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and
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Experimental studies for assessing spontaneous combustion risk of some Indian coals

The self-heating or the spontaneous combustion of coal is processed by which the freshly exposed coal at ordinary atmospheric temperature when is exposed to oxygen undergo self-heating i.e. increase in its temperature and ultimately leading to auto ignition and mine fire. This spontaneous combustion leads to mine fires and are prime concern in the mining industry and let to huge coal loss and mine disaster. For safe coal mining, transportation, storage and uses, understanding the coal liability towards spontaneous combustion is important. Spontaneous heating liability depends upon the intrinsic as well as the extrinsic properties of the coal. In the present work, the spontaneous combustion susceptibility of a number of coal samples belonging to two different coalfields e.g.Bharat Coking Coal Limited (BCCL) and Central Coalfields Limited (CCL) of Coal India Limited, have been studied and its correlation with different intrinsic properties have been made. The objectives of this study is to assess the spontaneous heating liability of coal samples using differential thermal analysis and crossing point temperature and to establish a relationship between the spontaneous heating liability risk and intrinsic properties of coal samples. For this study, seven coal samples were collected from BCCL and CCL. Proximate analysis, bomb calorimetry, crossing point temperature (CPT) and differential thermal analysis (DTA), experiments were conducted to find the intrinsic properties of coals and assess their liability towards spontaneous heating. The paper summarizes the liability of different coal samples to spontaneous heating based on experiments conducted as well as broadly classifies the coal samples into poorly, moderately and highly susceptible to spontaneous heating risk. The transition temperature (T_c) indicated a very accurate measure of liability to spontaneous heating as they show high correlation coefficients with volatile matter, moisture and fixed carbon. These were 0.88% with moisture, 0.84% with volatile matter and 0.74 for fixed carbon contents. Lower the transition temperature of coal is higher will be the liability of coals to spontaneous heating. It was also observed that DTA study was found to give better correlation and hence, it may be used for assessment of spontaneous heating susceptibility of coal. It was observed that the coal samples containing high moisture are in general more liable to spontaneous heating. Spontaneous heating also shows a direct relationship with volatile matter hence higher the volatile matter in the coal samples is more will be the liability towards spontaneous heating. Ash percentage also has negative slope [-1.87] with transition temperature but the correlation coefficient is very low [0.15]. It has also lowest correlation coefficient (0.10) values with CPT. Gross calorific value is also directly dependent on the fixed carbon. Coal samples having higher fixed carbon are less liable for spontaneous heating. Ash has very low correlation coefficients with CPT and transition temperature and hence is not helpful in the assessment of liability towards spontaneous heating and it is of least importance.

Keywords: *Spontaneous combustion, Indian coal, proximate analysis, transition temperature, crossing point temperature (CPT), ifferential thermal analysis (DTA)*

1. Introduction

Coal is the source of around 27.2% of global energy consumption (BP, Statistical Review of World Energy, 2019) and it counts for about 38.3% of electricity generated across the world (IEA, Electricity Information, 2019). It also accounts for about 55% of India's primary commercial energy source. Nearly 72% of the entire power generated in the country is coal-based (CIL, 2019).

Mine fire continues to be a major threat to life and property even now. The spontaneous heating tendency of the coals is dependent on many factors viz. intrinsic, extrinsic, geological and mining methods. Many seams in our country cannot be worked or reopened because of spontaneous heating. Hence, risk due to the spontaneous heating must be assessed for proper planning of mines for safe operation as well as optimum production.

The spontaneous heating which leads to fire if not controlled also causes environmental problems, stockpile fires subsidence, exhalation cracks and loss of lives due to noxious gases emission, (D.S. Nimaje and D.P. Tripathy, 2010).

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Various researchers around the world using different methods have carried out an assessment of coal for spontaneous heating. These experiments are based on thermal studies, oxygen avidity studies and petrological studies. Thermal study includes crossing point temperature, wet oxidation potential, differential thermal analysis, differential scanning calorimetry, H_2O_2 studies, Olpinski index and puff temperature etc. The oxygen avidity studies include the peroxy complex, Russian U index and wet oxidation. Nimaje and Tripathy (2016) reported that to assess the spontaneous combustion liability of coal, intrinsic properties and susceptibility indices play a vital role. Experimentation of the samples was carried out for proximate, ultimate, and petrographic analysis; crossing point temperature; flammability temperature; Olpinski index; wet oxidation potential analysis; and differential thermal analysis to ascertain the proneness of coal to spontaneous combustion. From the statistical analysis of the samples, it was reported that the parameters of the ultimate analysis showed significant correlation with the Olpinski index as compared to other susceptibility indices and hence, it could be used as a reliable index to assess the susceptibility of Indian coals to spontaneous combustion. Nandy et al. (1972) had attempted to classify various Indian coals with respect to their susceptibility to spontaneous combustion based on their crossing point temperature. They reported that in general, higher crossing point temperature signifies lower susceptibility, whereas lower crossing point temperature indicates higher susceptibility to heating. They inferred that the coals that showed low crossing point temperature and a sudden sharp rise in the slope of the time-temperature curve may be considered to be highly vulnerable to spontaneous heating. It was also observed that higher rank coals are normally less susceptible to spontaneous combustion than lower rank coals.

The coal characterization is important in deciding the incubation period of coals, that helps in mine planning for determination of the size of the pillars and rate at which it must be extracted. If liability to self-heating is determined at an early stage, then proper mine planning can be done for timely extraction and many preventive methods used for mine fires can be applied to save the coal resource and prevent mine fires. Sahu et al. (2009) presented the application of an empirical approach for classification of coal seams based on their proneness to spontaneous heating. Using moisture, volatile matter, ash and crossing point temperature of the coal samples as the parameters, principal component analysis was applied to classify the coal seams into three different categories i.e. highly, moderately and poorly susceptible.

This paper focused on carrying out proximate analysis of coal samples, estimation of gross calorific value using bomb calorimeter, the differential thermal analysis and crossing point temperature for seven coal samples collected from different BCCL and CCL and based on the findings the coals were classified into poorly, moderately and highly susceptible to spontaneous heating risk.

2. Sample collection

Total seven numbers of samples were collected from BCCL and CCL coalfields. The channel sampling was used for the collection of coal samples following IS 436-1-1, 1964, Methods for Sampling of coal and coke. The method has been represented in Fig.1.

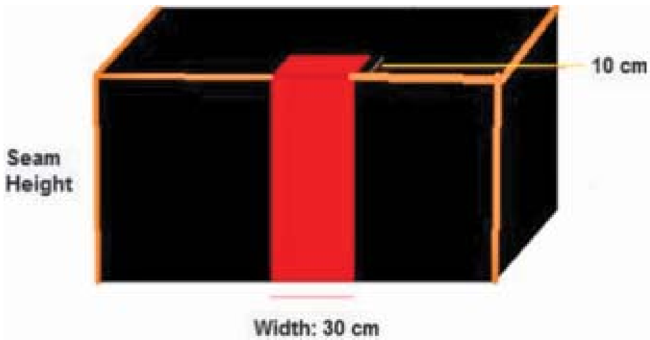

Fig.1 Representation of channel sampling

3. Methodology

In order to assess spontaneous heating liability of the coal samples, the proximate analysis, calorific value determination using bomb calorimeter, differential thermal analysis and crossing point temperature were done in the laboratory.

Fig.2 DTA instrument (DTG-60H)

Proximate analysis of all the seven coal samples were obtained using guidelines prescribed by Bureau of Indian Standards, New Delhi IS-1350 Part 1, 1984, Methods of Test for Coal and Coke: Proximate Analysis (Second Revision). Similarly, for calorific value guidelines prescribed by Bureau of Indian Standards, New Delhi 1350 Part 2, 1975, Methods of Test for Coal and Coke, Part II: Determination of Calorific Value was followed. Differential thermal analysis of coal samples were analysed using DTA (SHIMAZDU made DTG-60H) as shown in Fig.2. Crossing point temperature of coal samples were determined using the procedure laid out by Mahadevan and Ramlu (1985).

4. Results and discussions

4.1 Proximate analysis of coal samples

The proximate analysis involves the determination of intrinsic properties of the coal samples like fixed carbon (FC), volatile matters (VM), moisture (M), and ash. The measurement is done on weight per cent (wt.%) and the result of proximate analysis of the coal samples is given in Fig.3.

From, Fig.3, it was observed that the percentage of moisture of the coal samples varied from 1.01% (BCCL_2) to 12.1% (CCL_2). Thus, it can be inferred from the results that the BCCL coal, which is coking coal, has very less moisture compared to CCL non-coking coal samples. From experimental data, it can be stated that the high moisture coals aregenerally more prone to spontaneous heating.

The volatile matter of the coal samples varied from 22.88% (BCCL_2) to 30.96% (CCL_4). It was noted that the coal samples from BCCL have less volatile matter than CCL coal samples.

The ash percentage of the coal samples varied between 13.54% (BCCL_2) and 33.79% (CCL_5). The CCL coal samples showed a higher average ash percentage. The fixed carbon percentage was highest for BCCL_2 (62.57%) and lowest for the CCL_5 (30.77%).

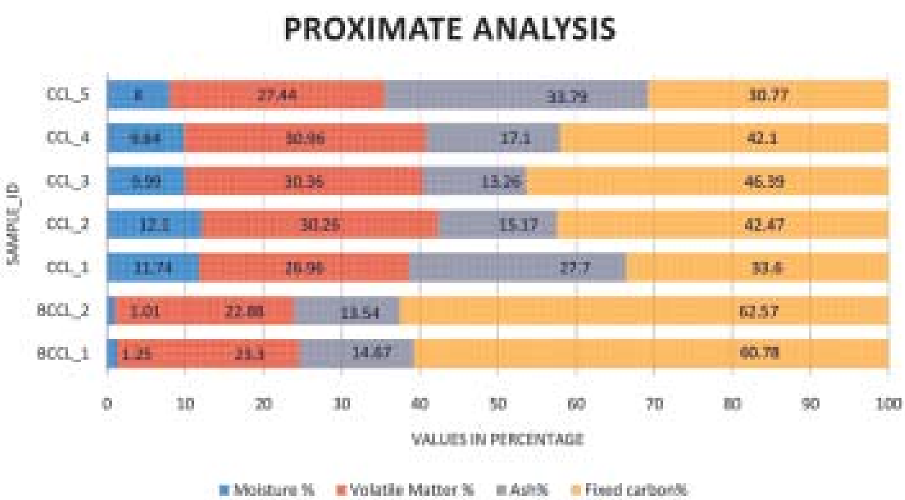

Fig.3 Plot of proximate analysis

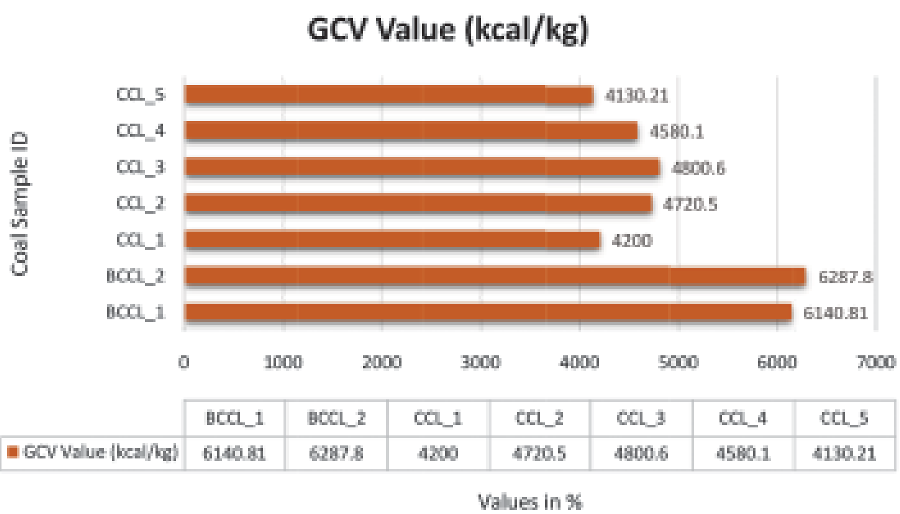

Fig.4 Plot of gross calorific value

4.2 Gross calorific value

The GCV of all the collected coal samples are listed in Fig.4.

The BCCL_2 coal sample, which is coking coal, gives highest gross calorific value of 6287.8 kcal/kg because it has highest fixed carbon percentage (62.57). Among the CCL coal samples that belong to the non-coking coal, CCL_3 has the highest calorific value of 4800.6 kcal/kg, which also has highest fixed carbon among CCL coal samples (46.39). CCL_5 coal sample has the lowest gross calorific value of 4130.21kcal/kg among all seven-coal samples and it has the lowest fixed carbon percentage (30.77).

4.3 Crossing point temperature

The sample with the highest CPT value is likely to be less liable to heating. Table 1 represents CPT values of coal samples and Table 2 shows the correlation of CPT with intrinsic properties.

The CPT values of BCCL_1 and BCCL_2 are relatively less compared to CCL coal samples because of less moisture and volatile matter content. The BCCL_1 has the highest CPT value (174°C) which signifies that it is least liable to self-heating compared to others coal sample. The CCL_3 has least CPT values (136°C) because it has high moisture and relatively less ash percentage. The correlation

Table 1: CPT values of coal samples

Sample_ID	CPT(^oC)
BCCL_1	174
BCCL_2	166
CCL_1	158
CCL_2	148
CCL_3	136
CCL_4	153
CCL_5	139

Table 2: Correlation of CPT and intrinsic properties

Parameters	Correlation coefficient	Slope
Moisture	0.47	-2.03
Volatile Matter	0.59	-3.17
Ash	0.10	-0.53
Fixed carbon	0.46	0.76

coefficient of CPT with proximate analysis, parameters (moisture, ash and volatile matter) are:

Moisture shows a negative slope [-2.03] with CPT value with correlation coefficient of 0.47, this means higher the moisture %, lower the CPT value and thus more is the liability towards spontaneous heating. The CPT value shows similar negative slope [-3.17] with the volatile matter with correlation coefficient of 0.59. This means that increase in volatile matter lowers the CPT value indicating higher liability. Fixed carbon has positive slope [0.76] with CPT with correlation coefficient of 0.46 and higher is the fixed carbon more will be the CPT value and hence less will be coal spontaneous heating liability.

4.4 Differential thermal analysis

Stage II is divided into two parts, IIA and IIB. In IIA, the heating tendency of coal starts with some residual endothermic reactions i.e. external heat is supplied to coal sample. In the second stage of Stage II, an exothermic reaction (heat is released) starts. Table 3 shows the observation from the DTA thermogram.

Table 3: Observation from DTA thermograms

Sample ID	Slope II A	Slope II B	Slope II	Transition temperature (T_c)
BCCL_1	0.02	0.12	0.05	233.62
BCCL_2	0.02	0.14	0.06	240.38
CCL_1	0.32	0.28	0.14	166.90
CCL_2	0.25	0.27	0.21	151.25
CCL_3	0.21	0.26	0.19	150.26
CCL_4	0.25	0.34	0.25	159.97
CCL_5	0.23	0.34	0.25	154.33

From Table 3 it is clear that the BCCL samples are less liable towards spontaneous heating than CCL coal samples. The first stage of the DTA curve represents the moisture loss hence minima of first stage thermogram of BCCL samples are less than CCL samples i.e. it has less moisture.

(a) It is evident from the Table 4 that susceptibility of coal towards spontaneous heating shows good correlation with moisture (R^2 = 0.88) with negative slope of 7.94.

(b) The transition temperature also has good correlation with volatile matter (R^2 = 0.84) with negative slope of 10.88.

(c) The ash percentage have correlation coefficient of 0.15 with negative slope of 1.87 with the transition temperature.

(d) The fixed carbon has correlation coefficient of 0.74 with positive slope of 2.78.

(e) Moisture and volatile matter have negative slope with transition temperature and hence higher is the moisture and volatile matter lesser will be the transition temperature resulting higher the liability of coal samples towards the spontaneous heating.

(f) Ash percentage also has negative slope [–1.87] with transition temperature but the correlation coefficient is very low [0.15] and hence it has less effect on spontaneous heating.

(g) The fixed carbon has a positive slope [0.74] with transition temperature that higher is the fixed carbon more will be the transition temperature and lesser the liability towards spontaneous heating.

(h) BCCL_2 coal sample has the highest transition temperate [240.38^{o}C] hence it has the lowest liability towards spontaneous heating because it contains least moisture and volatile matter and highest fixed carbon among all the samples.

Table 4: Correlation of transition temperature and intrinsic properties

Parameter	Correlation coefficient	Slope
Moisture	0.88	-7.94
Volatile matter	0.84	-10.88
Ash	0.15	-1.87
Fixed carbon	0.74	2.78

After analysing the results of the experiments for all the coal samples and based upon the transition temperature, and crossing point temperature, all the coal samples collected can be classified into three categories namely poorly susceptible, moderately susceptible and highly susceptible to spontaneous heating liability (Table 5).

The transition temperature can be used as indicator of liability to spontaneous heating. The spontaneous heating liability follow inverse relationship with transition temperature (Saikia et al., 2009).

Spontaneous heating liability $\alpha \frac{1}{Tc}$

Hence, lower the transition temperature of the coal samples is higher will be its liability towards spontaneous heating. Table 6 shows the liability of coal samples to spontaneous heating based on differential thermal analysis.

TABLE 5: SPONTANEOUS HEATING LIABILITY BASED ON CPT

	Susceptibility to spontaneous combustion	Coal samples
1	Highly susceptible	CCL_3, CCL_5
2	Moderately susceptible	CCL_1, CCL_2, CCL_4
3	Poorly susceptible	BCCL_1, BCCL_2

TABLE 6: SPONTANEOUS HEATING LIABILITY BASED ON DTA

Sample_ID	Transition temperature (T_c)	Highest liability to spontaneous heating
CCL_3	150.26	
CCL_2	151.25	
CCL_5	154.33	
CCL_4	159.97	
CCL_1	166.90	
BCCL_1	233.62	
BCCL_2	240.38	Lowest liability to spontaneous heating

TABLE 7: CORRELATION OF CPT AND TRANSITION TEMPERATURE WITH INTRINSIC PROPERTIES

Parameter	Crossing point temperature		Transition temperature	
	Correlation coefficient	Slope	Correlation coefficient	Slope
Moisture	0.47	-2.03	0.88	-7.94
Volatile matter	0.59	-3.17	0.84	-10.88
Ash	0.10	-0.53	0.15	-1.87
Fixed carbon	0.46	0.76	0.74	2.78

5. Conclusions

The correlation coefficients and slopes for CPT and transition temperature and intrinsic properties of coal are summarized in Table 7.

From the present investigations and Table 7, the following conclusions may be drawn:

- The results of CPT and transition temperature indicate that the coal samples containing high moisture are in general more liable to spontaneous heating. Spontaneous heating also shows a direct relationship with volatile matter hence higher the volatile matter in the coal samples is more will be the liability towards spontaneous heating.
- The transition temperature (T_c) indicates a very accurate measure of liability to spontaneous heating as they show high correlation coefficients with volatile matter, moisture and fixed carbon. These were 0.88% with moisture, 0.84% with volatile matter and 0.74 for fixed carbon contents. Lower the transition temperature of coal is higher will be the liability of coals to spontaneous heating. Accordingly, BCCL_2 is lowest
- Susceptible coal and CCL-3 coal is the most prone to spontaneous heating. Intrinsic properties show a significant correlation with transition temperature except ash and hence, it can be used for assessment of spontaneous heating liability of coal.
- Ash percentage also has negative slope [-1.87] with transition temperature but the correlation coefficient is very low [0.15] and hence it has less effect on spontaneous heating. Ash has very low correlation coefficient (0.10) with CPT and transition temperature and hence is not helpful in the assessment of liability towards spontaneous heating and it is of least importance.
- Gross calorific value is also directly dependent on the fixed carbon. Coal samples having higher fixed carbon are less liable for spontaneous heating.

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