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Assessment of Spontaneous Combustion Risks Associated with Water-Immersed Coal in the RV Seam of the Raniganj Coalfield

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Abstract

The swift extraction from underground coal mines in the Raniganj coalfield (RCF) encounters various safety challenges, including multi-seam operations, extraction of water-logged seams, areas where upper seams have been depleted, strata management issues, subsidence, ventilation problems, heat, humidity, spontaneous combustion, and mine fires. Among these challenges, many underground coal mines continue to operate after dewatering the coal seams for production purposes. Spontaneous combustion poses a significant risk in the dewatered coal seams of underground mines, impacting the safety of both the mines and the miners. This study aims to assess the risk of spontaneous combustion in a water-immersed coal seam of RCF by conducting proximate analysis, TGA/DSC, FTIR studies, and water analysis. One coal sample was obtained from the RV seam at the Kottadih coal mine in RCF and was immersed in tap water at a ratio of 1:10. The water-immersed coal samples were removed after 15, 30, and 90 days for sample preparation and other experimental investigations. The experimental results indicate that the water-immersed coal samples exhibit optimal moisture levels (4–8%), a higher volatile matter content (>30.0%) compared to fresh samples, and a gradual decrease in the ignition temperature of the water-immersed coal over time. There is an increase in concentrations of functional groups such as Ar-, -CHO, >C=O, and -C=C- due to the adsorption of dissolved organic compounds onto the coal surface. All analyses suggest that the rise in organic compounds contributes to the accelerated risk of spontaneous combustion.

1. Introduction

India is the second largest coal producer in the world and coal is mainly used in coal-based thermal power plants [1,2]. However, as the production progresses several technological, economic and environmental problems arise i.e., environmental pollution, acidic mine drainage, coal mine fires, and land subsidence etc [3-8]. Among all these issues the coal mine fires are a major issue to Indian coal mining industry for several decades [9,10]. The main cause of coal mine fires is the spontaneous combustion of coal which is a natural oxidation process in which coal oxidizes at a slow rate resulting to an exothermic reaction by the release of a small amount of energy [11-13]. This small amount of free energy gradually accumulates in the coal mines leading to a chemical reaction known as spontaneous combustion and eventually causing a coal mine fire [14,15]. Various literature studies on spontaneous combustion of coal reveals that the problem of coal mine fire increases in water immersed coal/ flooded mines due to its change in physical and chemical properties. Many water logged coal seams are dewatered for mining activities to achieve the country's coal demand. It was observed that after dewatering of water logged coal is dried out due to the adsorption of water vapour [16,17]. The moisture content of

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coal also increases due to water logging on coal. Thus, the moisture in coal was gradually lost through evaporation. Due to this loss of moisture the coal showed different degrees of drying and shrinkage and many cracks appeared on the surface. Long-term water logging on coal can increase the concentration of –OH. –C=O and other organic functional groups. The increased functional groups get attached to the coal cracks by chemical adsorption. This physico-chemical change in coal lowers its ignition temperature and makes it susceptible to spontaneous combustion which ultimately results in coal mine fires [18,19]. Researchers worldwide use various small- and large-scale laboratory methods to study the spontaneous combustion of coal. These methods include the crossing point temperature (CPT) method, differential scanning calorimetry (DSC), differential thermal analysis (DTA), thermogravimetric analysis (TGA), Russian U-index, Olpinski index in Russia, and R70 index, FT-IR. [20-26].

However, authors have used CPT, DSC, and TGA methods to determine the self-heating propensity of raw and water-immersed coal, due to their wide acceptability in terms of accuracy. Fourier transform infrared spectroscopy (FT-IR) is a method used to classify carbon by identifying the organic functional groups present for characterization. It can reveal the types and arrangements of hydrogenated carbon structure, hetero-atomic functional groups, and lattice knowledge. Therefore, this research focuses on the spontaneous combustion characteristics of raw and water-immersed coal, to predict the spontaneous combustion propensity dewatered coal of RCF**.**

2. Materials and Method

2.1. Sample collection and preparation

One coal sample is collected from a Kottadih Colliery of RCF following Indian standards. The collected coal sample was divided into two parts and the first part of sample is crushed to particle size of (-) 212 micron in laboratory condition by minimising aerial oxidation to stored in an air tight container for different experimental analysis. The other part of fresh coal sample was immersed in a container with coal: tape water in the ratio of 1:10 in the laboratory. The water immersed coal sample and water was removed from the container after certain time interval i.e., 15, 30 and 90 days for different experimental analysis. The water immersed coal samples kept for 24hr in air dried conditions and samples collected in different time intervals from immersed water were prepared to particle size <212 micron for above experiments [27-32]. The tap water and collected water samples were studied to investigate the changes in water quality parameters after immersion of coal. The complete process experimental process is shown in Figure 1.

A total of twelve parameters of water quality were determined, including pH, electrical conductivity (EC), total hardness (TH), calcium ion, magnesium ion, chloride ion, nitrate ion, sulfate ion, sodium ion, potassium ion, etc. The proximate analysis of both fresh and water-immersed coal was conducted according to Indian Standard IS: 1350 (Part 1) – 1984 for basic coal composition, i.e., moisture (M), ash (A), volatile matter (VM), and fixed carbon (FC) [33-34]. The results of the proximate analysis of fresh coal samples and water-immersed samples are presented in Table 1.

2.2. Spontaneous Heating Experiments

2.2.1. Crossing point temperature (CPT)

The spontaneous combustion characteristics of coal were determined using CPT methods according to Director General Mine Safety (DGMS) rules and circulars. The CPT experimental setup comprises a temperature controller, electric heater, glycerine bath, cylindrical combustion reactor tube, gas outlet tube, air motor, oxygen gas supply, and computer-based software. Glass wool is placed at the bottom of the combustion tube to trap dust and provide insulation. A 20-gram coal sample with a particle size of (-) 212 microns is carefully poured into the combustion tube, followed by covering the coal sample with another layer of glass wool. The coal sample is immersed in a glycerine bath and heated at a rate of 1 °C/min with a flow rate of 80 cc/min of oxygen gas. Continuous stirring of the glycerine bath is maintained by passing air through a small air motor, ensuring a consistent temperature throughout the process [35]. The temperatures of the glycerine bath and the coal are meticulously recorded using computer-based software to determine the CPT of the coal. The CPT values for all samples are presented in Table 2.

Table 1. Results of proximate analysis data of fresh and water immersed coal sample

Sample Name	WID	Sample Code	M %	VM %	Ash %	FC %
Kottadih Colliery/ KR5	---	KR5/0D	6.06	36.75	15.12	42.07
	15 days	KR5/15D	8.6	29.26	16.08	46.06
	30 days	KR5/30D	9.56	33.47	16.01	40.96
	90 days	KR5/90D	7.28	37.46	15.12	40.14

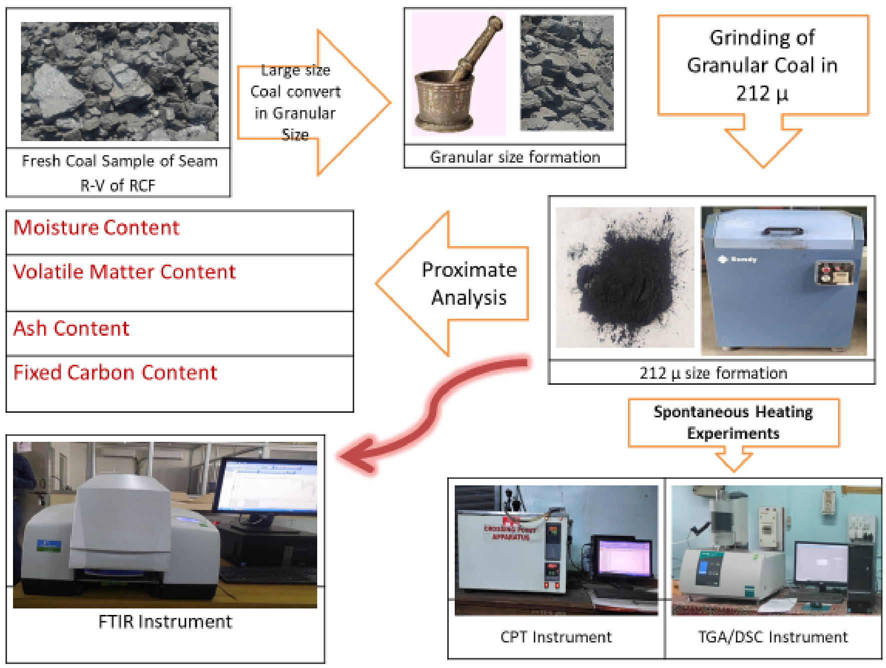

Figure 1. Graphical Representation of complete experimental process

2.2.2. TGA/DSC Experiments

Thermo-gravimetric Analysis (TGA)

TGA is a well-known thermal method for studying the spontaneous heating behavior of coal samples. The TGA experiments were performed in standard experimental conditions using a simultaneous thermal analyser (STA 443F3) instrument of M/s NETZSCH, Germany concerning weight, temperature, and sensitivity calibration (Fig. 4). A blank correction was implemented to reduce the buoyancy effect. The combustion experiments of the coal sample were carried out keeping the mass of sample mass 10 ± 0.5 mg, particle size (−) 212 µm, heating rate @5 °Cmin-1, in a normal air atmosphere at a flow rate of 100 mlmin-1, temperature range 30-750 °C, for all samples as shown in Fig. 2. The experiments were repeated three times for the repeatability of this study [36-37]. A total of 12 experiments including repeatability were performed for the coal samples from the RCF to determine their spontaneous heating behavior and their results i.e. TGign are presented in Table 2.

Differential scanning calorimetry (DSC)

DSC is a thermal analysis method in which the sample is heated to ascertain whether the sample reacts exothermically or endothermically with oxygen in the presence of air. The experimental methods described in TGA experiments are used with same instrument to study the heat flow behaviors of coal with respect to time/temperature [38-39].

2.2.3. Fourier transforms infrared spectroscopy (FT-IR)

FT-IR spectroscopy has been used to identify the functional groups present in the coal as it is a heterogeneous compound. As most organic functional groups (OH, NH2, C=O, C-H, etc.) absorptions occur in the mid-IR range (4000 - 400 cm-1) [26][38]. The mid-infrared spectral signals of coal samples were collected using Frontier FT-IR equipment of M/s Perkin Elmer. Approximately 2 mg of coal sample was taken in a sample holder and 20 scans through detectors in the wave number regions from 4000 to 400 cm-1 with spectral resolution of 8 cm-1. The absorption bands in the spectrum of each sample were identified to their matching functional groups with reference to the standard as shown in figure 3 [26][15]. The FT-IR spectra for the coal samples are determined for all coal samples and depicted in Table 3.

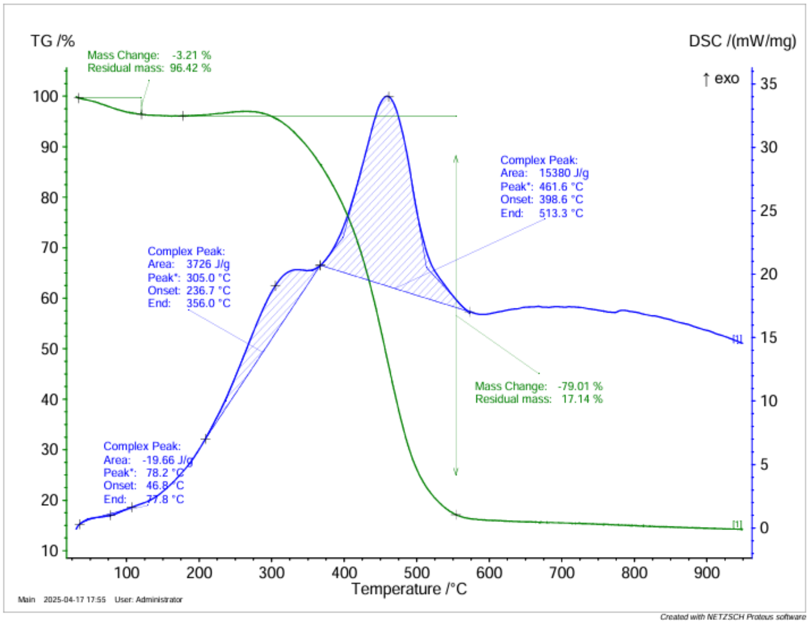

Figure 1. Add figure caption (10 pt) Figure 2. TGA/DSC Thermogram of fresh coal sample of Seam –RV, Kottadih Colliery

Table 2. Results of TGA and DSC data of fresh and water immersed coal sample

Sample Code	CPT (°C)	TG_{ign} (°C)	TG_M (%)	TG_C (%)	TG_A (%)	TD_o (°C)	TD_P (°C)
KR5/0D	151	278.5	3.21	79.01	17.14	236.7	461.6
KR5/15D	154	283.5	3.40	69.60	25.81	223.0	467.2
KR5/30D	147	281.0	3.43	69.60	23.23	226.0	459.0
KR5/90D	144	281.0	4.89	70.48	23.23	219.4	452.5

Table 3. Results of FTIR data of fresh and water immersed coal sample

KR5/0D		KR5/15D		KR5/30D		KR5/90D	
Wave number absorbed	**Functional gr. may be present**	**Wave number absorbed**	**Functional gr. may be present**	**Wave number absorbed**	**Functional gr. may be present**	**Wave number absorbed**	**Functional gr. may be present**
3692.5	-OH	3748.4	-OH	3757.7	-OH	3695.6	-OH
3618	-OH	3695.6	-OH	3695.6	-OH	3611.7	-OH
1741.8	-HC=O	1741.8	-HC=O	1741.8	-HC=O	1595.9	-COOM
1592.8	-COOM	1602	-COOM	1595.9	-COOM	1434.3	-COOM
1431.2	-COOM	1437.4	-COOM	1443.7	-COOM	1369.1	-COOM
1366	-COOM	1369.1	-COOM	1366	-COOM	1105	3°-amine
1210.7	3°-amine	1102	3°-amine	1210.7	3°-amine	1027.4	Si-O-C
1095.8	Si-O-C	1030.5	Si-O-C	1102	Si-O-C	1005.7	Si-O-C
1027.4	Si-O-C	1002.6	Si-O-C	1030.5	Si-O-C	909.4	Si-O-C
999.48	Si-O-C	909.4	Si-O-C	1005.7	Si-O-C	794.48	-OH
912.51	Si-O-C	794.48	-OH	912.51	Si-O-C	691.98	-C≡C-
747.89	-OH	751	-OH	751	-OH	533.56	2°OH, Ar
695.08	-C≡C-	695.08	-C≡C-	695.08	-C≡C-	468.33	2°OH, Ar
530.46	2°OH, Ar	530.46	2°OH, Ar	533.56	2°OH, Ar	427.96	2°OH, Ar
468.33	2°OH, Ar	468.33	2°OH, Ar	468.33	2°OH, Ar		
424.85	2°OH, Ar	427.96	2°OH, Ar	427.96	2°OH, Ar		

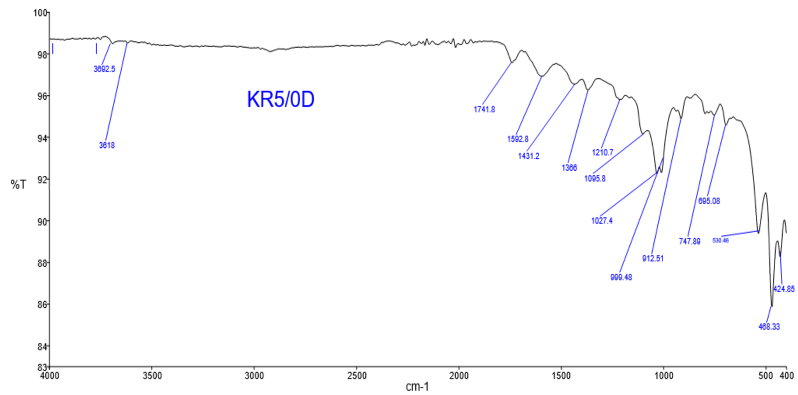

Figure 3. FTIR spectra of fresh coal sample KR5/15D

2.2.4. Water Quality Analysis

The water quality parameters of fresh tap water and water collected at different intervals from water-immersed coal samples were analyzed according to Indian Standards. Twelve parameters were determined, including pH, electrical conductivity (EC), total hardness (TH), calcium ion, magnesium ion, chloride ion, nitrate ion, sulfate ion, sodium ion, potassium ion, and others. These parameters were classified into five broad categories: all cations (basic radicals), all anions (acid radicals), EC, pH, and TH. Water samples were collected from the container in which the coal sample was immersed, using pre-washed 1-liter narrow-mouth polyethylene bottles. EC was measured using a conductivity meter, and the pH of the water samples was determined with a pH meter. The concentration of bicarbonate (HCO_3^-) was determined using acid titration. Major anions/acid radicals such as F^-, Cl^-, SO_4^{2-}, and NO_3^- were analyzed by ion chromatography (Dionex Dx-120) using AS12A/AG12 ion columns coupled with a self-regenerating ion suppressor (ASRS) in recycle mode. Major cations/basic radicals such as Ca^{2+}, Mg^{2+}, Na^+, and K^+ were measured using a double-beam atomic absorption spectrophotometer, calibrated with known standards prepared from 1000 ppm Merck solutions. The analytical accuracy of the ion measurements was verified by calculating the ion charge balance error, which was within ±10%. The results of the water quality parameters for fresh tap water and water from the water-immersed coal container are presented in Table 4.

Table 4. Water quality data of Fresh and coal-immersed water samples

Sample ID	KR5/W/0D	KR5/W/ 15D	KR5/W/30D	KR5/W/ 90D
EC (µS/cm)	509	534	526	462
pH	7.82	7.54	7.66	7.13
TH (mg/L)	210	220	250	156
Acid Radical (mg/L)	90.1	95.2	89.5	84.2
Basic Radical (mg/L)	226.17	238.77	239.72	261.55

3. Result and Discussion

3.1. Proximate Analysis

The proximate analysis results reveal that the moisture content in raw coal was 6.06%, while water-immersed coal had moisture contents of 8.6%, 9.56%, and 7.28% after immersion in water for 15, 30, and 90 days, respectively. The moisture content in coal increases due to water action. Similarly, the volatile matter content in fresh and water-immersed coal for 15, 30, and 90 days was 36.72%, 29.26%, 33.47%, and 37.46%, respectively. The ash content of fresh and water-immersed coal for 15, 30, and 90 days was 15.12%, 16.02%, 16.01%, and 15.12%, respectively. There was no change in the ash content of coal after water immersion. The fixed carbon content of fresh and water-immersed coal for 15, 30, and 90 days was 42.07%, 46.06%, 40.96%, and 40.14%, respectively. A slight variation in the fixed carbon content of coal was observed due to changes in moisture and volatile matter. An increase in the volatile matter content may lead to spontaneous combustion of coal [39,40]. The moisture and volatile matter content graph of fresh and water immersed coal samples are presented in figure 4.

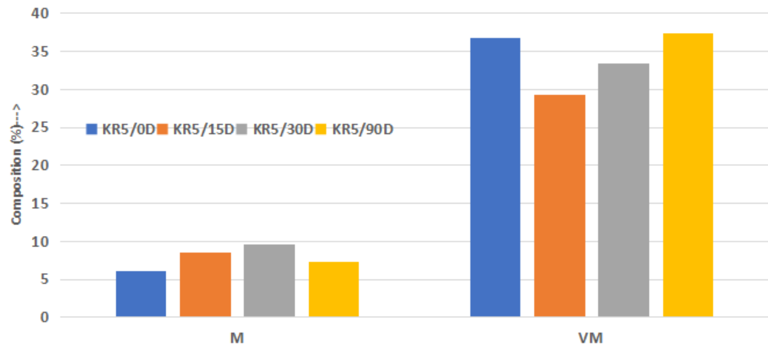

Figure 4. Moisture and Volatile matter content graph of fresh and water immersed coal samples

3.2. Spontaneous Heating Experiments

The CPT results of raw and water immersed coal samples, for 15, 30 and 90 days were 151 °C, 154 °C, 147 °C, 144 °C respectively. This decreased CPT value water immersed coal sample indicates more susceptible to spontaneous combustion. The thermal behaviour of fresh and water immersed coal samples showed that the TG_{ign} was in the range 278.5 °C to 283.5 °C and TD_o was in the range 236.7°C to 219.4°C. There was no variation in TGign temperature whereas the onset temperature gradually decreases with respect to duration of water immersed samples. Similarly, the combustion peak temperature also decreases in water immersed coal samples. It also reveals that the low minimum ignition temperature and onset temperature of water immersed sample for 90 days is more susceptible to spontaneous combustion. The CPT, TG_{ign} and TD_o graph of fresh and water immersed coal samples are shown in figure 5.

3.3. FTIR Analysis

Both raw and water immersed coal samples were further analyzed using the FTIR technique to investigate the changes in functional groups after immersed in water. The composite FTIR spectra of fresh coal and water immersed coal are shown in figure 6.

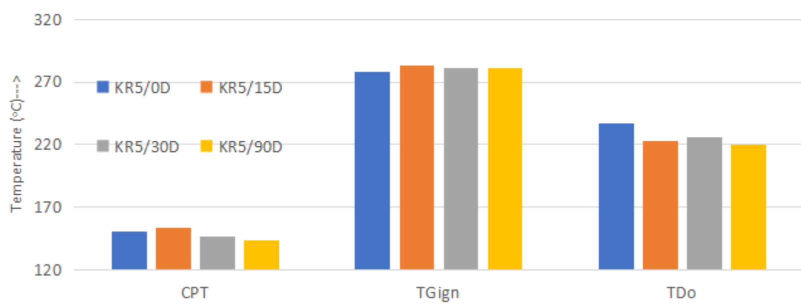

Figure 5. CPT, TG_{ign} and TD_o graph of fresh and water immersed coal samples

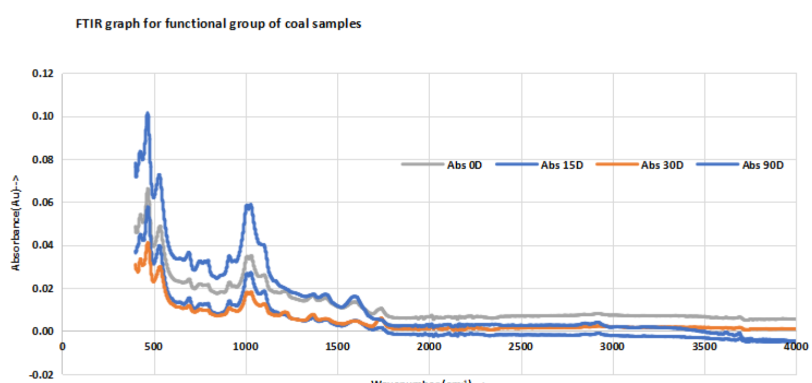

Figure 6. FTIR graph of Raw and Water-immersed coal samples (Absorbance V/S Wavenumber)

The FTIR curve indicates that there are three different peaks observed for all the coal samples. There was an intense peak at wave number 750 to 480 cm^{-1}, which indicates the presence of aromatic compounds. The second-highest peak was observed at wave number 1100 to 950 cm^{-1}, which indicates the presence of unsaturated hydrocarbons. The third-highest peak was found at 1800 to 1600 cm^{-1}, which indicates the presence of carbonyl compounds. The peak obtained after 90 days of water immersion was the highest number of aromatic hydrocarbons, unsaturated hydrocarbons and carbonyl compounds. These organic compounds are more volatile as well as flammable and will certainly increase the risk of spontaneous combustion.

3.4. Water Quality Analysis

The fresh tap water and water samples collected from water immersed coal containers at different intervals were analyzed for twelve different water quality parameters. The water quality results of different parameters for all four samples are represented in figure 7.

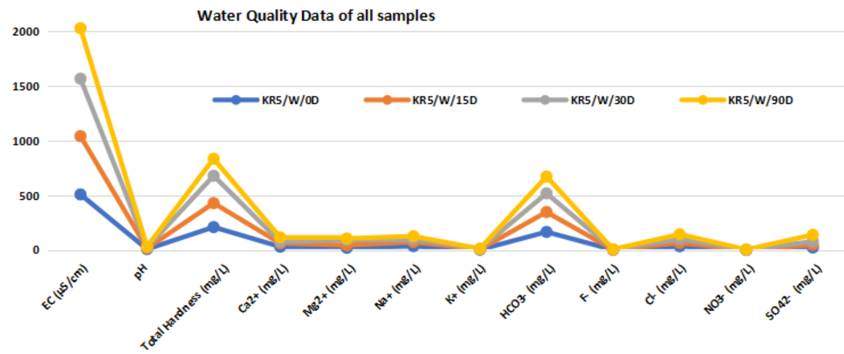

Figure 7. Variation in water quality due to the immersion of coal

Water quality results reveals that the EC, pH, TH, and acid radicals initially increases and then decreases, while basic radicals of water increase due to the action of coal. As a result of all these parameters the water becomes acidic due to the action of coal, whereas the nitrate and sulphate ions of water increases which definitely comes from coal. The variation in water quality is shown by graph in figure 7. The changes in water quality may contribute to an increases the propensity for spontaneous combustion in coal.

4. Conclusions

The spontaneous combustion characteristic of a dewatered coal seam in underground mines at RCF was investigated to assess the safety risks for both the mines and the miners. This study involved a coal sample immersed in water under laboratory conditions for 90 days, with various experiments conducted to observe changes in coal characteristics. The experimental results indicate that water-immersed coal samples exhibit optimal moisture levels (4–8%), a higher volatile matter content (>30.0%) compared to fresh samples, and a gradual decrease in the ignition temperature of the water-immersed coal over time. Additionally, there is an increase in the concentrations of functional groups such as Ar-, -CHO, >C=O, and -C=C- due to the adsorption of dissolved organic compounds onto the coal surface. All these experimental results suggest that exposure of coal to water increases the risk of spontaneous combustion and may lead to fires in the mine under favorable conditions.

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ارزیابی خطرات احتراق خود به خودی مرتبط با زغالسنگ غوطه‌ور در آب در درز RV میدان زغالسنگ رانیگانج

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کلمات کلیدی

احتراق خود به خودی زغال سنگ
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FTIR
ذغال سنگ غوطه ور در آب
گروه‌های عاملی آلی

چکیده

استخراج سریع از معادن زغالسنگ زیرزمینی در میدان زغالسنگ رانیگانج (RCF) با چالش‌های ایمنی مختلفی از جمله عملیات چند لایه، استخراج لایه‌های آب گرفته، مناطقی که لایه‌های بالایی تخلیه شده‌اند، مشکلات مدیریت لایه‌ها، فرونشست، مشکلات تهویه، گرما، رطوبت، احتراق خود به خودی و آتش‌سوزی‌های معدن مواجه است. در میان این چالش‌ها، بسیاری از معادن زغالسنگ زیرزمینی پس از آبگیری لایه‌های زغالسنگ برای اهداف تولید، به فعالیت خود ادامه می‌دهند. احتراق خود به خودی خطر قابل توجهی را در لایه‌های زغالسنگ آبگیری شده معادن زیرزمینی ایجاد می‌کند و بر ایمنی معادن و معدنچیان تأثیر می‌گذارد. هدف از این مطالعه ارزیابی خطر احتراق خود به خودی در یک لایه زغالسنگ غوطه‌ور در آب RCF با انجام تجزیه و تحلیل تقریبی، مطالعات TGA/DSC، FTIR و تجزیه و تحلیل آب است. یک نمونه زغالسنگ از لایه RV در معدن زغالسنگ کوتادیه در RCF گرفته شد و با نسبت ۱:۱۰ در آب لوله‌کشی غوطه‌ور شد. نمونه‌های زغالسنگ غوطه‌ور در آب پس از ۱۵، ۳۰ و ۹۰ روز برای آماده‌سازی نمونه و سایر بررسی‌های تجربی حذف شدند. نتایج آزمایش نشان می‌دهد که نمونه‌های زغال‌سنگ غوطه‌ور در آب، سطوح رطوبت بهینه (۴ تا ۸ درصد)، محتوای مواد فرار بالاتر (بیش از ۳۰ درصد) در مقایسه با نمونه‌های تازه و کاهش تدریجی دمای احتراق زغال‌سنگ غوطه‌ور در آب را با گذشت زمان نشان می‌دهند. به دلیل جذب ترکیبات آلی محلول روی سطح زغال‌سنگ، غلظت گروه‌های عاملی مانند -Ar، -CHO، <C=O و -C=C- افزایش می‌یابد. همه تجزیه و تحلیل‌ها نشان می‌دهند که افزایش ترکیبات آلی به افزایش خطر احتراق خود به خودی کمک می‌کند.

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