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RESEARCH ARTICLE

Optimization of techniques for the extinction and prevention of coal fires produced in final walls as a result of spontaneous combustion in the Cerrejón mine—Colombia

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Abstract
The Cerrejón mine has identified fires in its coal production seams for a few years in its operation. Fires are produced as a result of spontaneous combustion phenomena. Coal spontaneous combustion is a phenomenon that occurs naturally during coal oxidation when exposed to atmospheric conditions, due to erosion processes, geological and mining practices. This phenomenon is a subject of great concern in the world's coal mines, as it causes environmental problems, generating emissions of polluting gases into the atmosphere and economic losses due to reserve consumption. In this work, we seek to optimize the prevention and extinction processes used by the company. In terms of prevention, the current state was evaluated and alternatives, such as diluted bitumen and brine (combustion inhibitor), cement/slaked lime, fine sand cement, and clinker/slaked lime were developed to avoid ignition. As far as extinction is concerned, an additional methodology for medium magnitude fires was determined, in order to improve extinction times through the use of cooling. It was determined that the bitumen/brine has better adhesion and durability properties in the coal seam. Extinction through reagent cooling is quicker, thus improving the backhoe's productivity and minimizing costs.

Keywords Coal fire · Extinction · Prevention · Self-combustion · Endwalls · Coal seam

Introduction

The mining operation of Cerrejón is carried out in Colombia's northern region, specifically in the peninsula of the Department of La Guajira, covering an approximate area of 78,000 ha. It is located in a valley delimited by the northeastern foothills of the Sierra Nevada de Santa Marta on the east side, and by the Serrania Del Perijá and the Oca Mount, on the west side. Cerrejón has an approximate annual production of 32 Mtons, and it has identified fires during its operation that produced by the spontaneous combustion phenomenon in some of its explotation layers (Fig. 1). Actions are focused on the sealing of coal seams through the application of asphalt emulsion, also—known as bitumen—to exposed layers with high susceptibility to spontaneous combustion. Bitumen is an aqueous dispersion of asphalt with a mixture of biodegradable cationic and nonionic surfactants, dark brown to black. Removal consists of the construction of a ramp to access the fire and work on the burning coal seam wall. The coal seam is engaged at an angle of 45°, in the opposite direction to the gas emissions, thus avoiding the fall or detachment of hot material and loose rocks, protecting the operator's integrity until the fire is out. Finally, a temperature in the final wall oscillating between 40 and 60 °C is expected to be found through thermographic cameras or thermal guns.

Spontaneous combustion in coal seams is an issue that occurs in mines around the world. It causes environmental problems due to particulate matter emissions and polluting gases, such as carbon monoxide, carbon dioxide, sulfur dioxide, methane gas, and mercury vapor (Beamish 2015; Beamish et al. 2001; Pone et al. 2007; Timko and Derick 1995; Zhao et al. 2015), which represents an environmental

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Fig. 1 Typical fire in the endwalls of the Cerrejón mine

potential and a risk to human health (Finkelman 2004; Melody and Johnston 2015). Most of these gases are a product of the carbon oxidation at high temperatures and other elements that are present in it. This process occurs in nature by oxidation of carbon when it comes into contact with oxygen (Jing et al. 2016; Kim 2011; Wang et al. 2011), when exposed due to geological erosion processes as well as to underground and open pit mining practices (Heffern and Coates 2004; Kuenzer and Stracher 2012; Lu et al. 2015; Scott 1994; Singh 2013). Natural carbon oxidation reaction is feasible under the right conditions, considering that the equilibrium constant (K) is very large and oxygen's partial pressure is close to zero, which implies from a thermodynamics standpoint the reaction occurs throughout the range of possible temperature to infinity as seen in Fig. 2, allowing the reaction to be governed by chemical kinetics. The latter, accelerates rapidly from self-heating and heat release, resulting in ignition and subsequent propagation in coal seams.

Even though there are few published reports of health problems caused by gas emissions, consequences can be significant (Timko and Derick 1995). In India, for example, a large number of people have been displaced from their homes due to health issues caused by coal fire emissions. Volatile elements such as arsenic, fluorine, mercury, and selenium are usually found in coal deposits. These can or may volatilize and in turn be inhaled or adsorbed on crops, food, livestock, or bio-accumulated in birds and fish, in the presence of fires (Finkelman 2004; Melody and Johnston 2015). In addition to the aforementioned elements, such as selenium, arsenic, lead, tin, bismuth, and fluorine condense, where hot gaseous emissions come into contact with the air within fluids, forming layers that can be leached with rainwater and be wash in local bodies of water providing other potential routes of exposure. Studies have been conducted where different compounds are characterized in coal fires emissions as well as maximum concentrations registered in coal mines, where accumulations of these gases occur, such as CO (> 27,000 parts per million), mercury (> 2100 μg/m^3), benzene (> 400 parts per billion), toluene (> 397 parts per billion), and greenhouse gas CO2 (> 17% *v*/*v*). It should be noted that the concentration of these gases in open pit coal mines is lower due to the dilution generated in the environment. On a global scale, it has been estimated that CO2 emissions as a result of fires in coal mines varies between 12 and 8200 kg/m^2 per year (Carras and Young 1994; Dalverny and Chaiken 1991; Dodamani 2014; Fierro et al. 1999).

Coal spontaneous combustion can be divided into two processes: ignition and propagation (Fig. 3). The ignition process is related to the energy accumulation coal undergoes due to an oxidation reaction and the contribution of some variables, which allow coal to reach the minimum energy required to cause the spark that starts a fire, which is known as activation energy (Nordon et al. 1979; Singh 2014; Singh 2013). Subsequently, propagation begins, which is triggering a series of chemical reactions adding to an intense release of heat (Bustamante Rúa et al. 2018; Huo et al. 2015; Kaymakçi and Didari 2002; Smith et al. 1993). Coal self-combustion occurs in a timely manner in the final walls and abandoned pits in the Cerrejón mine (Cerrejón 2016; Quintero et al.

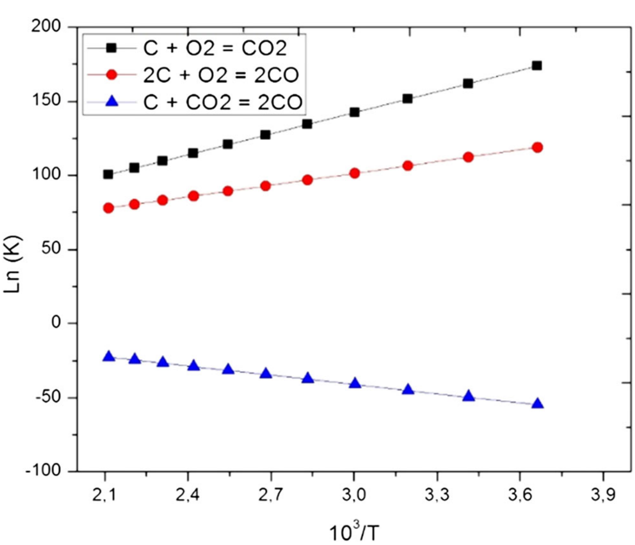


Fig. 2 Relationship of the equilibrium constant with the temperature in the oxidation reactions of the coal

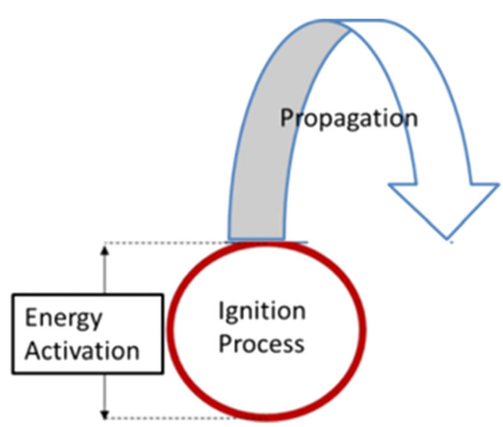


Fig. 3 Process of ignition and propagation of coal in spontaneous combustion (Bustamante Rúa et al. 2018)

2009). This implies large-scale environmental problems, significant loss of reserves, instability due to geotechnical affectation, and health issues due to the impact on surrounding communities (Bustamante Rúa et al. 2018; Finkelman 2004; Kaymakçi and Didari 2002; Moxon and Richardson 1985; Ren et al. 2017).

Fire prevention is the set of activities in all phases of mining activity, aiming at avoiding or reducing the chances of coal self-heating. Bustamante et al. (2018) developed a statistical analysis with the purpose of studying the susceptibility to spontaneous combustion of different coal seams in open pit mines in Colombia. The most influential variables are seam temperature, atmospheric pressure, wind speed, oxygen, methane, height, ash, volatile matter, calorific value, vitrinite, liptinite, and Hardgrove index (Chen et al. 2012; Gómez Rojas et al. 2007). Variables that could be controlled are seam temperature, wind speed, and oxygen. Some control measures that can be implemented are the sealing of coal seams with materials that have good thermal insulation and impermeability properties (Bustamante Rúa et al. 2018; Carras and Young 1994). Fire extinction is the elimination of conditions that allow a fire to continue to develop (fuel) (Wan-Xing et al. 2011). It is an expensive process and difficult to control because of the conditions to which coal fires spread within the seam (Lu et al. 2015). It is a costly and difficult process to control because of the conditions causing coal fires to spread within the seam. In this article, we deal with medium magnitude fires (up to about 700 °C of temperature) and a surface of less than 20 m^2 (Fig. 6a).

The strategy adopted for dealing with the fires is a two-phase operation—first, the fires must be contained, and secondly, it should be extinguished. The methods adopted for dealing with these fires as per fire situation are as follows (Dalverny and Chaiken 1991; Gao et al. 2018; Lu et al. 2017; Mine Safety Operations Branch Industry and Investment NSW 2011; Singh 2013): hydro-pneumatic stowing, fly ash flushing, trench cutting and its filling, water circulation under pressure, cementation, stowing, blanketing, digging out, nitrogen/carbon dioxide injection, sealing by construction of isolation stoppings, remote sealing–concrete cement injection, cement water slurry spraying, infusion of silicic acid, and application of fire protective coating material and chemical inhibitors for control and combating fire.

The abovementioned techniques are being applied for control of underground as well as surface fires, depending upon the situation of fire problem. It will vary case to case and site to site basis (Singh 2013). Cerrejón implements the sealing of the coal seams with bitumen/water as a preventive measure in its mining activity, as well as the use of a backhoe for removal present in fire extinction. However, but both are done without any study on its potential optimization from a physicochemical and operational perspective of the products and equipment. This article proposes the evaluation of different technological improvements for fire prevention and extinction through pilot tests developed directly in the mine pits.

Currently, the company has problems of fire reactivation associated with the output of equipment without controlling the entire fire, sealing efficiency, inadequate control of hot material, and lack of water or chemical products in the process of temperature control. For this investigation, in order to optimize the prevention techniques to avoid the appearance of new fires in the coal seams, pilot tests were developed with some products, due to their sealing properties that allow the isolation of the coal seam with the ambient. In the case of bitumen/water and bitumen/brine are solutions that are characterized by their high adherence to the surface of the coal seam according to the measurements of contact angle made in the laboratory. Brine is an inhibitor of the spontaneous combustion of coal, contributing to the increase of the energy required for coal to reach ignition. Bitumen is a complex mixture of petroleum hydrocarbons and water. It is an aqueous dispersion of asphalt with a mixture of biodegradable cationic and nonionic surfactants, which does not produce impacts on the environment, since it is used as a preventive measure in scenarios, where it is not subjected to high temperatures. On the other hand, cement/slaked lime, cement/fine sand, and clinker/slaked lime tests were used due to their pozzolanic properties, which guarantee a special bond to the surfaces of the materials. Clinker is an inert material obtained in the mine as a result of the alteration of thermal rock due to the spontaneous combustion of coal, which is not harmful to the environment. As for the extinguishing methods used to prevent the spread of fires, pilot tests were developed with FP Coal® and water in synergy with the removal to achieve greater efficiency in the extinct. The FP Coal® product is composed of nanoclays, salts of carbonic acid, and aniconic surfactants that extinguish fires with a high degree of energy, and its biodegradable compounds are friendly to the environment.

Materials and methods

Optimization flowchart

The methodology used to optimize the new proposals in the company is described in Fig. 4. The sealing process that is clarified in Prevention-sealing and the current leading to removal cooling that is clarified in Extinction-removal cooling.

Prevention-sealing

For prevention tests, different products were used in order to evaluate sealing improvement to avoid the ignition of coal seams. The products used were bitumen/water (70/30 % *v*/*v*) and (50/50 % *v*/*v*); bitumen/brine (70/30 % *v*/*v*) and (50/50 % *v*/*v*); cement/slaked lime in 2 to 1 relation, cement/fine sand in

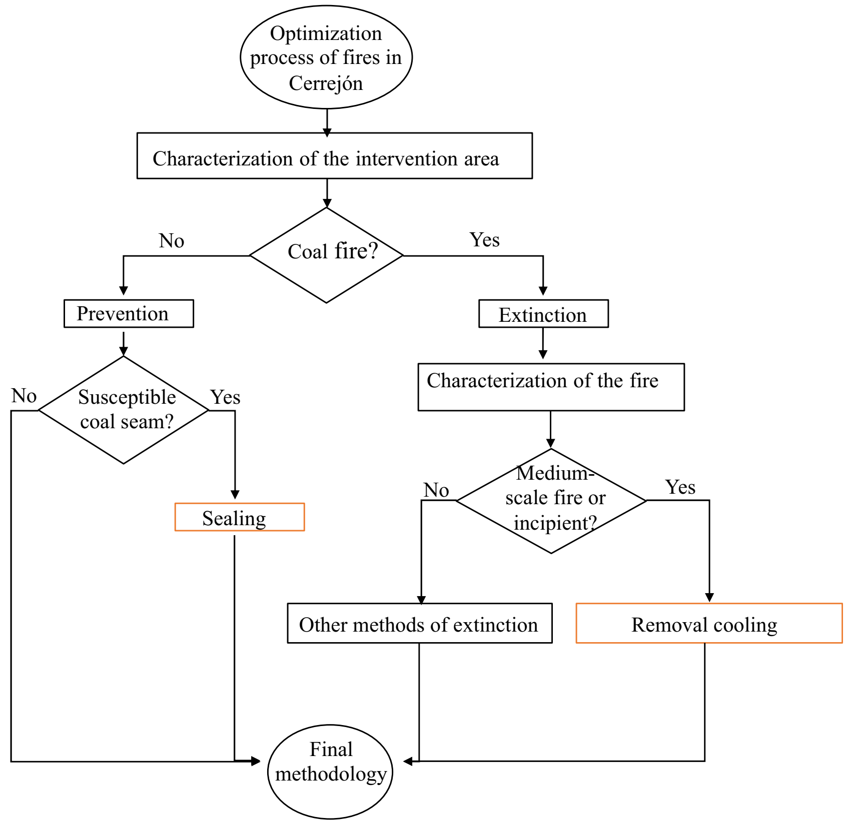


Fig. 4 Methodology used in the proposal for control optimization and fire extinction

1 to 10 relation, and clinker/slaked lime 2 to 1 relation. Clinker referred here as red and brick-looking burnt rocks found interbedded in the Upper Paleocene Cerrejón Formation is the result of spontaneous and natural combustion of coal seams in the recent geologic past (Barros Daza et al. 2016; Heffern and Coates 2004; Quintero et al. 2009). The clinker has pozzolanic properties, which translate into cementing properties when mixed with slaked lime.

As far as bitumen is concerned, contact angle measurements were taken in order to know the adherence degree to the coal seam surface (Fig. 5). These measurements were taken for pure bitumen and for the different concentrations of bitumen/water and bitumen/brine described (Table 1).

It was observed that pure bitumen has a greater degree of adherence to the coal seam surface, and that it loses adhesion capacity as water concentration increases, due to the natural hydrophobicity of coal and water (Chang et al. 2018; Huo et al. 2014). On the other hand, brine maintains the bitumen's adhesion capacity compared to water, which becomes evident when the angles so are so close to those used for pure bitumen.

Extinction-removal cooling

For extinction tests, two products were used to control fires. They helped support the removal work done by the backhoe. These products were FP Coal® and water. FP Coal® is used for

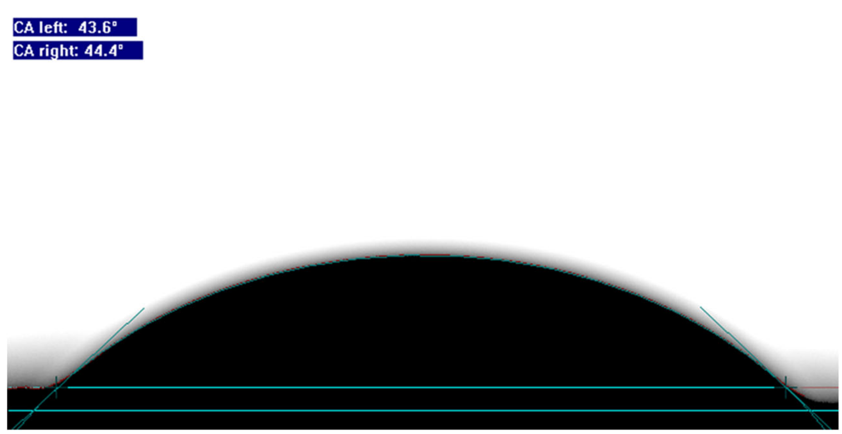


Fig. 5 Contact angle measurements

Table 1 Contact angle measurements

Bitumen contact angle		
Proportion (volume)	Left angle	Right angle
Bitumen/water 100/0	43.6°	44.4°
Bitumen/water 50/50	65.6°	61.8°
Bitumen/water 70/30	57.2°	55.9°
Bitumen/brine 50/50	50.9°	48.3°
Bitumen/brine 70/30	48.9°	44.9°

extinguishing fires that are caused by high temperatures in coal mines. It also acts as a fireproofing agent on the mineral's surface preventing the spread. The reagent concentrations were varied by 20 and 30% *v*/*v*.

Pilot testing for prevention and extinction

The procedure used for prevention testing was the selection of zones in the mine, which met optimum conditions of coal seam exposure and personnel safety. In order to prepare the bitumen, tanks with a capacity of 1 m^3 were used and mechanically stirred until the solution homogeneity was reached. Subsequently, for coal seam sealing, the bitumen was located in the study area along with auxiliary equipment, such as the Wilden® XP 4 pump, which operated at a pressure between 90 and 100 psi, the Kaiser M50 portable air compressor 185 cfm and some hoses. The coal seams were sealed until the total coverage of the exposed area was achieved (Fig. 6). The Chemgrout 500–206 machine was used for the preparation of cement/slaked lime, cement/fine sand, and clinker/slaked lime. The machine is characterized by having two mixing tanks of 70 gal approximately on a simple platform that allows continuous mixing, using a C6 pump with a progressive cavity for its injection.

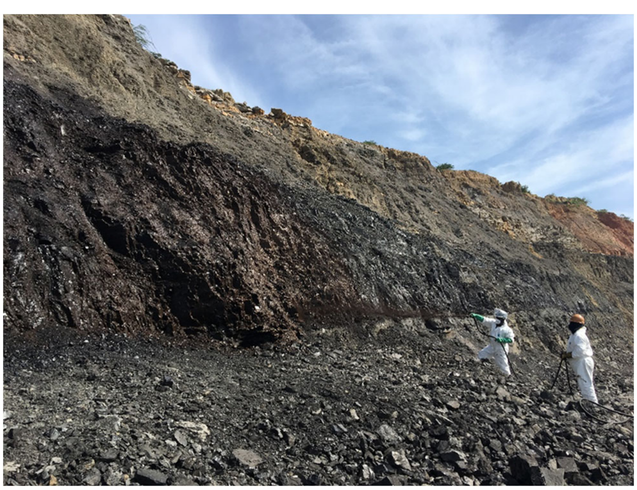


Fig. 6 Application of bitumen on the coal seam

The procedure used for extinction testing was the selection of fires that allowed good accessibility and safe conditions for the entry of equipment, personnel, and machinery. Average temperatures of 700 °C were registered with the aid of Fluke 556thermal cameras (as seen in Fig. 7a). The water used for testing comes from the mine. The FP Coal® product was prepared in 1 m^3 tanks, according to the aforementioned concentrations, mechanically stirring the solution until homogeneity is achieved. The auxiliary equipment used was the Wilden® XP 4 pump, Kaiser M50 portable air compressor, and hoses. The fire was extinguished by combining cooling (Fig. 7b, c) and removal (Fig. 7d) in time periods of 10 min each, until reaching a target temperature between 40 and 60 °C, where extinction is achieved.

Results and discussions

Prevention

A total of 14 sealing tests were carried out using the different products described above. The results of some of the seals made with each product are shown in Fig. 8. A total area of 1077 m^2 was sealed for the study.

The monitoring carried out on the different layers, where seals were applied showed that clinker/slaked lime and cement/slaked lime products were strongly affected by wind erosion, provided the layer formed was not thick enough to prevent the wind from having a direct effect on the coal seam edges, where the greatest irregularity occurred. This condition is unfavorable considering the fact that the coal seam still has exposed areas that can come into contact with oxygen in the air and facilitate a combustion reaction. The cement/fine sand product application, on the other hand, presented difficulties due to the fact that the appropriate equipment was not available, yet it achieved good adhesion and consistency properties in the areas of the seam where it was applied.

The bitumen/brine (50/50% *v*/*v*) is the best sealing alternative that was obtained from the tests, since it reaches a better adherence and consistency than bitumen/water at the same concentration. At the same time, brine seemed to improve bitumen's performance during application, since a larger area could be covered with the same amount of product. In the test with bitumen/brine (50/50% *v*/*v*) to 420:1 solutions was used to cover an area of 210 m^2, which would be precisely the necessary amount required to cover said area, if bitumen/water was used at an equal concentration. Savings of 80:1 of solution were obtained, which proves that the use of brine provides very important benefits with respect to sealing. Additionally, it is known that salt acts as an inhibiting substance for coal spontaneous combustion, increasing the energy required by the system to reach an ignition process. It is worth noting that bitumen/brine (70/30% *v*/*v*) was not selected in

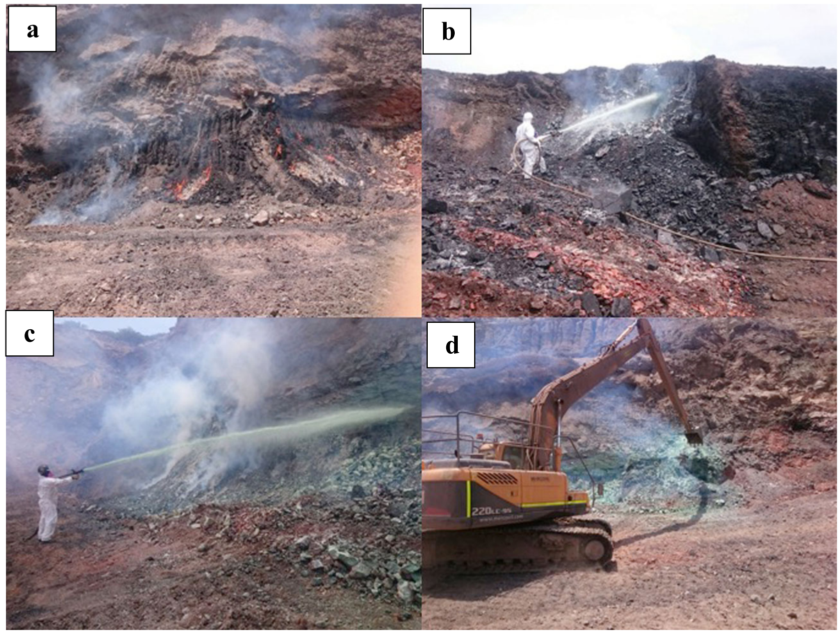


Fig. 7 Methodology used for extinguishing fires with removal and cooling in Cerrejón

spite of its good properties, considering it involves unnecessarily greater product expenditure as it forms an extremely thick layer. Figure 9 shows follow-ups performed 3 months after the tests were done.

Extinction

Results of tests carried out for fire extinction with the combination of removal and cooling are shown below in Fig. 10.

Removal as it is currently done in the company shows that the long arm backhoe requires longer times for total fire extinction due to the depth they reach inside the seam. For this study, the backhoe managed to reduce fire temperature to 340 °C in a time of 120 min. This results in operational expenses due to constant contact of equipment with high fire radiation. Shutdown operational conditions improve with the use of a cooling agent. The FP Coal® product, in concentrations of 20 and 30%, has better cooling properties compared to water. This is reflected in the time required by both products to reduce the temperature of a fire of approximately 700 °C to a temperature lower than 60 °C, where FP Coal® is 20 min faster than water (Fig. 11). In addition, the difference between the two is that the FP Coal® product generates less vapor than water when applied to a fire. The products' penetration

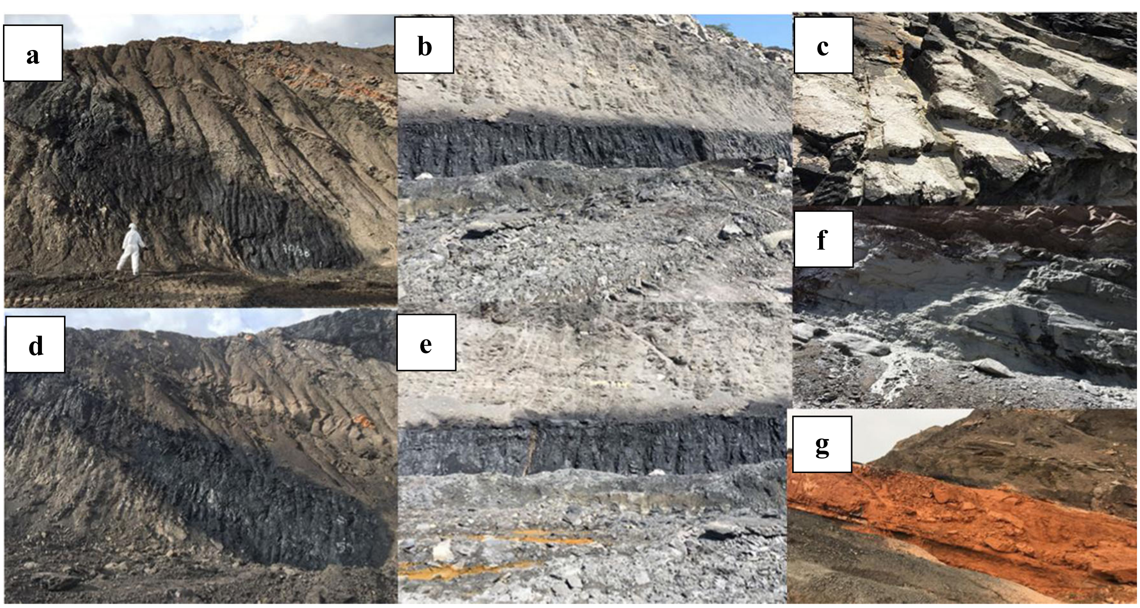


Fig. 8 **a** Sealing bitumen/water (70/30); **b** bitumen/brine (50/50% *v*/*v*); **c** cement/fine sand; **d** bitumen/water (50/50% *v*/*v*); **e** bitumen/brine (70/30% *v*/*v*); **f** cement/slaked lime; **g** clinker/slaked lime

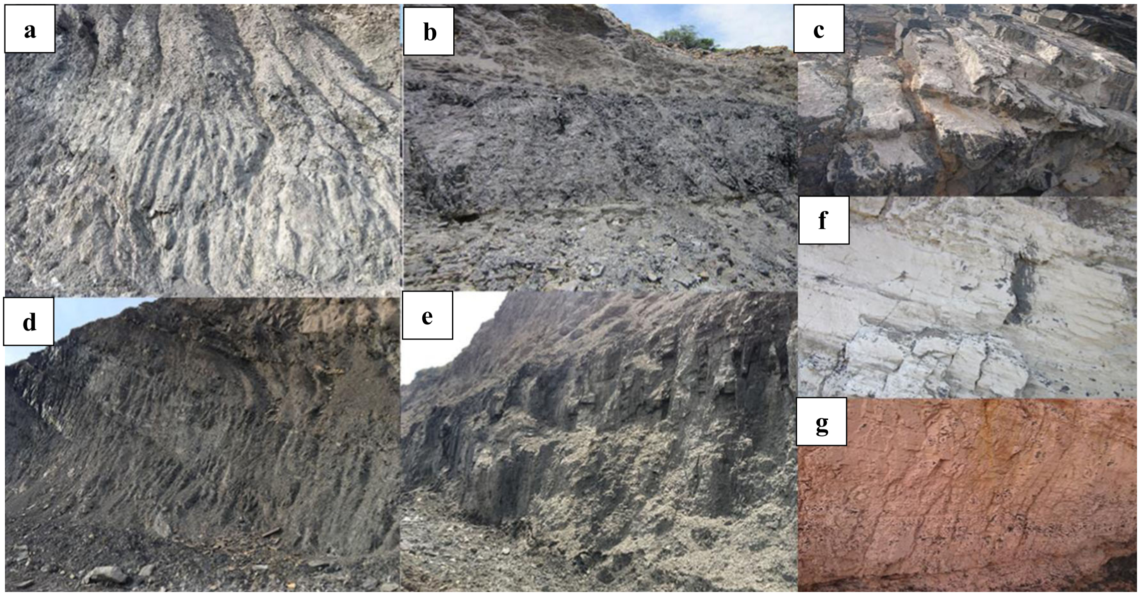


Fig. 9 **a** Sealing bitumen/water (70/30); **b** bitumen/brine (50/50% *v/v*); **c** cement/fine sand; **d** bitumen/water (50/50% *v/v*); **e** bitumen/brine (70/30% *v/v*); **f** cement/slaked lime; **g** clinker/slaked lime

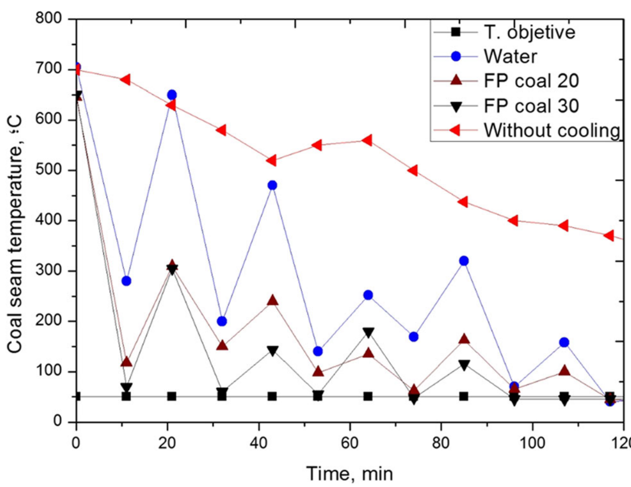
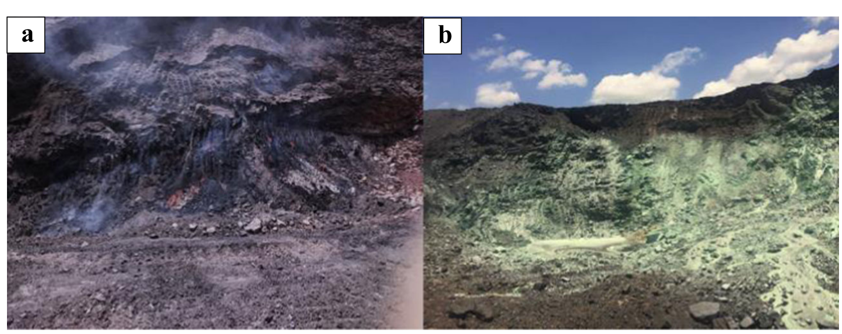


Fig. 10 Removal tests with and without cooling with water and FP Coal®

capacity (water and FP Coal®) is very low when the fire is attacked directly through the front, considering that only the coal seam surface layer cools down. This said, the synergy between cooling and removal processes facilitates fire extinction, by providing the backhoe operator with better working conditions and reducing the time of exposure to high temperatures and gas concentrations. The process of removal with cooling is only feasible for incipient fires and of medium magnitude, since these fires are at an early stage of propagation, therefore have failed to cover large areas and can be extinguished surface through this measure of control. On the other hand, fires of great magnitude thermodynamically are in an advanced stage of propagation, due to the mechanisms of heat transfer and chemical kinetics that allow fires to cover large areas at depth as time progresses. Therefore, for the extinction of these fires, other measures are required, such as a punctual attack in the home of the fire that is at depth.

Fig. 11 **a** Initial state of the mine fire; **b** fire extinguished by the intervention of the backhoe and FP Coal® solution



Conclusions

- Bitumen/brine (50/50% *v*/*v*) and bitumen/brine (70/30% *v*/*v*) were the products that achieved the best results after evaluating aspects, such as adhesion, resistance, wind erosion, and the thickness of layers formed after application; however, bitumen/brine (50/50% *v*/*v*) is the best option the company could implement, taking into account that the layer formed by bitumen/brine (70/30% *v*/v) is too thick, incurring unnecessary product costs and increasing the overall process cost.
- The sealing developed with the cement/slaked lime and clinker/slaked lime products did not provide satisfactory results as determined by the follow-ups, given the products presented very low adherence and consistency over time. In addition, they were strongly affected by wind erosion, due to energy concentration produced by the wind at the seam edges.
- Cement/fine sand sealing showed very good adhesion and consistency properties over time in spite of not being carried out correctly nor with the appropriate equipment. It was evident that the product reached high resistance in those areas where a homogeneous mixture resulted, which would be an excellent alternative to establish definitive seals inside the mine, especially in coal seams that would not be intervened later.
- For incipient or medium-sized fires, cooling is the best way to combat them. Cerrejón incorporated the application of the improved FP Coal® method using it at a 30% *v*/*v* as a result of this study, seeing how effectively and quickly fires can be put out, in a way that allows for an improvement in terms of the environmental impact represented in a reduction of greenhouse gases, and that is economic provided the reduction of costs and time of use of the backhoe.

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