).

To analyze these effects and determine how dangerous Colombian coals are, some mines in Antioquia have been selected, coal samples were taken and flammability, explosibility and thermal susceptibility parameters were measured.

2. Experimental methodology

To analyze the operating conditions in 12 Colombian coal mines belonging to the Department of Antioquia.

The full characterization program for coals included 3 stages:

- Tests for granulometry, moisture, ignition sensitivity, explosion severity and thermal sensitivity for 22 coal samples.
- Analysis of the influence of particle size by testing of particle size, moisture and some selected tests for 1 coal sample with 5 different particle sizes.
- Analysis of inerting ability by Pmax and Kmax tests on 2 samples of coal mixed with 3 different limestone percentages.

Then 22 coal samples were taken in those mines.

Table 1 present their characteristics. Sampling was directly done at the coal seam, avoiding any inerted dust deposited on galleries. All the samples were prepared by milling and sieving to obtain dust with similar particle size distributions as normal dust in the galleries, selecting for the tests the fine dust fraction having median diameters among 0.04 mm and 0.1 mm. Fig. 1 shows the typical particle size distribution of one of the samples measured by laser diffraction in a dry method using a Malversizer 2000 apparatus.

In a first stage of characterization in the laboratory, most flammability and explosibility parameters were measured: minimum ignition temperature in a cloud, minimum explosible concentration (lower explosive limit), minimum ignition energy, maximum explosion pressure (Pmax) and Kmax constant. For 5 samples also minimum ignition temperature on a layer was also determined.

Table 1
Coal samples.

Sample	Moisture (%)	d (0.1) μm	d (0.5) μm	d (0.9) μm
UNC-1	9.9	9.4	78.3	236.4
UNC-2	11.1	8.2	60.5	211.1
UNC-3	10.6	8.2	76.1	245.5
UNC-4	7.2	3.3	41.2	186.9
UNC-5	12.7	9.0	80.1	251.6
UNC-6	7.0	3.0	53.5	206.5
UNC-7	11.3	10.4	100.6	270.8
UNC-8	12.6	6.7	57.2	228.3
UNC-9	10.7	8.3	76.1	248.7
UNC-10	5.4	7.7	65.6	211.3
UNC-14	7.8	8.5	60.5	216.8
UNC-15	12.0	10.5	96.6	258.9
UNC-16	10.2	7.6	72.8	246.8
UNC-18	10.2	4.7	103.7	294.7
UNC-19	9.1	4.5	39.4	201.3
UNC-20	11.8	8.5	68.8	249.3
UNC-22	3.2	3.8	54.7	223.1
UNC-23	9.2	8.0	82.6	245.9
UNC-24	10.9	8.2	75.3	254.2
UNC-25	6.8	4.0	48.1	220.6
UNC-26	3.1	6.8	54.3	205.9
UNC-27	4.7	2.6	36.9	189.3

Tests were done following standard procedures and using regular equipment for ignition temperatures (EN 50281-2-1, 1999), a 20 L apparatus for lower ignition limit (EN 14034-3:2006+A1, 2011) and a Mike-3 device for ignition energies (EN 13821, 2002). Explosibility tests for Pmax and Kmax were carried out also in a 20 L apparatus with the standard ignition delay of 60 m and ignition energy of 10 kJ following standard procedures (EN 14034-1:2004+A1, 2011, EN 14034-2:2006+A1, 2011).

For thermal susceptibility analysis 5 samples were selected. Thermal susceptibility tests include Maciejasz Index (MI) as a measure of reactivity and avidity for oxygen when sample is attacked with oxygen peroxide, Temperature of emission of flammable volatiles (TEV) as a sort of flash point for solids, Thermogravimetry test (TG), Differential Scanning Calorimetry (DSC), Activation energy (Ea) and Characteristic oxidation temperature (Tcharact.). The meaning and the experimental procedures for these parameters have been previously described in detail (Ramírez et al., 2009, Pejic et al., 2015). The DSC analysis allows determining the characteristics of the combustion reaction of solid fuels. Three characteristic parameters are obtained with this analysis, the Initial Exothermic Temperature (IET), the Final Exothermic Temperature (FET) that is the starting point and the end of the combustion reaction and the Change of Slope Temperature (CST), representing the temperature at which the slow combustion changes to a quick combustion.

In the second stage, to analyze the influence of coal particle size on the selected parameters of flammability and explosibility, 5 different size fractions were studied. The coal sample UNC-19 producing the highest Kmax value and also providing high sensitivity to ignition (low temperatures, concentrations and energies for ignition) was selected as suitable for this study. Since mining operations had advanced as to when the initial sample was taken, a new sample was taken as close as possible to the previously analyzed coal.

For the third stage, two different grain sizes for coal and several mixtures with different percentages of limestone were analyzed. To study the most disparate behavior, samples with the most different