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Korkinsk Brown Coal Open Pit as a Case Study of Endogenous Fires

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A B S T R A C T

Abrupt termination of the coal open pit operation is complicated in many cases by endogenous fires that not only cause significant damage to property but also worsen sanitation and hygienic conditions for human life in nearby settlements, as well as those for fauna and flora. Therefore, the purpose of the research was to prevent endogenous fires at Korkinsk brown coal open pit. In this connection, we used an analytical method to process the statistical data obtained from observations. The laboratory method included the study of coal samples for moisture exchange intensity by creating conditions with relative humidity up to 97 %, temperature up to plus 50°C and air speed up to 0.5 l/minute. Dependencies were determined for fire occurrence frequency, relative humidity, and average temperature of the air upon the time of day, the intensity of moisture evaporation and initial coal humidity on equilibrium coal humidity as well as the intensity of moisture absorption and equilibrium coal humidity upon initial humidity in different temperature periods. An environmentally friendly solution was created that featured good adhesion to the materials being coated, fire and explosion resistance. The results obtained make it possible to understand the causes and methods of fighting endogenous fires.

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1. INTRODUCTION

There is a fair amount of scientific theories and reasons for spontaneous coal combustion. The theory of absorption is the most credible and is based on oxygen absorption by coal matter. According to research, coal reacts not only with atmospheric oxygen but also with one contained in water [1]. Practical experience confirms this fact as wet coal self-ignites easier. Oxygen sorption by coal increases with the moisture content increase in the mineral to a particular value and vice versa. This is due to the intensification of electrochemical processes in the presence of a certain moisture amount.

As of now, numerous studies of coal self-ignition have been carried out. The issue was studied by leading scientists like Skochinsky and Makarov [1] and others [2-9]. Examinations have shown that coal adsorbs oxygen by its surface resulting in an exothermic reaction of carbon with oxygen ($C+O_2 \rightarrow CO_2$). Therefore, two factors caused the self-ignition process – the surface area of coal matter and the amount of oxygen contacting it. The higher is coal area, the more is the probability of its spontaneous combustion with approximately the same oxygen amount [1-8].

Spontaneous coal combustion may occur not only in areas of direct coal contact with airflows that are insufficiently intensive to remove accumulated heat. It may take place in areas well isolated at first glance and containing coal residues. The oxygen amount necessary for the reaction often penetrates a coal block through cracks during fluctuations of barometric pressure. The atmospheric pressure drop causes a pressure decrease in it. Air pressure in the confined area, which is in equilibrium with initial pressure in the open area, tends to equalize the resulting difference. At the same time, coal oxidation products pass via cracks in rocks [9-14].

Based on the theory of the "coal-oxygen" complex, coal ignitability depends on the intensity of oxidation process during coal reaction with atmospheric oxygen. The more intensive oxidation reaction, the more coal tends to spontaneous ignition [1, 5, 8].

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There are three phases of oxidation progress when using methodology [1], which allows observations over the coal self-heating process and is widely tested in practice: moisture evaporation from coal, intensive oxidation, and low-temperature combustion.

The first phase – moisture evaporation from coal – features insignificant oxygen sorption and emission of gaseous oxidation products. Oxygen taken by coal is consumed for adsorption, formation of water CO and CO_2. Adsorption prevails during this phase.

The second phase features an intensive increase of coal heating rate, oxygen uptake, and emission of CO and CO_2. During this phase, chemisorption is simultaneously observed with adsorption since oxygen is not only adsorbed but also significantly consumed to form CO and CO_2.

The third phase features decreased coal heating rate and intensive CO and CO_2 emission due to insufficient oxygen supply.

Temperature ranges for the above phases depend on coal metamorphism and atmospheric oxygen sorptivity [5,7,9,10,15]. Decreased metamorphism shifts these intervals to lower values and increases coal heating rate as well as the amount of absorbed oxygen and emission of oxidation products – CO and CO_2 per 1g of coal. Intensive oxidation of Korkinsk brown coals takes place at a temperature of >49 °C to > 69 °C [16].

Mining completion at Korkinsk brown coal open pit resulted in the appearance of endogenous fire seats that polluted the environment in the neighboring settlements and caused sliding of quarry benches. Up to now, there are no efficient methods and means to fight endogenous fires, which are acceptable for open pit conditions [16].

In this regard, the purpose of the research was to prevent endogenous fires at Korkinsk brown coal open pit aiming at improvement of the environmental situation in neighboring areas as well as the bench sliding prevention.

This article contains the data regarding endogenous fires at Korkinsk brown coal open pit over the period of 2012 to 2014. It identifies places of spontaneous combustion and evaluates antipyrogens used in Russia and abroad. Experimental data processing made it possible to determine dependencies for fire occurrence frequency, relative humidity, and average temperature of the air on the time of day, the intensity of moisture evaporation and initial coal humidity upon equilibrium coal humidity as well as the intensity of moisture absorption and equilibrium coal humidity upon initial humidity in different temperature periods.

Based on the results, an environmentally friendly solution was created that combines positive properties of all existing antipyrogens and inhibitors, varies in the composition according to application conditions, and features good adhesion to the materials being covered.

Practical relevance of the study covers the determination of parameters and conditions for spontaneous ignition of brown coal using Korkinsk open pit as an example and finding the solution with high adhesion, stability to high temperatures, and water repellence.

2. MATERIALS AND METHODS

The study covered 3 periods: analytical period, field period and laboratory period. During the analytical period, the data were assessed regarding endogenous fires at the open pit over the period of 2012 to 2014; the annual fire frequency was defined; climatic conditions were assessed in the open pit region.

This period also included evaluation of existing antipyrogens for brown coal and processing of laboratory results.

During the laboratory period, samples were prepared for laboratory tests to study the impact of the particle size distribution (0.25 mm to 0.5 mm, 0.5 mm to 1.0 mm, 1.0 mm to 2.0 mm, 1.0 mm to 3.0 mm, 0.0 mm to 6.0 mm, and 0.0 mm to 10.0 mm) on the intensity of moisture exchange by creating relative air humidity up to 97 %, at temperatures up to 50 ˚C and air speed up to 0.5 l/minute.

We studied the change in sorption capacity and chemical activity of usual Korkinsk coal and one activated by preliminary heating (50 to 70˚C) using the procedure developed at Skochinsky Institute of Mining [1, 17, 18].

Strength indicators of the designed formulation were measured by destructing 5 cylindrical specimens (50 mm in diameter, 100 mm long) by co-axial counter-directed indenters. The method comprised testing the specimens by the axial force created by two indenters (steel balls of 15 mm in diameter) until samples splitting, recording destructive force, measuring the separation surface areas according to Russia's State Standard (GOST) 24941-81 rocks. Methods for determination of mechanical properties by pressing with spherical indenters. Additionally, the area was measured for destructed rock zones in contact with indenters [19-22].

Ultimate strength during uniaxial expansion was measured according to Russian Patent No. 2435955. Ultimate strength during uniaxial compression and ultimate shear resistance without normal stresses (cohesion) were measured according to Russian Patent No. 2521116 [19-22].

The solution was testing for fire resistance and explosion safety by its application on the flammable surface and exposing to direct fire from a gas burner.

During the field period, brown coal samples weighing 25 kg each were taken from four quarry faces.

3. RESULTS

3. 1. Deposit Features Spontaneous coal ignition (endogenous fire) is typical for many collieries both in Russia and abroad.

Coal combustion on exposed coal surfaces, at warehouses and in coal piles, overburden spoil heaps cause both economic loss and environmental problems.

Korkinsk brown coal open pit is among the main environmental problems of the Chelyabinsk Region in Russia. Endogenous fires occurred at the open pit pollute the air in the town of Korkino and other regional settlements as well as in Chelyabinsk. Coal combustion products released into the atmosphere may affect humans, crops, fauna, and different materials [23, 24, 25].

Slides on pit walls threaten destruction of residential buildings and social facilities in nearby settlements [26, 27].

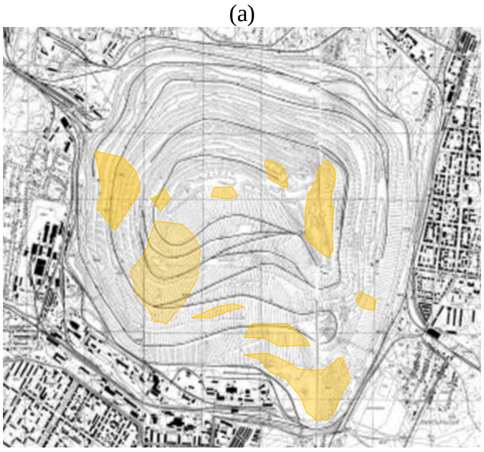
Brown coal from Korkinsk open pit contains rock and mineral inclusions (Figure 1): Al, Fe, Ca, Mg, Na, and K silicates, carbonates ($CaCO_3$, $MgCO_3$, $FeCO_3$, etc.), sulphates ($CaSO_4$, $FeSO_4$, $A1_2(SO_4)_3$, etc.), oxides (FeO, CaO, etc.), sulphides (FeS_2), organic minerals – humic acid salts (humates) and 46 % of carbon. Combustion heating value is 29 MJ/kg [16, 28].

There were 10 sites in the open pit prone to spontaneous combustion, where oxidation processes and fire spots emitted much heat, which resulted in the formation of carbon dioxide, benzapyrene, sulphur dioxide, hydrogen sulphide, sulphurous oxide (near fire-impacted areas). Their concentration exceeds MAC and causes rheum, cough, hoarseness, throat irritation, and specific after-taste. The last one is typical for high concentrations of bituminous substances, bleedings at a depth of 265 m to 345 m, which are linked genetically with oil shows. The issue of combating endogenous fires has become especially topical due to significant depth and closing the open pit (Figure 2).

3. 2. Evaluation of Climatic Conditions at Korkinsk Open Pit Taking into account the coal self-ignition theory, we studied climatic conditions at Korkinsk brown coal open pit, which featured meteorological variability. Climatic properties at the quarry depend upon atmospheric conditions in the neighboring area and are caused by various terrain forms, including mined-out area.

Figure 1. Brown coal mined at Korkinsk open pit

(a)



(b)

Figure 2. Korkinsk brown coal open pit: a – smog at Korkinsk open pit (March 2014); b – layout of possible self-heating areas

The largest amplitudes of temperature fluctuations were observed during summer and fall and were plus 12° to plus 15°, sometimes plus 20˚C to plus 25˚C. The amplitude of relative humidity daily fluctuations was 40 to 45% [29, 30].

Airflows moving over the open pit space and local flows formed due to uneven heating of individual quarry areas with specific terrain built the quarry wind pattern [31].

The intensity of local flows decreased at the quarry during winter. Moreover, temperature inversions appeared at its bottom after long cold periods and during gentle breeze/still air. During inversions, wind did not remove all harmful impurities from the quarry atmosphere, and they were accumulated in concentrations hazardous for human health. When winding, their large quantities were blown out of the open pit towards nearby settlements. During those periods, there were favorable conditions to form fog or smog as well as man-induced fires (Figure 2a).

Temperature increase in the inversion layer at the bottom of Korkinsk open pit-earth surface was up to plus 9˚C. Simultaneously, there was fog in the quarry that reduced visibility up to 4 m [16, 32].

Thus, different steps of oxidation process were the main sources of the quarry pollution.

Calculations have shown that up to 0.00135 m^3/hour of carbon monoxide may emit from one square meter of a fire-impacted zone [16].

Statistical data featured the number and locations of fires occurrence at Korkinsk open pit are given in Table 1.

Table 1 illustrates that most fires appear in burden-coal piles, coal slides, caved benches, broken faces, and coal storage sites.

Existing layer-by-layer mining of thick coal beds and using rock mass as a basis for placing railroads promoted the accumulation of significant pile volumes inside the quarry.

Coal outbreaks make a significant fire hazard, especially when the part of their thickness was mined in closed long faces. In certain cases, loosen coal was left in solid one due to poor bench dressing by a shovel bucket.

Previous observations at Korkinsk open pit have shown that the latent duration depended on the pile shape and dimensions, coal compaction degree and particle size distribution [32]. The above factors adjusted fresh air inflow into the mass and dissipation of generated heat.

Compaction of rocks and increasing their outer surface promoted the fire hazard decrease. On the contrary, coarse rock pieces in the lower part of piles(material segregation) and their significant height created favorable conditions for spontaneous combustion seats [33-36].

In addition to the above factors, quarry microclimate significantly affected the fire hazard of mining operations. It featured extreme variability of air temperature and humidity, wind speed and direction, solar radiation and other factors [34].

The frequency of endogenous fires increases during the periods with increased air humidity at the quarry, especially during autumn and spring, when air humidity drastically increases after warm sunny days. In this case, somewhat dried coal intensively absorbs water vapor and causes the temperature increase inside the loosed rock pile [32].

However, Figure 3 illustrates the different numbers of fire seats in different years. This is due to the implementation of fire-fighting measures in different quarters. At the same time, the intensity of further self-ignition progress at high temperatures poorly depended upon air temperature that could explain the appearance of endogenous fires in quarries during the cold period [12, 15].

TABLE 1. Data about endogenous fires at Korkinsk brown coal open pit over 2012 to 2014

Observation period	Number of fires				Total area of a fire-impacted zone, m^2
	Total	In piles	In coal blocks	In slides	
			2012		
Quarter 1	44	22	20	2	199435
Quarter 2	37	18	17	2	171710
Quarter 3	28	15	12	2	164910
Quarter 4	15	12	1	2	104660
			2013		
Quarter 1	15	12	2	1	92400
Quarter 2	30	25	4	1	109100
Quarter 3	27	22	4	1	104600
Quarter 4	23	20	2	1	23000
			2014		
Quarter 1	19	12	6	1	104200
Quarter 2	19	12	6	1	104200
Quarter 3	18	11	6	1	10320
Quarter 4	17	12	3	2	7360

3. 3. The Study of Brown Coal at Korkinsk Open Pit

Laboratory study of the effect of the particle size distribution on moisture exchange intensity has shown that the air volume passed through coal particles sized 0.25 to 0.5 mm; 0.5 to 1.0 mm; 1.0 to 2.0 mm; 1.0 to 3.0 mm; 0.0 to 6.0 mm and 0.0 to 10.0 mm was 0.7 l per minute.

At the same time, coal particles sized 0.25 to 0.5 mm featured maximum evaporation intensity. For the first 3 hours, it was 1.1% per hour. The maximum evaporation intensity (0.8 % per hour) was for coal particles 3 to 6 mm.

Thus, the particle size distribution of coal significantly affected moisture absorption intensity. This impact was explained by the fact that the total surface area of coal particles per volume unit increased with the particle size decrease. On that basis, fine coal fractions were more dangerous regarding fire occurrence. Visual observations over the places, where endogenous fire occurred, have confirmed this conclusion (Figure 4).

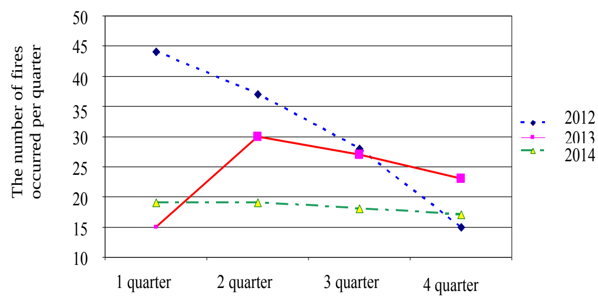


Figure 3. The fire occurrence frequency at Korkinsk brown coal open pit

Figure 4. Self-heating area (March 2014)

Fire seats in loosen coal piles, burden-coal piles and in slides occurred usually at the border between the lower coarse part and upper fine fractions.

At the same time, increased airflow speed resulted into increased moisture exchange intensity (Figure 5).

Hygroscopic equilibrium (complete termination of moisture exchange) attained between coal and air at a temperature of plus 40, plus 25, plus 10, 0 and minus 10˚C. Coal particles sized 1mm to 3mm were put in vessels, and air with different moisture content was pumped through them at a speed of 0.5 l per minute.

Research results have shown that coal hygroscopic equilibrium was caused mainly by relative air humidity. Meanwhile, it depended upon ambient temperature. At the same time, evaporation of moisture from Korkinsk coal, which was pumped with completely dry air, stopped at moisture content 1.5 to 2.1% in coal.

The intensity of moisture exchange decreased in due time, when coal humidity became close to the moisture content in the equilibrium state. In certain cases, coal could lose more than 1% of moisture during the first hour. In 20 to 50hours, coal lost moisture 0.005% and less per hour.

Maximum evaporation intensity was at a temperature exceeding plus 40˚C. Moisture evaporated less intensively at a temperature of plus 25, plus 10, 0 and minus 10˚C. Experiments have shown that temperature insignificantly affected evaporation intensity within these limits.

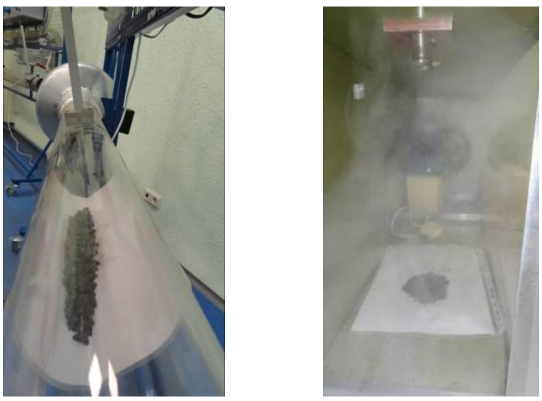


Figure 5. Laboratory study of the size distribution effect on moisture exchange intensity

It was found out that the maximum intensity of moisture absorption took place at a temperature of 0 to plus 25˚C. Moisture was absorbed with less intensity at a negative temperature. Coal virtually did not absorb moisture at plus 40˚C.

Relative humidity and temperature were taken for Korkinsk open pit using statistical meteorological data typical for Chelyabinsk (Figures 6 and 7), which were used when calculating hygroscopic characteristic [29].

Precipitation factor played an important role in activating the self-ignition process during moisture decrease in oxidizing coal. At the same time, fall-out ambivalently influenced the temperature behavior of self-heating minerals in bulk (Figure 8). Self-heating temperature dropped during the initial rainfall period due to heat absorption by moisture. After a certain period, self-heating intensity drastically increased that may be explained by intensification of electrochemical oxidation taking into account oxygen content up to 30% in rainwater. However, self-heating can attenuate and completely stop during long periods and significant precipitation amounts. It was noted that moisture content in ore could increase from (6 to 7%) up to (14 to 20%).

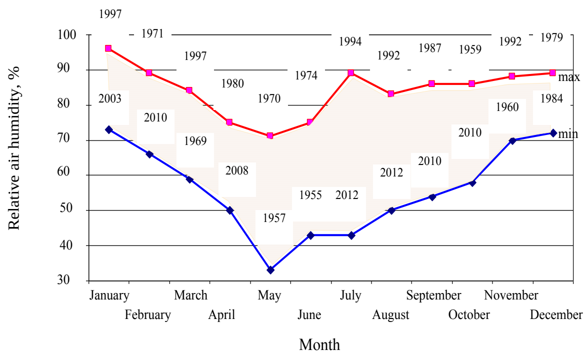


Figure 6. Relative humidity, %

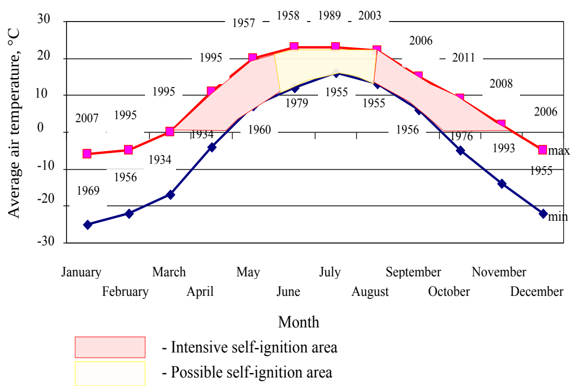


Figure 7. Average air temperature, °C

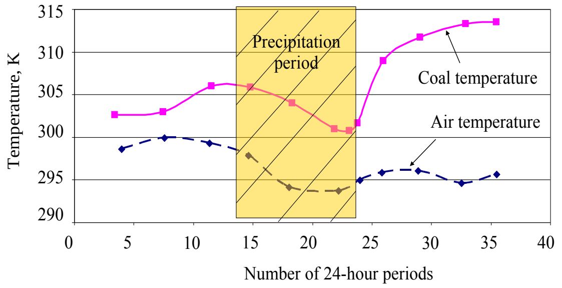


Figure 8. Change in coal and air temperature during the precipitation period

Experimental data processing made it possible to determine the following coal hygroscopic characteristic as a function of ambient relative humidity and temperature (Figure 9).

Figure 10 illustrates the function of moisture evaporation intensity.

Figure 10 shows that the intensity of moisture evaporation from coal depends on the initial and equilibrium moisture content. A sharp increase in moisture evaporation up to 0.6% per an hour in the temperature range from minus 10 to plus 25˚C is due to an increase in the initial moisture content of the coal over 2%, with a constant value of equilibrium moisture content (4%). The reverse process is observed when the equilibrium moisture content of coal rises above 4%, and when the equilibrium moisture content reaches 12%, the evaporation rate stops.

Figures 11 and 12 show the function of moisture absorption intensity.

When the evaporation rate decreases (Figure 10), the process of moisture absorption rate starts (Figure 11).

That is, in the temperature range from 0 to plus 25˚C, equilibrium moisture content of 12% and initial moisture coal content of 2%, the maximum intensity of moisture absorption occurs (1% per an hour, while the intensity of moisture evaporation is stopped). The process of moisture absorption intensity decreases up to 0.6% per an hour when the temperature drops from 0 to minus 10˚C (Figure 12).

The above dependences allowed defining quantitative significance of moisture exchange in the heat balance of self-heating coal for particular conditions.

The moisture exchange share may be set in the heat balance only by comparing this value with oxygen sorption heat by coal. The last one depends upon oxygen sorption rate that features the coal chemical activity.

Changes in sorption capacity and chemical activity have shown that even insignificant heating increased the chemical activity of brown coal several times. This property explained frequent fire repetitions in the areas located in immediate vicinity of fire-impacted zone.

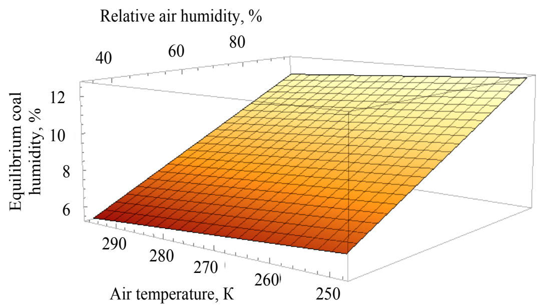


Figure 9. Moisture content in coal in equilibrium state (equilibrium coal humidity)

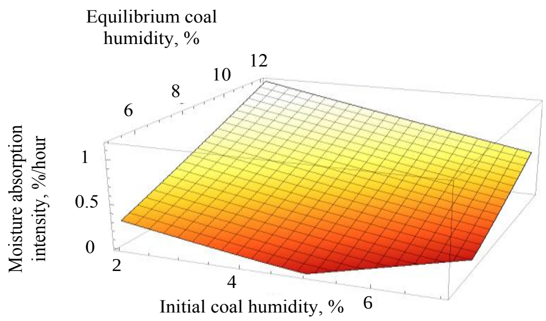


Figure 11. Moisture absorption intensity at temperatures from 0 to plus 25°C

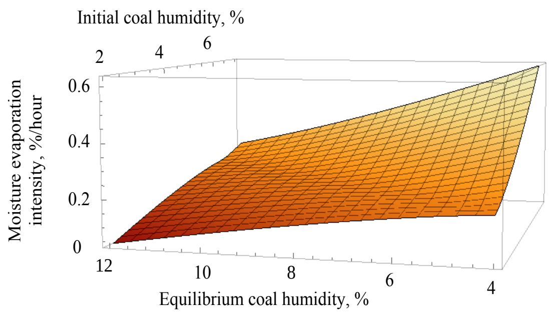


Figure 10. Moisture evaporation intensity at temperatures of minus 10 to plus 25°C

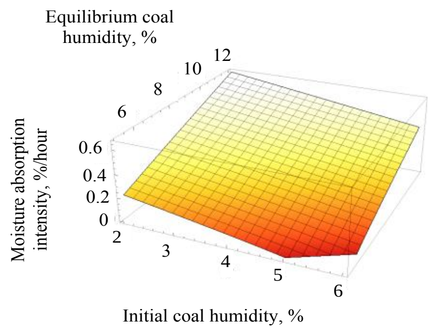


Figure 12. Moisture absorption intensity at a temperature minus 10 to 0°C

Sorption rate constant calculated by the specified procedure was (0.07 to 0.12mm/g.h).

Calculations performed using the above data have established that minor (less than 0.02%/h) intensity of moisture evaporation from coal was necessary to compensate oxygen sorption heat. However, the coal open pit featured extreme variability in microclimate parameters that created conditions, where sorption heat of water vapor could significantly exceed oxygen sorption heat.

Thus, laboratory tests have confirmed that moisture exchange at Korkinsk open pit could affect the initial period (1^{st} and 2^{nd} phases) of self-heating quite significantly and even decisively in some cases.

Taking the foregoing into consideration, the possibility to decrease the intensity of moisture exchange between air, water, and coal due to its treatment with solutions is of significant interest when designing means and ways for endogenous fire prevention. That is why antipyrenes to be tested should satisfy the following requirements: to prevent oxygen sorption by coal with simultaneous decrease of the moisture exchange intensity, and to save moisture sometimes by preventing its evaporation from coal.

3. 4. Analysis of Existing Antipyrogens for Brown Coal Numerous methods and ways were used for endogenous fire prevention at Korkinsk open pit, both engineering methods and chemical/mineral substances capable to decelerate initiating effect of coal active organic and mineral ingredients, for example, peroxides and iron compounds, etc. [15, 16, 32].

Various reagents were analyzed as antipyrogens (Table 2) in different combinations and concentrations, neutralized black contact (NBC), the NBC mixture with calcium chloride ($CaCl_2$) as well as aqueous solutions of organic and inorganic acids, chlorides, ammonium salts, sodium fluoride, triethanolamine, polyvinyl acetate, polyacrylamide, K-4, production wastes for oxyethylated fatty acids, carboxymethyl cellulose [37-46].

TABLE 2. Antipyrogen solutions used in the world

No.	Antipyrogen solution	Actual ignition point, °C
1.	Coal impregnated with tap water	192
2.	Dry coal	243
3.	Coal impregnated with 1 % solution of MF-17 resin	287
4.	Coal impregnated with 2 % solution of MF-17 resin	250
5.	Coal impregnated with 3 % solution of MF-17 resin	262
6.	Coal impregnated with 1 % solution of MF-17 resin with oxalic acid addition	299
7.	Coal impregnated with 2 % solution of MF-17 resin with oxalic acid addition	283
8.	Coal impregnated with 1 % liquid glass solution	250
9.	Coal impregnated with 3 % liquid glass solution	250
10.	Coal impregnated with 5 % liquid glass solution	287
11.	Coal impregnated with 7 % liquid glass solution	225
12.	Coal impregnated with aqueous solution (5 % $CaCl_2$, 2.5 % liquid glass)	275
13.	Coal impregnated with aqueous solution (10 % $CaCl_2$, 1 % MF-17 resin)	350
14.	Coal impregnated with aqueous solution (10 % $CaCl_2$, 1 % MF-17 resin)	260
15.	Coal impregnated with aqueous solution (10 % $CaCl_2$, 1 % MF-17 resin, 1 % liquid glass)	323
16.	Coal impregnated with aqueous solution (5 % $CaCl_2$, 1 % MF-17 resin)	320
17.	Coal impregnated with aqueous solution (5 % $CaCl_2$, 1 % MF-17 resin, 1 % liquid glass)	290
18.	Coal impregnated with aqueous solution (5 % $CaCl_2$, 1 % liquid glass)	280
19.	Coal impregnated with aqueous solution (10 % $CaCl_2$, 1 % liquid glass)	295
20.	Coal impregnated with 1 % soda solution (Na_2CO_3)	310
21.	Coal impregnated with 5 % soda solution (Na_2CO_3)	310
22.	Coal impregnated with 10 % soda solution (Na_2CO_3)	320
23.	Coal impregnated with 20 % soda solution (Na_2CO_3)	330
24.	Coal impregnated with aqueous solution (1 % soda Na_2CO_3, 1 % liquid glass)	315
25.	Coal impregnated with aqueous solution (20 % soda Na_2CO_3, 1 % liquid glass)	320
26.	Coal impregnated with 10 % table salt solution (NaCl)	315
27.	Coal impregnated with 1 % table salt solution (NaCl)	-
28.	Coal impregnated with 5 % table salt solution (NaCl)	-

NBC both pure and mixed with $CaCl_2$, lime were the most promising antipyrogens among the studied ones [15, 16, 32].

The NBC demulsifier is an aqueous solution of ammonium salts of water-soluble sulphonic acids, an oil-refining product. It is a dark brown liquid with ammonia odor, non-toxic, free from resorptive impact, non-flammable, soluble in water in any proportions. Its freezing point is minus 17°C, the reagent has good wetting and adhesion properties.

NBC antipyrogen was successively used previously for fire prevention at Korkinsk open pit but was not widely used due to its low applicability. [16].

After studying the effect of different substances on coal porosity, it was found that film-forming compositions decreased the intensity of moisture exchange between coal and air while $CaCl_2$ featured plugging properties. Blocking the access of air oxygen to active surfaces was carried out by forming hardly soluble calcium sulphate and calcium salts of sulphonic acids due to NBC interaction with $CaCl_2$ [37].

$$2RSO_3NH_4 + CaCl_2 \rightarrow (RSO_3)_2Ca \downarrow + 2NH_4Cl$$

However, coal treatment with $NBC+CaCl_2$ mixture made it impossible due to high reaction rate with sedimentation.

It is possible to use appropriate oxidants (more active than water) in the low-temperature oxidation zones and to create a thickened film near coal surface, which prevents further oxidation in coal depth.

Lime as a chemically active oxidant reacts with brown coal 3 to 9 times more intensively than with hard coal. [32] Owing to high dispersion, lime is the best isolating material for the medium-temperature oxidation zone as compared with sandy-argillaceous or argillaceous pulps.

For ignition and combustion, lime (in particular, white lime or limestone) is a good fire extinguisher. Lime solution successfully prevents gas flares and explosions when extinguishing seats with high temperature [15].

Lime has a significant drawback – it quickly precipitates from the solution and may be neutral regarding coal oxidation or catalyze oxidation in certain conditions. [1, 40, 41, 45] Even 7 to 10% lime solutions should be intensively mixed to supply the suspension with desired concentration into coal block. The lack of mixing results in the lime content in the solution and injection quality.

Liquid glass solutions 1 to 7% do not yield good results when treating brown coal. Application of liquid nitrogen is short-term during extinguishing endogenous fire, which is accompanied with temperature drop inside the block and strong deoxidation that results in more powerful new fire after a while [42, 45- 48].

All the above solutions have a common shortage: they turn in gels after exceeding the flash point for impregnated brown coal. Gels are decomposed in the fire seat (plus 500 to plus 1000°C) and turn into grey sand-like substance [1].

Mud accumulation widely used in flat-lying seams is not efficient since it is difficult to achieve uniform distribution of slushing pulp over cracks. Besides, clay and sand precipitate, filled cavities and cracks may be easily washed with water [15, 17, 49].

Efficiency of fire isolation using clay depends upon the layer thickness and particle size of inert material. Non-uniform stocking thickness is a significant drawback for this method as well as high transportation costs. Due to the difference between the slope angle for inert material (30° to 40°) and bench (75° to 80°), most clay drops to the bench basis and forms a thick layer there. The upper part of the bench is not covered. Material loses its properties when exposed by precipitate and solar radiation.

Fire extinguishing with water does not yield the result since self-ignition seats become more active with the increase of pit water acidity. [50, 51] Thus, there were attempts to extinguish endogenous fire seats using quarry water with pH 2 to 3 at Korkinsk open pit. However, flooding the seat with water resulted in temperature drop at first and abrupt repeat of endogenous fire soon. That is why using water (quarry or process) to extinguish endogenous fire events is inappropriate; its result is temporary (5 to 7 days). It should be noted that the most intensive coal self-ignition was observed at coal moisture approx. 2 to 4% [32, 35, 42, 50].

3. 5. Surveying a New Way to Fight Man-Induced Fires at Korkinsk Coal Open Pit

Today, preventing treatment with antipyrogens or inhibitors does not have a meaningful effect in decreasing the number of self-ignition seats for coal pillars of Korkinsk open pit. Due to rock pressure, coal block crumbles away and form new non-treated surfaces accessible for oxygen effect, which may result in coal spontaneous ignition under certain conditions.

Examinations have established that the treatment with film-forming and plugging substances provided the decease of coal chemical activity by 85%. Moreover, the solution resulted during the treatment formed an airtight layer. However, insulating film lost its tightness after a short time, allowed air and water to pass through due to its destruction caused by various factors (water flow, cliff debris, block motion, wind) [6, 9].

It is possible to prevent coal spontaneous combustion by its strengthening with solidifying solutions featuring high adhesion, stability to high/low temperature, outside environment and rockslides. [5, 10, 15, 30, 32] In this case, it was possible to attain the decrease in the susceptibility to spontaneous combustion for the coal treated with such solutions due to increase of the coal block strength and stability, formation of predominantly coarse fractions during its destruction and decreasing coal sorption capacity. Neutral metals could prevent oxidation processes.

An environmentally friendly solution was designed for Korkinsk open pit. It combined positive properties of all existing antipyrogens and inhibitors and varied in composition according to the above factors (Figure 13).

Dissolution of used components results in formation of calcium acetate $(C_2H_3O_2)_2Ca$, silicic acid H_2SiO_3, lactic acid $nC_3H_6O_3$. Depending upon coal oxidation degree, neutral metal Al may be also used.

The designed solution was tested to define the efficiency of its application in simulated process and climatic conditions.

All experiments were carried out using heated activated (plus 227˚C) and non-activated samples of coal taken from Korkinsk open pit (Figure 14).

Initially, we measured coal self-ignition temperature by putting samples into a metallic cylinder and uniform heating. When the first ignition signs appeared, fire supply was stopped, and the temperature was measured using the laser pyrometer, which was plus 227˚C.

Then, work solution was supplied on heated sample using a compressor and a hopper gun.

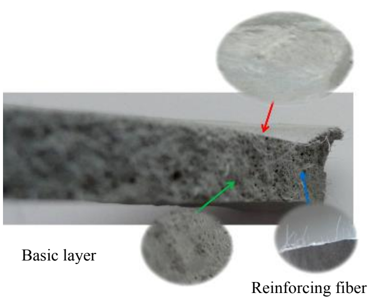


Figure 13. Solution for endogenous firefighting at Korkinsk coal open pit

Figure 14. Coal activated samples with temperature plus 227 °C

When the ignition area surface was treated with the prepared solution, significant extinguishing was observed as well as considerable heat absorption from 4,500 to 6,000kJ. Besides, solid dense coating was formed (Figure 15) and prevented oxygen and water ingress.

The material hardened when coating the entire surface or after it. According to exact composition of the solution, it looked like a point coagulant during application, which adhered to the rock and to itself. As a rule, the material dried in the air and solidified during (8 to 24) hours depending on the additives used. To visualize the application place, it is possible to use a dye.

The resulting hard coating was tested for strength, dissolution (decrease of water permeability due to the particle void decrease) and ignitability.

High content of solids in the solution was ideal for fire extinguishing or fighting. The natural mineral basis did not ignite by its nature even after long and direct exposure by a burner, which was also revealed during the experiment (Figure 16).

Solidified solution may form long-time coating or membrane over the material being protected, thus preventing emission of any harmful substances, gases, and smells; prevents the possibility of fire occurrence; material moving or spraying, for example, due to wind or precipitation. It prevents penetration of any substances in the material and strengths solid mass slopes.

Figure 17 and Table 3 illustrates the research results for the solidified solution.

Figure 15. Solid surface formation over the coal ignition area

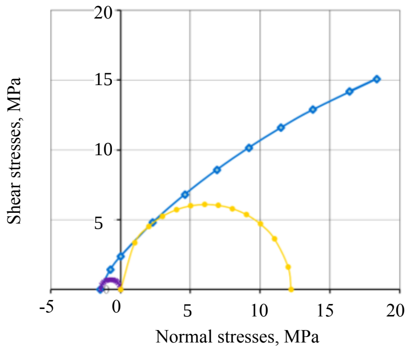
(a) (b)

Figure 16. Solution during ignition testing

(a)

(b)

(c)



(d)

Figure 17. Results of physical and mechanical tests of solution samples: a – hydraulic press; b, c – crack formation in samples; d – strength certificate.

TABLE 3. Strength indexes of KKV solution

Sample number	Ultimate strength during uniaxial extension, MPa	Ultimate strength during uniaxial compression, MPa	Ultimate shear resistance without normal stresses, MPa
1	1,81	13,18	3,15
1-1	1,24	8,64	2,12
2	1,45	14,45	2,98
2-1	1,35	11,68	2,58
3	1,41	13,14	2,80
Average value	1,46	12,22	2,73
Number of tests		5	
Variation factor	14,6	18,3	14,7

By analyzing results given in Figure 17 and Table 3 it is possible to conclude that the solution is ductile (ultimate strength during uniaxial extension is 1.46 MPa) and rigid (ultimate strength during uniaxial compression is 12.22 MPa, shear resistance without normal stresses is 2.73 MPa).

Thus, the recommended thickness of the applied solution layer on the treated surface depends upon the time, when the material should remain coated. For example, the layer thickness should be 5 mm to isolate the material for up to 30 days, 10 mm – for 31 to 180 days, 15 mm – 181 and more days.

4. DISCUSSION

Anthropogenic fires are a serious factor of environment contamination, and there is still no universal way to fight them [52-56]. Most miners face this problem, especially when mining works stop in an open pit. Man-induced fires in Korkinsk brown coal open pit are very dangerous; approximately 0.00135 m^3/hour may emit from 1 m^2 of a fire-impacted zone; and totally, up to 140 m^3/hour of harmful impurities may release due to coal spontaneous ignition and affect nearby settlements.

It was found that coal grain size distribution considerably affects the intensity of moisture evaporation, which was observed as the highest for coal fineness of 0.258 mm to 0.5 mm and is the lowest for coarseness of 3.0 mm to 6.0 mm. This phenomenon is explained by increase in total area per volume unit for the surface, which is the most prone to self-ignition. Therefore, it may be considered that fine coal fractions are the most dangerous regarding the fire. In most cases, they are in rockslides on the border between upper and lower coarse-size fractions as well as in burden-coal piles, abandoned faces. At the same time, the intensity of moisture absorption is observed at a temperature of 0°C to plus 25°C and is virtually stopped at plus 40°C.

During rainfall, self-heating temperature decreases due to heat absorption by water. After a certain period, the intensity of self-heating drastically increases. This phenomenon may be explained by the intensification of electrochemical oxidation processes considering the oxygen content up to 30% in rainwater. However, self-heating may completely stop during long precipitation, but coal humidity may increase up to 20%.

Our study has confirmed that moisture exchange could affect the initial period (1st and 2nd oxidation phases) of self-heating quite significantly and even decisively in some cases.

The assessment of antipyrogens that are applied globally revealed that the materials with film-forming effect and plugging properties are the most efficient and make it possible to decrease coal activity by 85%. The solution combines all positive properties of all existing antipyrogens and forms a rigid (ultimate strength during uniaxial compression is 12.22 MPa, shear resistance without normal stresses is 2.73 MPa), non-combustible, explosion-safe, ductile (ultimate strength during uniaxial extension is 1.46 MPa) layer, which is formed by calcium acetate $(C_2H_3O_2)_2Ca$, silicic acid H_2SiO_3, lactic acid $nC_3H_6O_3$. Depending on coal oxidation degree, neutral metal Al may be used as well.

5. CONCLUSIONS

Summing up, we can conclude that the fractional composition of coal significantly affects the intensity of moisture evaporation: the maximum was observed for coal with fractions of 0.258-0.5 mm, the minimum was 3.0-6.0 mm. This is due to the increase in the total surface area, which is most likely to spontaneous combustion, per unit volume. Therefore, areas with talus, rock-coal heaps, abandoned slaughterhouses, in which the bulk of the fine fraction is concentrated, can be attributed to the most fire hazardous items . At the same time, the intensity of moisture absorption is observed at the temperatures from 0˚C to plus 25˚C and varies from 0 to 1% per an hour, and when it reaches plus 40˚C it practically stops. However, a negative temperature from 0˚C to minus 10˚C slows down the process of moisture absorption by 40 %.

The data obtained confirm that, under the conditions of the Korkinsky coal mine, moisture exchange can have a significant effect on the self-heating of coals.

Taking into account the above, as well as the advantages and disadvantages of antipyrogens existing in the world for brown coals, a solution has been developed that has the following strength properties, namely: tensile strength in uniaxial tension is 1.46 MPa, ultimate strength in uniaxial compression is 12.22 MPa and average tensile strength shear without normal stresses is 2.73 MPa. It will be possible to strengthen the slopes and isolate them from external influences, which will lead to a reduction in the number of endogenous fires in the Korkinsky open-pit mine, and as a result, to a decrease in emissions of pollutants from coal combustion into the atmosphere.

The dependencies for fire occurrence frequency, relative humidity and average temperature of the air upon the time of day, the intensity of moisture evaporation and initial coal humidity on equilibrium coal humidity as well as the intensity of moisture absorption and equilibrium coal humidity upon initial humidity in different temperature periods contribute to the theoretical study of endogenous fires and makes it possible to understand the essence of their occurrence and design efficient ways and means to fight them under various conditions.

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Persian Abstract

چکیده

خاتمه ناگهانی عملیات استخراج روباز ذغال سنگ در بسیاری از موارد با آتش سوزی های درون زا پیچیده است که نه تنها صدمه قابل توجهی به اموال وارد می کند بلکه شرایط بهداشتی و بهداشتی را برای زندگی انسان در سکونتگاه های مجاور و همچنین شرایط مربوط به جانوران و گیاهان گیاهی بدتر می کند. بنابراین ، هدف از تحقیق جلوگیری از آتش سوزی های درون زا در گودال روباز زغال سنگ قهوه ای کورکینسک بود. در این ارتباط ، ما از یک روش تحلیلی برای پردازش داده های آماری بدست آمده از مشاهدات استفاده کردیم. روش آزمایشگاهی شامل مطالعه نمونه های ذغال سنگ برای شدت تبادل رطوبت با ایجاد شرایط با رطوبت نسبی تا ۹۷٪ ، دما تا ۵۰ درجه سانتیگراد و سرعت هوا تا ۰٫۵ لیتر در دقیقه بود. وابستگی ها برای فرکانس وقوع آتش سوزی ، رطوبت نسبی و متوسط دمای هوا بر زمان روز ، شدت تبخیر رطوبت و رطوبت اولیه ذغال سنگ بر روی رطوبت ذغال تعادل و همچنین شدت جذب رطوبت و رطوبت ذغال تعادل بر اساس مقدار اولیه تعیین شد. رطوبت در دوره های مختلف دما یک راه حل سازگار با محیط زیست ایجاد شد که دارای چسبندگی مناسب به مواد پوشش داده شده ، مقاومت در برابر آتش و انفجار است. نتایج به دست آمده درک علل و روش های مبارزه با آتش سوزی های درون زا را ممکن می کند.