Shahrood University of Technology

Iranian Society of Mining Engineering (IRSME)

Journal of Mining and Environment (JME)

journal homepage: www.jme.shahroodut.ac.ir

THOMSON REUTERS

Vol. 11, No. 1, 2020, 315-333.
DOI: 10.22044/jme.2018.7524.1605

Studying relationship between coal intrinsic characteristics in spontaneous combustion of coal potential using crossing point temperature test method A case study: Tabas Parvadeh coal mines, Iran

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Received 6 October 2018; received in revised form 24 October 2018; accepted 3 November 2018

Keywords

Spontaneous Combustion of Coal

Tabas Parvadeh Coal Mines

Coal Intrinsic Characteristics

Crossing Point Temperature Test Method

Abstract

Spontaneous combustion of coal is one of the most horrifying hazards in coal industries, especially in underground coal mines. Thus having a prior knowledge about the occurrence of this phenomenon in underground coal mines is of crucial importance in preventing this process, loss of life, huge economic loss, and environmental pollution. The aim of this work is to determine the spontaneous combustion of coal potential in the Tabas Parvadeh coal mines in Iran in order to assess the effect of coal intrinsic characteristics on its occurrence. For the purpose of this investigation, the coal samples were collected from Parvadeh I to IV, and the coal intrinsic characteristics of the samples were tested. In order to determine the spontaneous combustion of coal propensity in this case study, the Crossing Point Temperature (CPT) test was used. Then the relation between the coal intrinsic characteristics and the CPT test values was determined. The results obtained showed that the B1 seam in Parvadeh II and C1 seam in Parvadeh III had a high potential of spontaneous combustion of coal potential. These results also show that an increase in the moisture, volatile matter, pyrite, vitrinite, and liptinite contents enhance the spontaneous combustion of coal tendency in these mines. The results obtained have major outcomes for the management of this phenomenon in the Tabas Parvadeh coal mines. Therefore, evaluation of the spontaneous combustion of coal hazards in coal mines should start in the first stage of design and carried on during their whole lifecycle, even after mine closure.

1. Introduction

Fossil fuels contain about 90% of the proved reserves of global energy. Today, coal is the major part and most plentiful and economical fossil fuel including approximately 90% of the fossil fuel energy around the world and as the basic energy source in the production industry of many countries [1, 2].

Regardless of all its benefits, coal mining is a very intricate system. The rough working conditions and the hazardous environment are the most important parameters that affect a coal mining process. The hazards of underground mining are critical parameters, which should be considered in the design and planning step of coal mines. Some significant hazards in underground coal mining can be summarized as subsidence, outburst, spontaneous combustion, roof instability, passing through faulted and crushed zones, groundwater inflow, high methane gas content of the coal seam, and presence of combustible coal dust [3-6]. Therefore, it is necessary to accurately identify the risks involved and to find the ways to forecast, prevent, and control them [7, 8].

Oxidation of coal is the major heat source responsible for the occurrence of spontaneous combustion of coal [9-11]. Spontaneous

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combustion of coal is a key safety issue in coal mining [12-17]. This event has threats to valuable energy resources [17], and is an environmental, economic, and social threat in all stages of coal mining [18-20]. Huge economic losses and personal casualties, and the damage resulting from spontaneous combustion of coal have also led to massive environmental contaminations. Thus spontaneous combustion of coal is an urgent problem that should be solved [1].

This process is an oxidation reaction that occurs without an external heat source, which is due to a number of complex exothermic reactions [14, 21]. Coal intrinsic characteristics are consistently referred to as having a major influence on the spontaneous combustion of coal in comparison with the geological and mining characteristics [3, 4].

This process changes the internal heat properties of the coal, leading to a rise in the temperature. This can eventually lead to an open flame and burning of the coal [9, 12, 22-26].

In coal seams, stockpiles, and coal wastes, spontaneous combustion occurs when the rate of heat generated by the oxidation of organic matter trespasses the rate of heat dissipation [27, 28]. According to Banerjee [29], Pone et al. [30], Mohalik et al. [31], and Yuan and Smith [32], oxidation of coal starts with exothermic chemical reactions; it is a complicated process that involves a series of reaction steps, which can be described as a process including four sequential steps. These steps are as follow:

1) Physical adsorption of oxygen on the coal surface, resulting in a temperature rise;

2) Chemical absorption (chemisorption) (over 50 °C), which leads to the formation of coal-oxygen complexes;

3) Decomposition of oxygenated hydrocarbons when self-heating temperature is reached (over 70 °C) with concurrent oxidation of unaltered coal matter; in this step, the chemical reaction breaks down the less stable coal-oxygen complexes, and results in the formation of gaseous products, typically CO and CO_2, and water vapor;

4) Spontaneous combustion may then occur if all the above-mentioned processes result in temperatures higher than 150 °C, typically referred to as the ignition threshold. This ignition threshold seems to depend on the coal rank with values around 130 °C for the lowest rank [33], and probably even lower values for peat. In this respect, the 60-80 °C range is regarded as critical [34].

This event occurs in numerous countries in the world, and extensive research works have been carried out on this issue in these countries. Therefore, awareness of the spontaneous combustion of coal potential before starting, during, and after coal mining operations has a significant effect on preventing the loss of a sustainable development. In this research work, evaluation of the spontaneous combustion of coal potential in the Tabas Parvadeh coal mines was carried out.

The Tabas Parvadeh coal mine district, located in the central Iran, is the most important coal production area in Iran. Due to the specific climate conditions, this area has a high potential for spontaneous combustion of coal. One block of the B1 seam in Parvadeh II was closed in 25 December 2016 because a spontaneous combustion process occurred in the whole of this block in this seam. Despite the importance of this issue, this hazard has still not been fully evaluated in Iran, and there is no crisis management program. Therefore, in this work, the spontaneous combustion of coal propensity was measured experimentally using the CPT test in the Tabas Parvadeh coal mines. The results of this research work are helpful for the assessment and management of spontaneous combustion of coal issues in the Tabas Parvadeh coal mines.

2. Materials and method

2.1. Coal samples and preparation

In this work, seven coal samples (from the Tabas Parvadeh coal mines) were freshly collected directly from the worked face of the mines.

The conditions for collection of samples and their transfer to the laboratory so that their possible peroxidation is avoided as well as the amount of sample required for each experiment were determined in accordance with the patterns provided by Xuyao et al. [35] and Zhang et al. [36]. Based on the patterns, after removing a coal seam of approximately 25-cm thickness to avoid the possibility of peroxidation, the samples were sent to an air-sealed plastic container that was completely filled with nitrogen and contained approximately 5 kg of coal, mostly in the lump form. The samples were transported to the laboratory in an ice-filled insulated container to avoid their peroxidation [35, 36].

The samples were delivered to the laboratory as rapidly as possible. On entry, they were transferred to a freezer for storage until required for testing. In order to minimize unnecessary oxidation, the samples were maintained in lump condition and were kept undisturbed in the laboratory prior to each test. After the test facility was ready, the plastic bag was unwrapped, its surface was removed, and its interior core was crushed to obtain the samples. Then the coal particles ranging in size from 0.18 mm to 0.38 mm were sieved to provide the experimental coal test samples just before each run in order to minimize the effect of oxidation on the fresh surfaces created by grinding the coal. Each test required 60 g (±0.01 g) of crushed coal sample, packed in the coal reaction vessel [35, 36].

2.2. Experimental apparatus and method

2.2.1. Literature review of CPT

Management of spontaneous combustion of coal is a key issue for safety and productivity in coal industries, especially in underground coal mines. There are a number of laboratory methods available for evaluating the spontaneous combustion, one of which is the crossing point temperature (CPT) method.

Nubling and Wanner [37] were the first who implemented an oil-bath using a constant heating rate to test the CPT of coal. Bagchi [38] studied the effects of the experimental conditions and proposed the most appropriate flow rate of oxygen and the surrounding heating rate for a 20 g coal sample. Banerjee et al. [39] proposed a method to evaluate the tendency of coal for a spontaneous combustion based on the CPT values. Nandy et al. [40] suggested that CPT dropped with an increase in the volatile matter, oxygen content, and moisture content. Barve and Mahadevan [41] determined a binary quadratic equation for CPT that was related to the moisture and ash contents. Küçük et al. [42] tested CPT using a column reaction vessel and suggested that CPT dropped with a decrease in the coal particle size and air humidity but rose with a decrease in the moisture content of coal. Kadioglu and Varamaz [43] suggested that CPT rose with an increase in the moisture content and the particle size of coal. Mandai et al. [44] found that CPT rose if an inhibitor was added to the coal sample. Chen and Chong [45] and Chen [46], proposed a new testing method to determine CPT using a cubic or column basket. Chen's method was subsequently used by other investigators [47, 48].

These previous studies were done under different experimental conditions. Some of the results were disputed and the most appropriate experimental conditions were also determined. Regardless, the CPT method is a very important way to reveal the mechanism of coal self-heating, and it is still widely used today.

2.2.2. CPT method

The temperature at which the coal temperature begins to exceed the surrounding temperature is the so-called crossing point temperature (CPT) [35].

The CPT method is a very important way to disclose the mechanism of spontaneous combustion of coal, and it is still widely used today. In the experiment, a prepared coal sample is placed in a gauze container, and the oven temperature is controlled. The progression of temperature with time in the process of coal reaction with air or oxygen and the oven temperature are recorded. When the coal sample temperature equals the linearly ramped oven temperature, the temperature is called CPT, as shown in Figure 1. CPT is used as an index to classify the propensity of coal to spontaneous combustion [46]. The CPT method is widely used in India, Turkey, New Zealand South Africa, Poland, and China, and it has recently been improved [49].

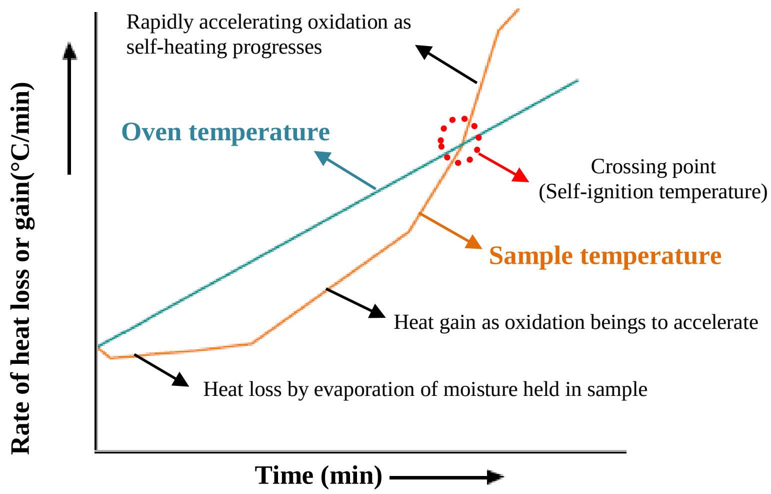


Figure 1. A schematic diagram of CPT [50].

The essence of this method is as what follows. The coal sample was placed in a programmed adiabatic oven, being heated at a constant rate. The oven was set to run at a constant temperature of 50 °C, while dry air with oxygen was permitted to flow through the coal reaction vessel at a rate of 50 mL/min. The temperature logger was used to continuously monitor the coal temperature and the surrounding temperature. When the coal temperature reached 50 °C, the oven was set to increase the temperature at a programmed rate of 1 °C/min, while the flow rate of dry air was maintained at 50 mL/min. The experiment was ended when the coal temperature was higher than the surrounding programmed adiabatic oven. When the coal sample temperature equals the linearly ramped oven temperature, the temperature is called CPT [35, 47].

2.2.3. Testing system

Figure 2 shows a schematic diagram of the apparatus applied for the low-temperature oxidation of coal. Figure 3 shows a schematic sample container (bomb) of the apparatus. The testing system consisted of an experimental apparatus for simulation of coal oxidation. The instrument consisting of the following tools (Figure 4) was made in Shahrood University of Technology in Iran (Faculty of Mining, Petroleum & Geophysics Engineering).

- Temperature-programmed adiabatic oven (Temperature-programmed adiabatic oven can set up relevant parameters related to the range and the rise rate of the temperature, and keep the temperature constant. It is applied to control the temperature of the coal samples, whose temperature ranges from room temperature to 400 °C with a precision of 1°C in the control.)
- Electric heater
- Fan (used to strengthen and uniform temperature convection in the oven)
- Coal sample reaction vessel (The coal sample reaction vessel was made of pure aluminum; it has a very good thermal conductivity. Coal sample reaction vessel is respectively connected with an inlet for air supply path, thermocouple for temperature measurement, and an outlet for the air outlet path.) (Figure 3).
- 15 m gas pre-heating copper tube (Pre-heating was achieved by passing the air through copper tube located inside the programmed adiabatic oven.)
- Thermocouples (Thermocouple 1, fixed at the center of the temperature-programmed adiabatic oven, was used to monitor the surrounding temperature, while thermocouple 2, positioned at the middle part of the coal reaction vessel, was used to measure the coal sample temperature.)
- JUMO Dicon touch (control panel) consisting of:
- Data logger (The temperature changes in the coal sample with time was obtained by a data logging system for later analysis.)
- Micro-controller (The programmed adiabatic oven was set to increase the temperature with a micro-controller.)
- Computer
- 50 kg O_2 gas cylinder (The air supply system sends gas into the reaction vessel, and takes gas after the reaction with the coal sample out of the reaction vessel along the exhaust pipe.)
- 50 kg N_2 gas cylinder (for pre-heating the coal sample to 50 ºC for start test)
- Pressure reducing valve
- Flow-meter

3. Case study: Tabas Parvadeh coal mines

Two main basins of coal resources exist in Iran, one in the northern and the other in the Central Iran, and are well-known as the Alborz and Central basins, respectively. The Tabas coalfield is a major contributor to Iran metallurgical coking coal deposits, which is located in Tabas block in Central Iran [51].

The Tabas coalfield district is about 1200 square kilometers, which is divided into different sub-zones, namely Parvadeh, Mazinu, and Nayband [52]. General descriptions of the Tabas coalfield geology have been studies by Alavi [53]; Naimi Ghassabiyan [54]; Afzal et al. [55]; Farahbakhsh et al. [56]; Sereshki et al. [57]; Afzal [58]; Mohtasham Seyfi et al. [59]; and Saffari et al. [60].

The Parvadeh coal deposit in the middle of Tabas coalfield is located about 85 km SE of the city of Tabas in the Southern Khorasan Province in Central Iran, where the climate is hot and dry (Figure 5). This deposit is structurally a long anticline, which is oriented E-W. The studied area is one of the very active and complicated areas from the viewpoint of tectonics and seismicity in Iran.

The Parvadeh region consists of six zones, named A, B, C, D, E, and F, divided by major faults (Figure 6). The Parvadeh basin includes five coal seams, namely C_1, C_2, B_1, B_2, and D; it is worth noting that the B and C coal seams are minable based on their quality and quantity, especially the C1 and B2 seams that have better qualities; C1 is shown in Figure 7. The Tabas coal basin stratigraphic column is illustrated in Figure 8 [57-59]. The average thickness, gas content, and geological reserve for each coal seam are given in Table 1.

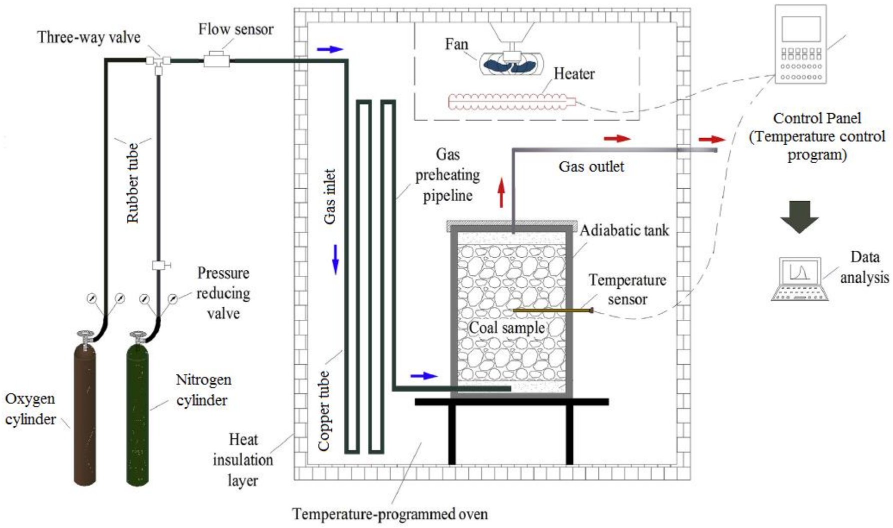


Figure 2. A schematic diagram of the apparatus applied for low-temperature oxidation.

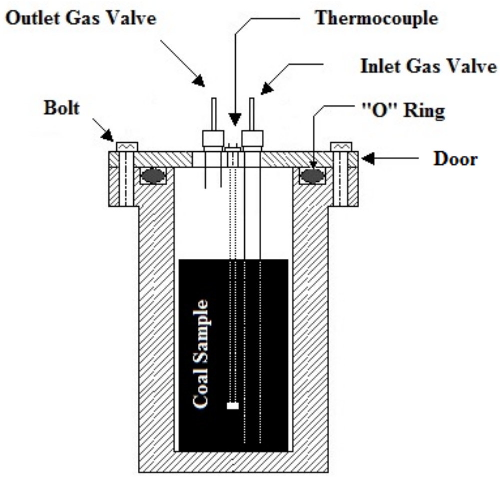


Figure 3. Sample container (bomb).

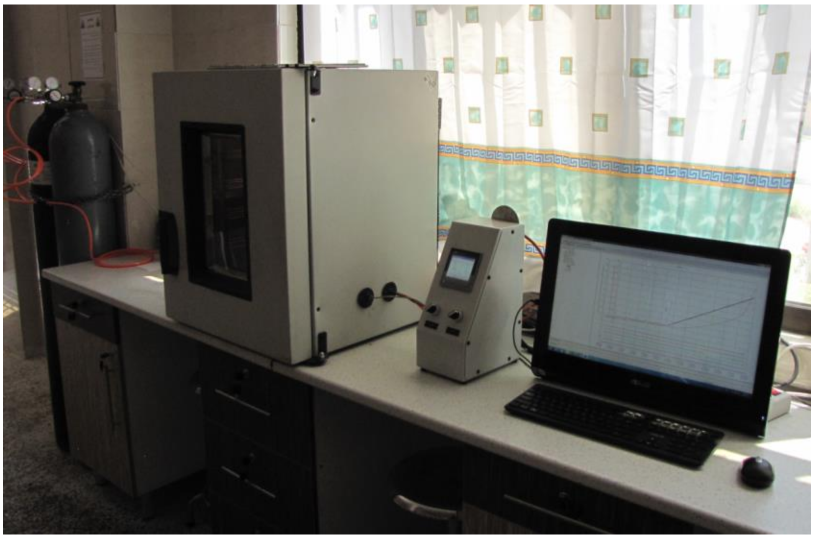


Figure 4. The testing system.

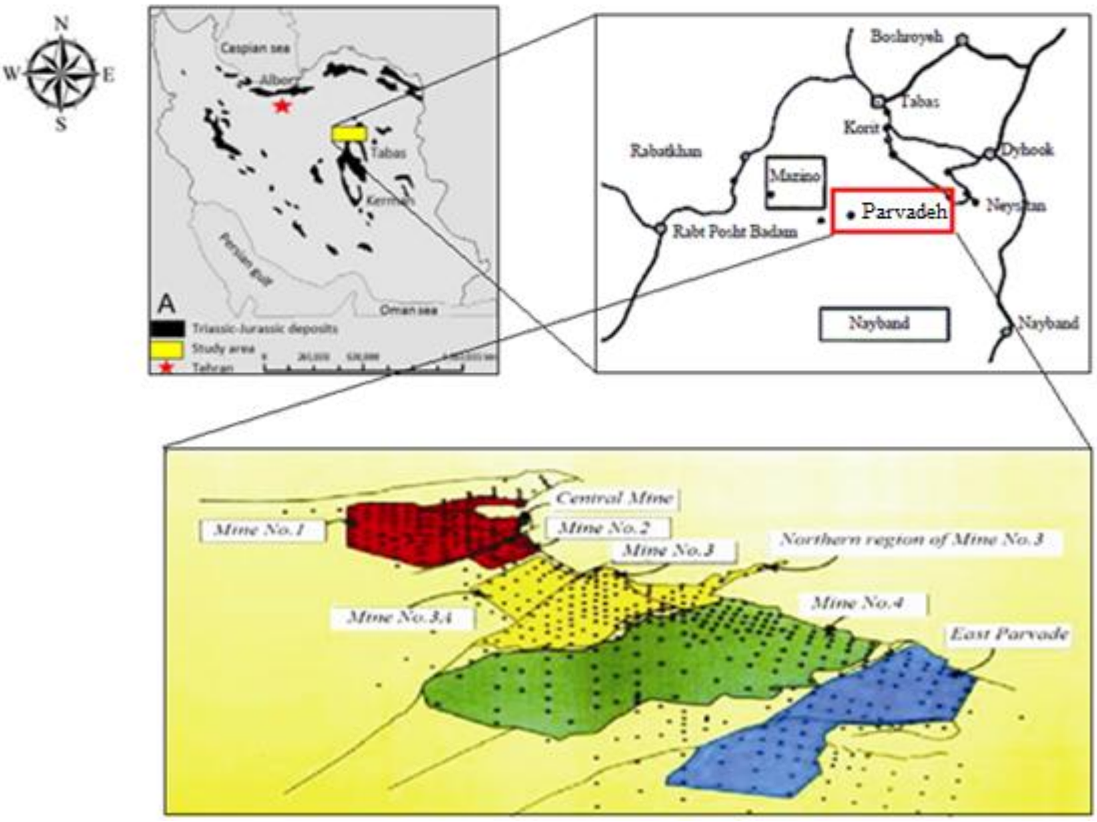


Figure 5. Geographical location of Tabas Parvadeh coal mine.

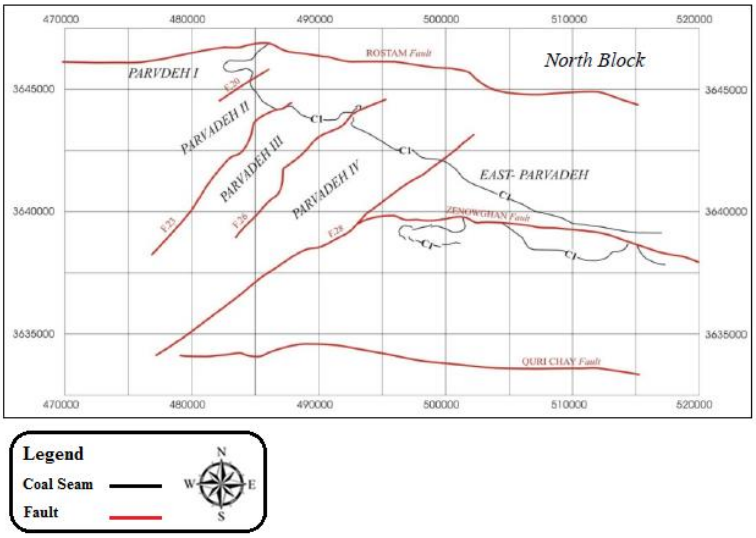


Figure 6. Locations of faults in Parvadeh deposits [55].

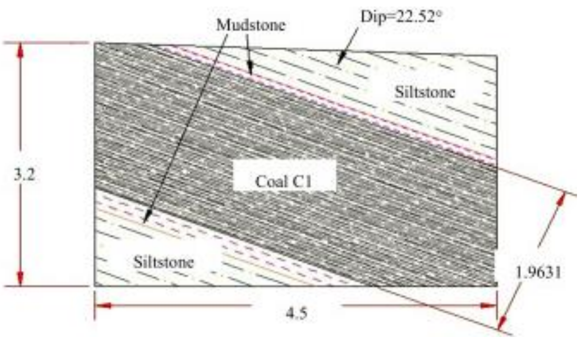


Figure 7. C1 coal seams in Parvadeh deposits.

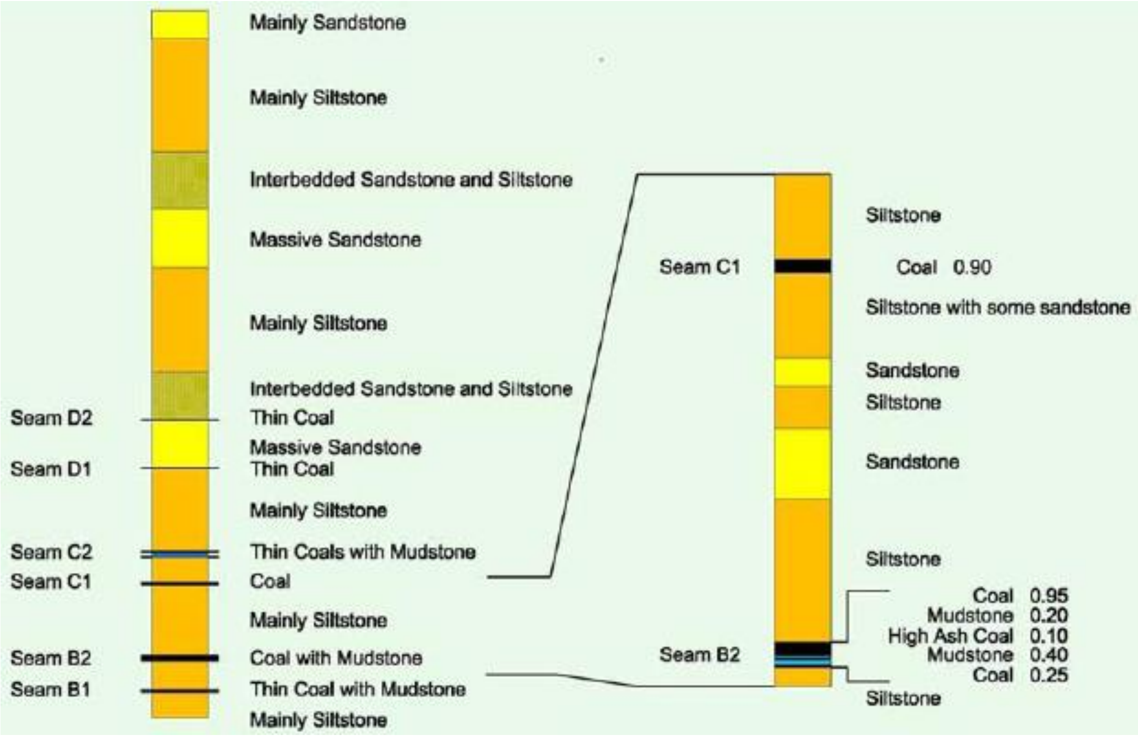


Figure 8. Tabas coal basin stratigraphic column (Modified after [6, 57, 59, 61]).

Table 1. Average thickness, gas content, and geological reserve of Parvadeh coal [59].

Coal seam / Parameter	D	C_2	C_1	B_2	B_1
Average thickness (m)	0.6	0.52	1.83	0.87	0.99
Geological reserves (million tons)	5824000	4696000	37469000	7342000	20873000
Gas content (m^3/ton)	8.64	12.42	17.06	12.07	13.04

4. Experimental investigations

4.1. Proximate analysis

The proximate analysis of coal essentially involves the determination of moisture, ash, volatile matter, and fixed carbon contents according to the American Society for Testing and Material (ASTM) standards [62-64]. Fixed carbon was obtained by subtracting the sum of the percentage of ash, moisture, and volatile matter from 100 [65].

4.2. Maceral petrographic analysis

For petrographic analysis, all samples were crushed to pass through a 1-mm sieve and then riffled to produce a representative sample of about 1 kg of each sample from which a mass of 14 g of coal was weighed using a scale for analysis. The final ground sample was mixed with epoxy (50 g of resin and 6 g of hardener) and moulded into particulate blocks using moulds and hydraulic coal press. Once the blocks were produced successfully, the surface of each one was ground and polished to the required level for petrographic studies. In the final preparation stage, the sample blocks were placed in the ultrasonic bath (ultrasonic cleaner with ultrasound between 20 and 400 KHz and water as a cleaning solvent) to remove the suspended particles. The polished blocks were used in the maceral group characterization. Maceral characterization was used to study the three main maceral groups; vitrinite, liptinite, and inertinite, and the mineral matter contents of the coal samples following standard procedures [66, 67].

The polished surface was examined using an OLYMPUS BX51 microscope, with 4x under oil immersion objective and an internal 10x lens creating 40x total magnification under reflected light (Figure 9). The microscope has a photomultiplier, digital read-out, and a computer attachment for processing of data. The photomultiplier attached allowed measuring the reflected light beam intensity for rank analysis. The standard procedures used are as recommended by the International Committee for Petrography [68, 69], and the International Standards: ISO 7404-3 [70] and ISO 7404-5 [71].

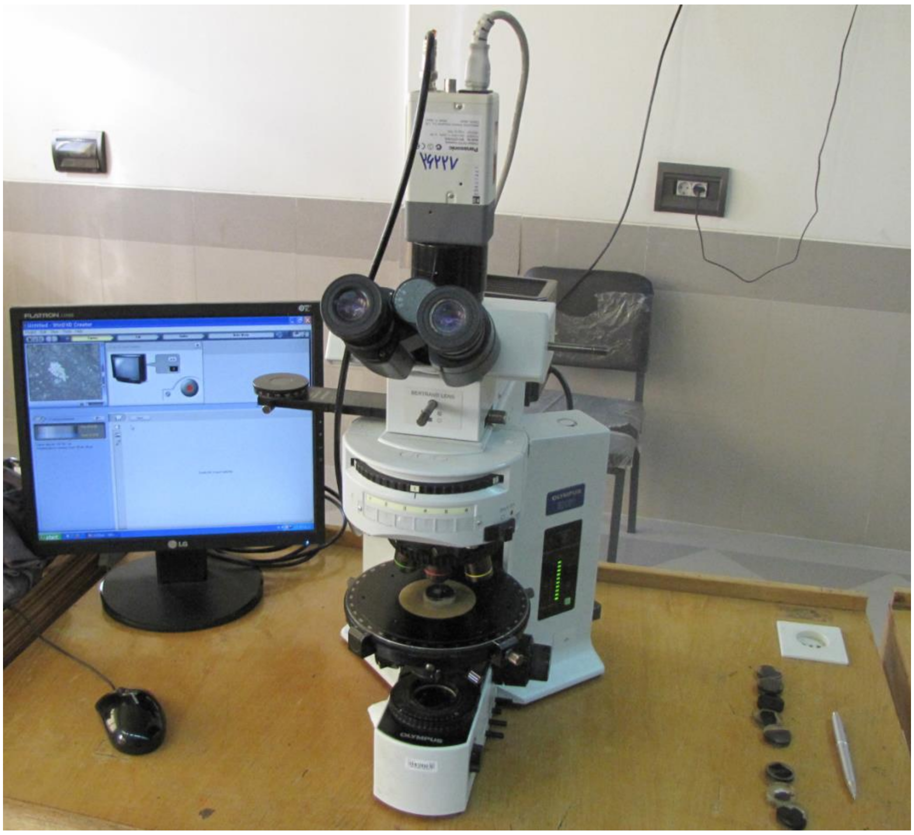


Figure 9. OLYMPUS BX51 microscope.

4.3. Results of tests

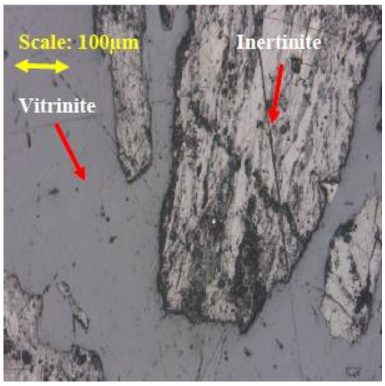
To evaluate the propensity of coals to spontaneous combustion, it is important to carry out the coal intrinsic characteristic analysis to establish the relationship between these characteristics and the CPT values; the results of experimental investigations, based on Sections 2, 4.1 and 4.2, are given in Table 2 and Figures 10 and 11.

Table 2 shows the results of proximate analysis, maceral petrographic, and CPT values of the coal samples. Figure 10 shows the macerals and minerals found in the coal samples. The coal samples were tested with CPT experimental setups. The testing results for the Tabas Parvadeh coal mine samples are given in Table 2 (end row) and Figure 11.

The CPT curves for the samples are shown in Figure 11. Their respective CPT values are contained in Table 2. As it can be seen, the coal samples 4 and 6 have a high potential of spontaneous combustion. This high potential is due to the high moisture content, high pyrite content, high vitrinite content, high liptinite content, and no inertinite content, in comparison to the other samples. These values and ratings are generally consistent with the characteristic differences between the samples.

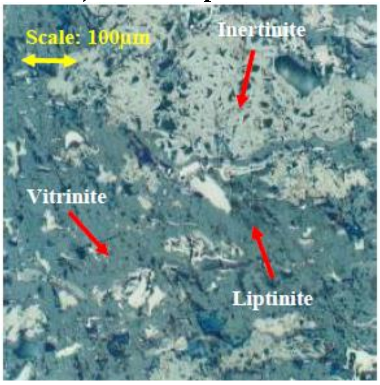
Table 2. Coal intrinsic characteristic analysis of Tabas Parvadeh coal mines.

Sample No.	1	2	3	4	5	6	7
Parvadeh No.	Parvadeh 1	Parvadeh 1	Parvadeh 2	Parvadeh 2	Parvadeh 2	Parvadeh 3	Parvadeh 4
Seam-Panel	C1-W3	C1-E3	C1-Block 4	B1-Block 3	B2-Block 2	C1-Block 1	C1-Block 1
Moisture Content (%)	0.768	2.739	4.680	6.556	3.732	7.940	2.560
Ash Content (%)	27.932	36.588	33.107	32.301	43.951	24.386	15.114
Volatile Matter (%)	17.383	14.936	17.968	17.645	15.379	21.113	23.114
Fixed Carbon (%)	53.917	45.737	44.244	43.498	36.938	46.561	59.212
Pyrite Content (%)	0.11	0.45	1.78	4.52	1.53	4.66	1.51
Vitrinite (%)	47.31	36.17	46.22	80.23	44.73	78.97	39.44
Liptinite (%)	3.89	8.15	10.69	15.25	5.8	16.37	9.25
Inertinite (%)	48.69	55.23	41.31	0	47.94	0	49.8
CPT Values (°C)	190	180	146	105	165	100	153

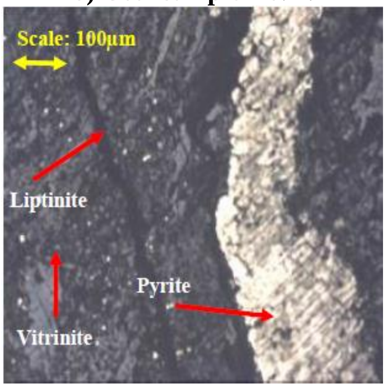


a) Coal sample No. 1.

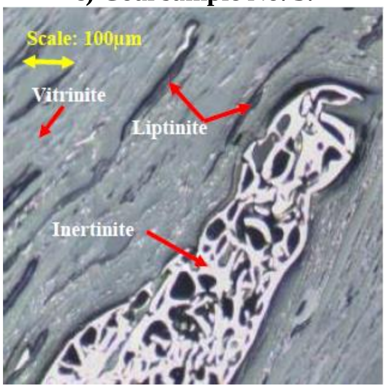
b) Coal sample No. 2.



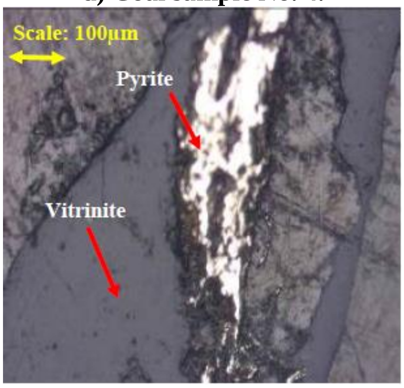
c) Coal sample No. 3.



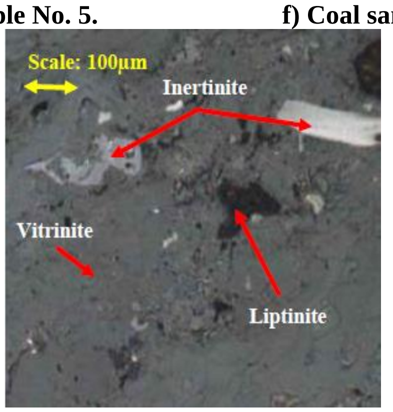
d) Coal sample No. 4.



e) Coal sample No. 5.



f) Coal sample No. 6



g) Coal sample No. 7.

Figure 10. Macerals and minerals found in coal samples.

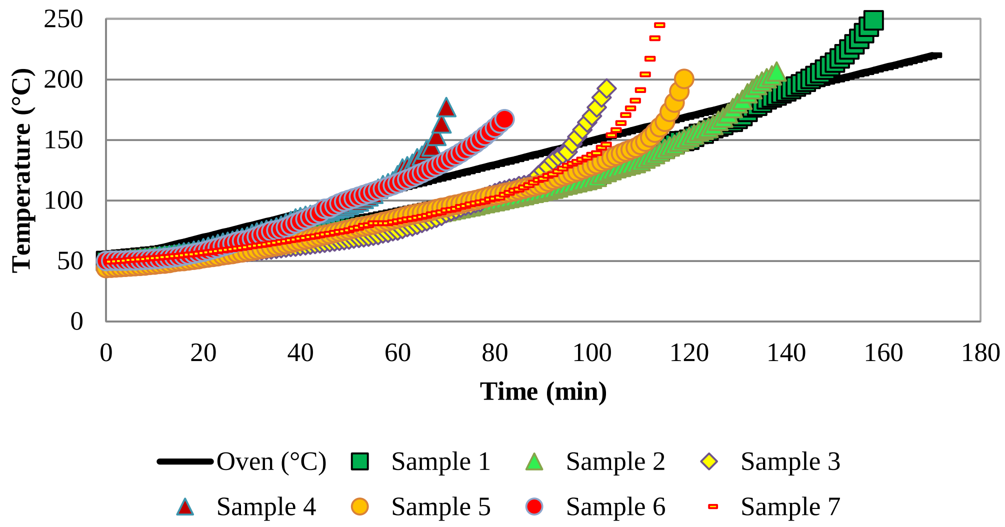


Figure 11. CPT test results for Tabas Parvadeh coal mine samples.

5. Relationship between coal intrinsic characteristics and CPT method

It is important to have an in-depth understanding of the relationship between the coal intrinsic characteristics and the spontaneous combustion propensity. This knowledge is necessary not only for detecting and preventing the spontaneous combustion of coal but also for reducing the degradation of sustainable development. Spontaneous combustion of coal performance is not a simple predictable manner. Coal intrinsic characteristics can affect the phenomenon of spontaneous combustion of coal; some of these characteristics accelerate the process and the other ones reduce it. Therefore, in this section, based on the relationship regression between these characteristics and the CPT values, these relationships were described and their role was determined.

5.1. Mutual effect of moisture and pyrite contents

The tests performed show that the moisture and pyrite contents play a very important role in initiating the spontaneous combustion of coal. Again, spontaneous combustion of coal is accelerated by a combination of pyrite and moisture at the same time. It acts as an important foundation for spontaneous combustion of coal (Figures 12 and 13).

Pyrite plays a vital role in the occurrence of the process of spontaneous combustion of coal. Generally, Pyrite acts as an effect as its oxidized product accelerates the rate of oxidation of the organic compounds present in coal. The pyrite oxidation leads to the formation of ferric ions, which catalyzes the reaction (Equations (1)-(4)). Also pyrite oxidation results in swelling, which, in turn, causes breakage of the coal particles, increasing their surface area for an enhanced oxidation.

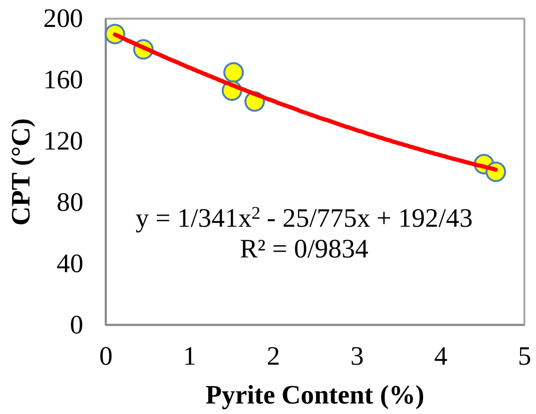


Figure 12. Correlation between pyrite content and CPT values.

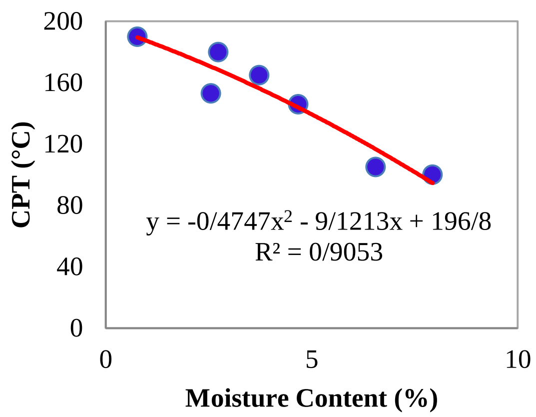


Figure 13. Correlation between moisture content and CPT values.

The specific heat of pyrite is only one-third of that for coal; but with the same heat absorption, the temperature rise of pyrite is three times higher when compared to coal [72]. Moreover, pyrite does not react effectively without the presence of moisture, and in a dry state does not contribute to the thermal runaway process [73].

Coal with increasing reactive pyrite content does not reach thermal runaway any faster in a dry state but in a moist state it does. Thus the key exothermic pyrite reaction takes place with oxygen in the presence of moisture.

Several equations for the reactions of pyrite, oxygen, and moisture are available in the past research works. For example, the reactions for pyrite oxidation are given in Equations (1)-(4).

$$FeS_2 + 8H_2O + \frac{7}{2}O_2 \rightarrow \qquad (1)$$
$$FeSO_4.7H_2O + H_2SO_4 \ (\Delta H = -1465.49 kJ) \qquad [74]$$

$$FeS_2 + 8H_2O + 7O_2 \rightarrow \qquad (2)$$
$$FeSO_4.7H_2O + SO_4^{2-} + 2H^+ \qquad [75]$$

$$FeS_2 + 7O_2 + 16H_2O \rightarrow \qquad (3)$$
$$2H_2SO_4 + 2FeSO_4.7H_2O + 1321\ kJ \qquad [73]$$

$$FeS_2 \xrightarrow{O_2 + H_2O} \qquad (4)$$
$$FeSO_4 \underset{O_2 + H_2O + FeS_2}{\overset{O_2 + H_2O}{\rightleftarrows}} Fe_2(SO_4)_3 \qquad [71]$$

The above-mentioned equations propose that oxygen and moisture are two prime weathering parameters, which contribute to the pyrite alteration shown, leading to the formation of sulfuric acid as the by-product of the alteration process. Presence of moisture doubles the reactivity rate of coal and presence of pyrite in dispersed form 10 folds the actual reaction rate [76].

These reactions can occur at low temperatures, and additionally, all of the reactions are exothermic. The heat generation from these reactions doubles that of coal with the same oxygen [77, 78]. As shown in Figure 14, the existence of moisture and pyrite contents on coal can be accelerated, and is a big promoter for the occurrence of spontaneous combustion of coal, described based on Equations (1)-(4).

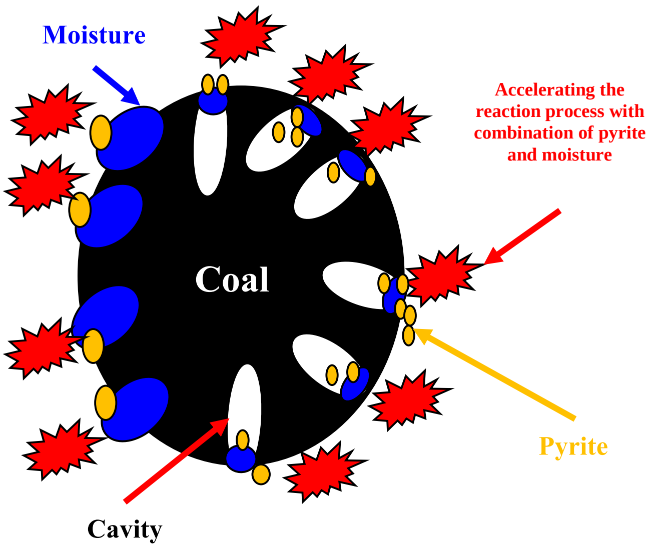


Figure 14. Effect of moisture and pyrite on accelerating the spontaneous combustion of coal [79, 80].

5.2. Effect of ash content

In Figure 15, the general trend effect of ash content on the spontaneous combustion of coal using CPT test is shown. R^2 is low in this correlation but based on the literature, there is an increase in the CPT values and an increase in the time to reach the thermal runaway as the ash content in the coal increases. It is able to define a negative correlation existing between the ash content and the spontaneous combustion of coal potential.

The results obtained indicate that with increase in the ash content on coals, the CPT values are increased and the spontaneous combustion of coal potential decreases. This relationship is due to the ash content in the coal acting as a heat sink, and absorbs heat from oxidation reactions, and ash contents prevents coal temperature rising. This is in-line with the studies reported on coal by Humphreys et al. [81], Smith et al. [82], Panigrahi and Sahu [83], and Beamish and Arisoy [26].

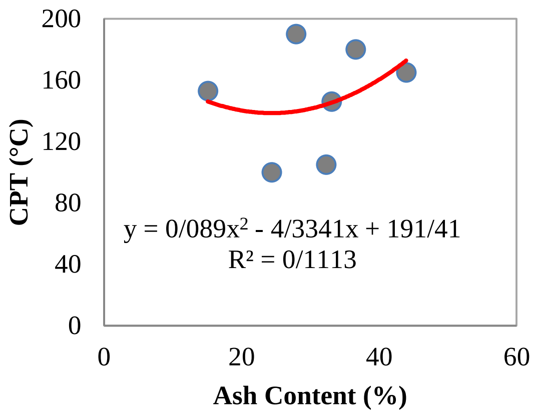


Figure 15. Correlation between ash content and CPT values.

5.3. Effect of volatile matter

In Figure 16, the effect of volatile matter on the spontaneous combustion of coal using the CPT test is shown. R^2 is low in this correlation but based on the literature, with increase in the volatile matter on coal, the CPT values are decreased and the spontaneous combustion of coal potential is enhanced. This relation is due to the volatile matter acting as a fuel and forming one of the sides of the fire triangle. Thus in coal samples with high volatile matter, the propensity of spontaneous combustion of coal is increased. This is in-line with the study reported on coal by Singh and Demirbilek [84], Raju [85], and Chandra and Prasad [33].

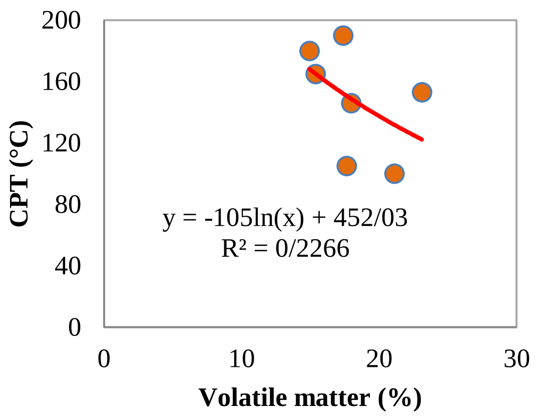


Figure 16. Correlation between volatile matter and CPT values.

5.4. Effect of fixed carbon

In Figure 17, the general trend effect of fixed carbon on the spontaneous combustion of coal using the CPT test is shown. R^2 is low in this correlation but based on the literature, with increase in the fixed carbon on coal, the CPT values are increased and the spontaneous combustion of coal potential is decreased. It has been known that the low rank coals (low fixed carbon) have a high propensity to spontaneously combustion because this coal will have a high moisture and high volatile matter contents in comparison with the high rank coals. Thus the mining, storage and transport of such coals create a significant hazard for management planning.

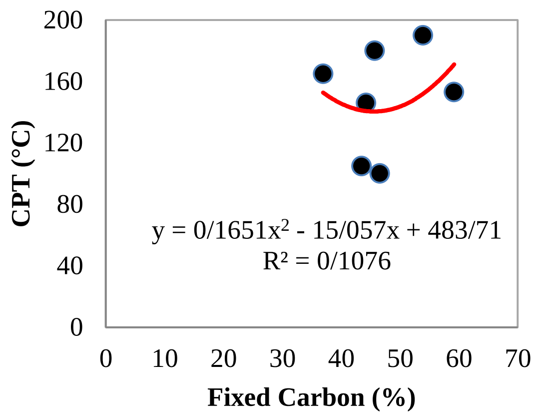


Figure 17. Correlation between fixed carbon and CPT values.

5.5. Effect of macerals content

Coal is a heterogeneous natural substance consisting of a number of constituents. Microscopically, the basic coal constituent is maceral, which is synonymous to minerals in inorganic rocks. Macerals are classified into three major organic groups, viz., vitrinite, liptinite, and inertinite based on their compounds. One of these classifications was given by Van Krevelen [86] and is shown in Figure 18. The plot shows the differences between macerals, variation within macerals, and changes in their composition with increasing coalification.

Maceral petrographic analysis provides important information for evaluation of spontaneous combustion of coal potential.

As seen in Figure 18, liptinite and vitrinite have higher H/C and O/C ratios, respectively, in comparison with inertinite. Existence of H and O in coal accelerates the spontaneous combustion of coal potential [87]. Thus existence of liptinite and vitrinite in coal samples causes the spontaneous combustion of coal potential. For a closer look at this issue, the vitrinite, liptinite, and inertinite contents of the Tabas Parvadeh coal mine samples were measured, and the results obtained were presented in Table 2 and Figure 10.; this will be followed in more details in the continuing sub-sections.

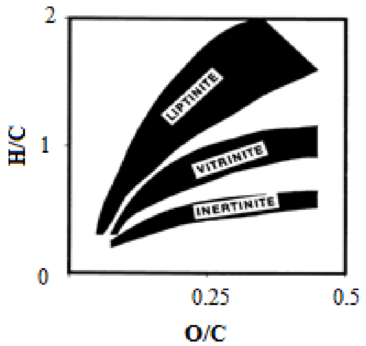


Figure 18. A Van Krevelen plot showing approximate bands for the three main maceral groups [86].

5.5.1. Vitrinite group

The main characteristics of vitrinite group were described by Stach [68], Sengupta [88], and Chaudhuri [89]. The most important processes of vitrinite formation from precursors are humification and gelification. Humification involves slow progressive oxidation, which may be accelerated by addition of oxygen. In the presence of oxygen, the lignin is first attacked by wood destroying fungi and then aerobic bacteria, and is converted into a humic substance [88].

As stated earlier, "humification involves slow progressive oxidation, which may be accelerated by addition of oxygen", coal with a high percentage of vitrinite contents; when oxygen reaches these groups of macerals, the sustainability of this coal to spontaneous combustion is accelerated. Moreover, these groups of macerals have higher H/C and O/C ratios (Figure 18); existence of H and O in coal accelerates the spontaneous combustion of coal potential. In Figure 19, the results of vitrinite fit CPT values are shown. The results show that with increase in the vitrinite in coal samples, the sustainability of these coals to spontaneous combustion is enhanced.

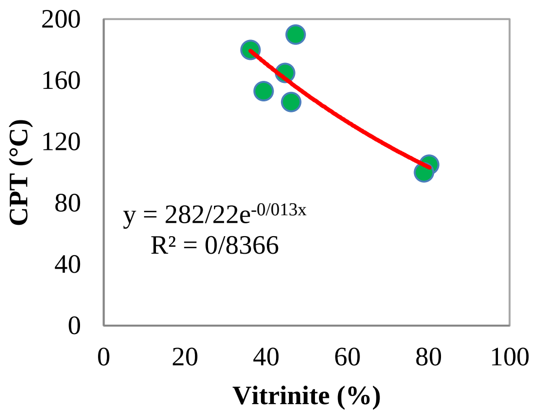


Figure 19. Correlation between vitrinite and CPT values.

5.5.2. Liptinite group

The main characteristics of liptinite group were described by Stach [68], Sengupta [88], and Chaudhuri [89]. It originates from a relatively hydrogen-rich plant material, and generally, the liptinite contents have high hydrogen content within it, influencing the technological properties of coal [89].

As stated earlier, "liptinite group originates from a relatively hydrogen-rich plant material", and has higher H/C and O/C ratios (Figure 18); existence of H and O in coal accelerates the spontaneous combustion of coal potential. Thus coal with a high percentage of liptinite contents is sustainable for spontaneous combustion of coal. In Figure 20, the results of liptinite fit CPT values are shown. The result show that with increase in the liptinite in a coal samples, the sustainability of these coals to spontaneous combustion is enhanced, and the CPT values are decreased.

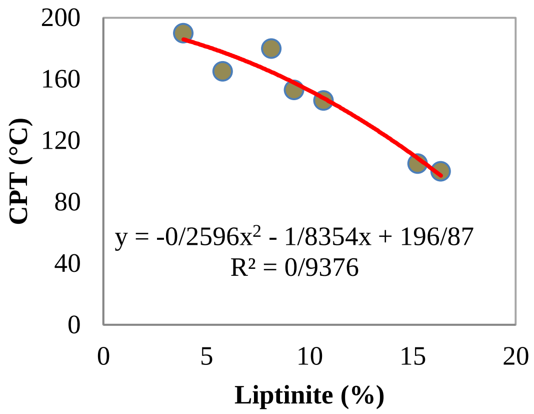


Figure 20. Correlation between liptinite and CPT values.

5.5.3. Inertinite group

The main characteristics of inertinite group were described by Stach [68], Sengupta [88], and Chaudhuri [89]. The chemical composition of inertinite suggests higher carbon and lower oxygen and hydrogen contents compared with vitrinite [90]. Thus their rank is higher in comparison with the macerals of the vitrinite and liptinite groups [89].

As stated earlier, "chemical composition of inertinite suggests higher carbon and lower oxygen and hydrogen contents compared with vitrinite", and have lower H/C and O/C ratios in comparison with liptinite and vitrinite (Figure 18). Thus coal with a high percentage of inertinite content is not sustainable for spontaneous combustion of coal. The inertinite fit CPT values are shown in Figure 21. These results show that with increase in inertinite in a coal sample, the sustainability of this coal to spontaneous combustion is decreased and the CPT values are increased.

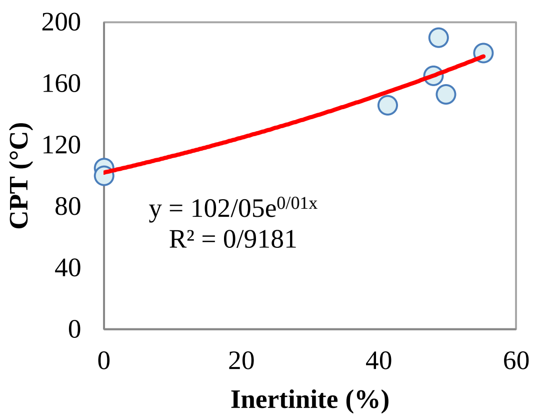


Figure 21. Correlation between inertinite and CPT values.

6. Conclusions

The phenomenon of spontaneous combustion of coal is one of the main vital events in coal fields. This process is responsible for polluting the environment and creating contamination, which results in the instability of sustainable development, and affects the environmental, economic, and social problems. Spontaneous combustion of coal is affected by coal intrinsic characteristics. Thus a better understanding about the tendency of spontaneous combustion of coal could greatly benefit the schematization of coal mining. Hence, in this work, the spontaneous combustion of coal propensity was measured experimentally using the crossing point temperature (CPT) test in the Tabas Parvadeh coal mines. The results obtained show that the B1 seam in Parvadeh II and the C1 seam in Parvadeh III have high potentials of spontaneous combustion of coal, which is due to the high moisture content, high pyrite content, high vitrinite content, high liptinite content, and no inertinite content, in comparison with the other seams in the other mines in Tabas Parvadeh.

The following conclusions were drawn from the present investigation:

1. Statistical analysis revealed that CPT and coal characteristic analysis had coefficient of determination (moisture (R^2 = 0.9053), ash (R^2 = 0.1113), volatile matter (R^2 = 0.2266), fixed carbon (R^2 = 0.1076), pyrite (R^2 = 0.9834), vitrinite (R^2 = 0.8366), liptinite (R^2 = 0.9376), inertinite (R^2 = 0.9181)); and can be used to predict the spontaneous combustion of coal but moisture, pyrite, vitrinite, liptinite, and inertinite contents have high influences on the spontaneous combustion of coal liability in this coal field.
2. An increase in the moisture, volatile matter, pyrite, vitrinite, and liptinite contents enhances the spontaneous combustion of coal potential in the Tabas Parvadeh coal mines.
3. From the statistical analysis, it could be also be resulted that the propensity of the Tabas Parvadeh coals to spontaneous combustion decreases with increase in the ash, fixed carbon, and inertinite contents.
4. The CPT test can be used as a reliable method to predict the potential of coals to spontaneous combustion.

Acknowledgements

Authors acknowledge the help of all staff members of Parvade I, II, III, IV Coal Mine. The authors are also grateful to Eng. Montazeri (CEO at Samin-e-Sabz Golshan Shomal Company) for his kind permission and his contribution to sample collection.

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بررسی رابطه‌ی بین مشخصات ذاتی زغال‌سنگ در پتانسیل خودسوزی با استفاده از روش دمای نقطه تقاطع مطالعه موردی: معادن زغال‌سنگ پروده طبس، ایران

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ارسال ۲۰۱۸/۱۰/۶، پذیرش ۲۰۱۸/۱۱/۳

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چکیده:

پدیده خودسوزی زغال‌سنگ یکی از خطرناک‌ترین مخاطرات در صنایع زغال‌سنگ به ویژه در معادن زیرزمینی زغال‌سنگ است؛ بنابراین داشتن دانش اولیه در مورد رخداد این پدیده در معادن زیرزمینی زغال‌سنگ برای جلوگیری از این فرآیند، از دست دادن زندگی، هدر رفت منابع عظیم اقتصادی و آلودگی محیط‌زیست دارای اهمیت به سزایی است. هدف از این پژوهش، تعیین پتانسیل خودسوزی زغال‌سنگ در معادن زغال‌سنگ پروده طبس با استفاده از ارزیابی تأثیر مشخصات ذاتی زغال‌سنگ در رخداد این پدیده است. برای این منظور، نمونه‌های زغال‌سنگ از معادن پروده یک تا چهار جمع‌آوری و مشخصات ذاتی نمونه‌های زغال‌سنگ در آزمایشگاه تعیین شد. به منظور تعیین میزان خودسوزی این نمونه‌ها، از روش دمای نقطه تقاطع استفاده شد. سپس ارتباط بین مشخصات ذاتی نمونه‌های زغال‌سنگ و مقادیر روش دمای نقطه تقاطع تعیین شد. نتایج به دست آمده نشان داد که لایه B_1 در پروده دو و لایه C_1 در پروده سه دارای پتانسیل بالای خودسوزی هستند. نتایج همچنین نشان داد، با افزایش رطوبت، مواد فرار، پیریت، ویترینیت و لیپتینیت محتوی در نمونه‌های زغال‌سنگ تمایل زغال‌سنگ به خودسوزی در این معادن افزایش می‌یابد. نتایج حاصل از این پژوهش برای مدیریت این پدیده در معادن زغال‌سنگ پروده طبس بسیار حائز اهمیت است. ارزیابی پدیده خودسوزی زغال‌سنگ در معادن زغال‌سنگ باید در مراحل اولیه طراحی و در کل چرخه‌ی معدنکاری زغال‌سنگ حتی پس از بسته شدن معدن انجام شود.

کلمات کلیدی: خودسوزی زغال‌سنگ، معادن زغال‌سنگ پروده طبس، مشخصات ذاتی زغال‌سنگ، روش دمای نقطه تقاطع.