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CLASSIFICATION OF COAL SEAMS WITH RESPECT TO THEIR SPONTANEOUS HEATING SUSCEPTIBILITY USING K-MEANS CLUSTERING

H. B. Sahu[1], D. C. Panigrahi[2] and S. S. Mohapatra[3]

[1] Asst. Professor, National Institute of Technology, Rourkela – 769 008, India
[2] Professor, Indian School of Mines University, Dhanbad – 826 004, India
[3] Professor, National Institute of Technology, Rourkela – 769 008, India

ABSTRACT

The current paper presents the k-means clustering approach for classification of coal seams with respect to their spontaneous heating susceptibility. To apply this technique, a number of coal samples of varying ranks have been collected from different coalfields of the country. These samples include some of the coal seams, which are well known for their high and low susceptibility as observed in the mines. The intrinsic properties of the coal seams have been determined by proximate, ultimate and petrographic analyses. The spontaneous heating proneness of the samples has been studied using different experiments in the laboratory, viz. crossing point temperature, differential thermal analysis, critical air blast test and differential scanning calorimetry. Correlation studies between the intrinsic properties and susceptibility indices have been carried out to identify the parameters for clustering purposes. The identified parameters have been used as inputs in the k-means clustering algorithm and coal seams have been classified into four different categories. This classification approach will help the planners and mining engineers in the field to adopt appropriate measures for preventing the occurrence of mine fires.

Key words: Spontaneous heating; coal; classification; k-means clustering.

1. INTRODUCTION

Coal mine fire is a major problem worldwide and has been a great concern both for the industry and researchers in this field. It has been reported that majority of fires existing today in different coalfields are mainly due to spontaneous combustion of coal (Feng et al., 1973; Saghafi and Carras, 1997; Sensogut and Cinar, 2000). Most mine fires start very small and gradually expand in size. These fires endanger not only the valuable lives of men in a mine, but also cause considerable economic losses to the organisation. In addition, it causes serious environmental pollution affecting all four major sectors, viz. land, water, air and society. Most of these fires could be averted if suitable preventive measures are taken. The first step for taking proper preventive measure is to assess the susceptibility of coal seams and classify or categorise them on the basis of their proneness to spontaneous heating, which could dictate the type of advance precautionary measures against the occurrence of these fires. Therefore, the determination of susceptibility potential of coals due to spontaneous heating and their classification are essential to plan the production activities and storage capabilities in a coal mine.

Researchers of different countries follow different methods to assess the spontaneous heating tendency of coal by carrying out different experiments in the laboratory such as crossing point temperature (CPT) in India, Russian U-index in Russia, Olpinski index in Poland, adiabatic calorimetry in U.S.A. etc. Some of the other methods attempted by researchers are peroxy complex analysis (Jones and Townend, 1949; Yohe and Harman, 1941), differential thermal analysis (Banerjee and Chakravarty, 1967; Gouws and Wade, 1989a), wet oxidation method (Singh et al., 1985; Tarafdar and Guha, 1989), modified CPT index (Feng et al., 1973; Gouws and Wade, 1989b; Mahadevan and Ramlu, 1985), self heating temperature (Miron et al., 1990; Smith and Lazzara, 1987), gas indices studies (Kuchta et al., 1980; Panigrahi and Bhattacharjee, 2004; Singh et al., 2007) etc. Some of the researchers have used the results obtained from the experimental methods and attempted to classify the coal seams according to their proneness to spontaneous heating, but most of these classifications are empirical in nature (Feng et al., 1973; Mahadevan and Ramlu, 1985). Some of these classifications are based on crossing point temperature method. However, it has been observed in the past (Banerjee, 2000) that in case of high moisture coals usually with high susceptibility, there is a shift of the crossing point temperature to a high value, because of release of moisture during heating. This indicates that the coal is poorly susceptible, but in reality it is a highly reactive coal. Thus, there is no universally accepted criterion for classification of coals with respect to their proneness to spontaneous heating and the degree of their shift from one coal to other.

In this study, an attempt has been made to develop a classification system of coal based on their spontaneous heating susceptibility by using k-means clustering algorithm, which has been shown to be effective in producing good clustering results for many practical applications (Ahmad and Dey, 2007). To apply this technique, a number of coal samples both from fiery and non-fiery seams of different coal fields were collected and their intrinsic properties were determined by carrying out proximate, ultimate and petrographic analyses. The spontaneous heating susceptibility potential were determined by four different methods, viz. crossing point temperature, differential thermal analysis, critical air blast analysis and differential scanning calorimetry. Statistical analysis has been carried out to determine the appropriate intrinsic properties and susceptibility indices required for classification purposes. These parameters have been used in the k-means clustering approach for classification of Indian coals with respect to their spontaneous heating susceptibility.

2. DETERMINATION OF INTRINSIC PROPERTIES OF COAL SAMPLES

In order to study the intrinsic properties of coal governing spontaneous heating, 31 coal samples were collected from different Indian coalfields covering both fiery and non-fiery coal seams of different ranks spreading over 8 different mining companies. Table 1 presents the details of samples collected. The coal samples were collected from different seams following channel sampling procedure (Peters, 1978). The intrinsic properties of these samples were determined by proximate, ultimate and petrographic analyses.

The moisture (M), volatile matter (VM) and ash content (A) of coal samples were determined by proximate analysis following the method specified by IS (Indian Standard) 1350 Part – I (1969). The carbon (C) and hydrogen (H) contents of coal samples were determined by ultimate analysis, as per IS 1350, Part – IV/Sec1 (1974), nitrogen content by Kjeldhal method as per IS 1350 (1975), total sulphur content as per IS 1350, Part III (1969) and oxygen content (O) by difference. In petrographic analysis the vitrinite (V), Liptinite (L) or exinite and inertinite (I) contents of coal samples were determined by following standard procedures under a Leitz Orthoplan microscope in both white and fluorescence light (Stach et al., 1982; ICCP, 1971 and 1994; IS 9127 (part I and II of 1979)). The results of proximate, ultimate and petrographic analyses have been presented in Table 1.

It may be observed from Table 1 that the total sulphur content of all the coal samples are less than 1.20% and a part of this will be pyretic sulphur. Munzer (1975) and Banerjee (2000) have inferred that pyrite might have an appreciable effect if its concentration in finely dispersed form exceeds 5 to 10%. If the pyretic sulphur is less than 5%, its effect would not be of much importance. Therefore, the results of only carbon (C), hydrogen (H) and oxygen (O) have been taken into consideration for further analysis.

Table 1: Intrinsic properties of coal samples

Sample no.	**Coal seam and Colliery**	**Proximate analysis**			**Ultimate analysis**				**Petrographic analysis**		
		M%	**VM%**	**A%**	**C%**	**H%**	**O%**	**S%**	**V%**	**L%**	**I%**
1	Seam-IX Hingula	11.13	25.19	38.46	66.38	8.77	21.22	0.62	34.68	6.36	16.38
2	Seam-VII Lingaraj	14.29	31.25	16.27	72.62	6.63	17.44	0.55	56.24	2.18	11.68
3	Seam-V Lingraj	7.25	23.9	40.50	71.48	8.71	17.23	0.41	51.62	8.38	14.67
4	Seam-IV Lingaraj	9.59	28.93	7.68	80.61	5.69	11.23	0.72	16.47	7.34	28.37
5	Seam-III Ananta	8.97	29.49	22.88	75.78	7.00	14.50	0.69	20.85	10.09	20.00
6	Seam-III Bharatpur	10.02	26.06	31.57	71.91	7.76	17.67	0.61	27.9	12.32	21.20
7	Seam-II Ananta	14.5	31.97	12.35	73.85	6.33	17.83	0.25	29.67	2.61	30.22

8	Seam-II Bharatpur	11.32	29.81	21.80	73.67	6.98	16.93	0.48	42.37	2.27	33.61
9	Seam-II Jagannath	6.67	27.9	36.40	77.72	8.43	15.74	0.53	24.12	2.48	24.82
10	Seam-II Lingaraj	6.65	30.31	22.53	77.94	6.96	12.88	0.38	21.5	5.75	26.00
11	Seam-I Deulbera	9.12	33.51	8.37	80.20	6.51	10.22	0.83	36.63	8.24	23.99
12	Seam-I Nandira	8.72	25.14	13.75	80.83	5.86	10.47	0.52	27.67	4.80	24.91
13	Lajkura-IV Orient-3	6.78	26.82	33.09	74.79	7.87	14.68	0.74	9.44	6.29	35.84
14	Lajkura-III Orient-3	6.94	28.48	28.22	76.11	7.42	14.27	0.48	39.77	1.52	22.35
15	Lajkura-II Orient-2	11.34	23.48	30.56	72.01	7.44	18.24	0.46	14.07	1.67	37.78
16	Lajkura-I Orient-3	6.74	26.14	34.89	69.11	8.05	20.04	0.57	27.64	2.69	13.24
17	Rampur-IV Hingir-Rampur	7.64	22.13	37.02	73.85	8.00	15.67	0.47	18.62	5.85	30.50
18	Rampur-B Hirakhand Bundia	5.00	24.01	32.40	78.47	7.46	11.55	0.37	13.13	7.72	42.66
19	Rampur-A Hirakhand Bundia	4.88	24.17	38.87	75.61	8.32	12.91	0.66	9.3	4.75	39.46
20	Ib Belpahar	6.31	28.39	32.42	75.76	7.92	13.69	0.35	9.44	6.29	35.84
21	Seam – 0 Bastacola	1.00	17.36	15.73	88.7	4.71	3.48	1.20	51.12	2.51	40.50
22	Mahuda bottom Murlidih	1.90	33.08	16.00	87.86	4.12	5.24	0.35	64.8	8.60	20.00
23	Laikdih West Victoria	0.60	22.32	10.73	86.75	5.33	5.58	0.42	68.63	4.90	24.18
24	Samla Samla	8.43	24.43	9.60	80.85	5.73	10.48	0.38	80.13	1.30	12.38
25	Burra Dhemo Methani	1.80	36.13	14.27	80.6	5.99	10.36	0.66	65.36	9.78	16.20
26	Dakra Dakra Bukbuka	10.00	32.27	18.00	77.71	5.26	14.83	0.46	71.20	6.60	14.20
27	Hatidhari Saunda	10.52	29.47	11.91	80.44	5.01	11.28	0.85	77.12	3.45	15.04
28	Seam - III Chirimiri	7.67	29.83	18.88	79.80	4.97	13.31	0.77	35.18	5.93	53.26
29	Seam - IVB Kampti	14.39	29.31	12.76	79.40	3.73	14.75	0.50	26.40	10.80	50.60
30	Jhingurda Jhingurda	9.68	29.80	18.12	76.83	6.58	13.93	0.59	37.13	0.39	40.48
31	Neyveli lignite	37.3	32.32	3.40	71.30	5.00	22.46	0.26	83.96	5.24	6.10

Sample nos. 1-20 : Mahanadi Coalfields Ltd., Sample nos. 21-23 : Bharat Coking Coals Ltd.
Sample nos. 24-25 : Eastern Coalfields Ltd., Sample nos. 26-27 : Central Coalfields Ltd.
Sample no. 28 : South Eastern Coalfields Ltd., Sample no. 29 : Western Coalfields Ltd.
Sample no. 30 : Northern Coalfields Ltd., Sample no. 31 : Neyveli Lignite Corp.

3. FIELD EXPERIENCE ON OCCURRENCE OF FIRE IN DIFFERENT COAL SEAMS

A few samples mentioned in Table 1 are known for their susceptibility to spontaneous heating and experiences of fire in these seams are as given below:

- Seam - 0 of Bastacola Colliery (sample no. 21) and Laikdih seam of West Victoria Colliery (sample no. 23) take a very long time to catch fire in the mine as well as in coal stacks. These seams are considered to be the least susceptible.
- The lignite of Neyveli (sample no. 31) occurs in aquifers. Once it is taken out and stacked, it catches fire in a short time compared to all other seams from where samples have been taken.
- Jhingurda seam (sample no. 30), Samla seam (sample no. 24), Chirimiri III seam (sample no. 28), Dakra Bukbuka seam (sample no. 26) and Burradhemo seam (sample no. 25) are well known for their high susceptibility in Indian coalfields. However, these seams take more time compared to lignite of Neyveli to catch fire.

- Occasional fires have been observed in seam III of Bharatpur Colliery (sample no. 6), and Rampur – IV seam of Hingir-Rampur colliery (sample no. 17).

4. DETERMINATION OF SUSCEPTIBILITY INDICES

Susceptibility indices of coal samples were determined by different experimental methods, viz. crossing point temperature (CPT) method, differential thermal analysis (DTA), critical air blast (CAB) analysis and differential scanning calorimetric (DSC) studies. First a brief description about the procedure followed in each experiment are described and thereafter the results of experiments are presented.

Crossing Point Temperature

The crossing point temperatures (CPT) of the coal samples were determined following the procedure and experimental set up described by Panigrahi et al. (1996). Glycerine bath was used as the heating medium. The rate of rise of temperature was maintained at 1°C per minute and air was supplied at 80cc per minute.

Differential Thermal Analysis

Differential thermal analysis was carried out by a Differential Thermal Analyser. The standardised parameters suggested by Banerjee and Chakravorty (1967) were followed while performing the experiments. DTA thermograms were obtained upto 350 **°C** at a heating rate of 5 **°C** per minute. In the initial stage of heating (stage I), the endothermic reaction predominates, probably due to the release of inherent moisture in coal. In the second stage (stage II), the exothermic reaction becomes significant, but the rate of heat release is not steady all through, as it changes with temperature. A steep rise in heat evolution is observed in the third stage (stage III).

The rate of temperature rise in stage II has been cited by different researchers viz. Banerjee and Chakravorty (1967), Gouws and Wade (1989) as being less for coals with less susceptibility to spontaneous heating. The exothermicity in stage III is not regarded as a reliable indicator of the self heating risk, because it may be equally high for low rank coals. However, the temperature of transition or characteristic temperature or onset temperature is considered to be significant. It is observed that lower is this temperature, more susceptible is the coal towards spontaneous heating. Therefore, all the thermograms were analysed for the determination of the transition temperature (T_c) by the following procedure:

- A tangent was drawn at the inflexion point of the endothermic region and another tangent was drawn at the rising portion of the curve of stage III.
- The intersection between the two tangents gives the characteristic temperature.

Determination of characteristic temperature or onset temperature for sample number 29 has been demonstrated in Figure 1.

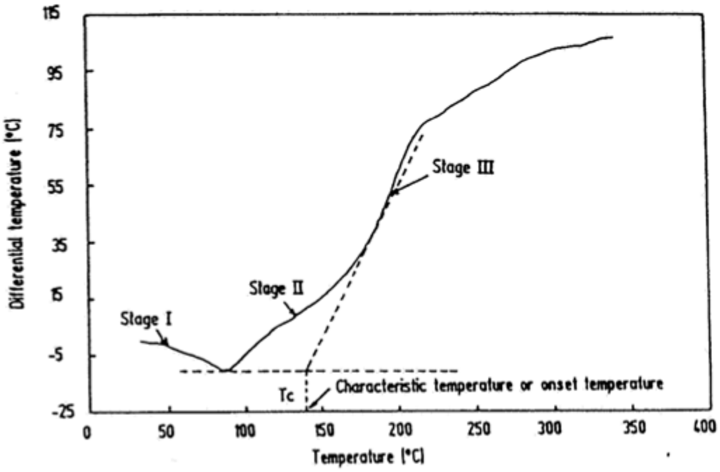

Figure 1: Determination of characteristic temperature (T_c) from DTA thermogram

Critical Air Blast Analysis

Critical air blast (CAB) is a measure of the reactivity of coal to air. It is the minimum rate of air blast, which will maintain combustion of closely graded coal in an ignition bed of specified dimensions. More reactive the coal towards air is, lower is its CAB value. The critical air blast values (litre/min) of all the coal samples were obtained following the procedure described by Panigrahi et al. (1999).

Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) is used to measure heat flow into or out of a sample as it is exposed to a controlled thermal profile. A Perkin-Elmer DSC-7 calorimeter was used in the present study. About 10 mg coal sample was weighed accurately and placed in the sample holder while the reference holder was kept empty. The DSC thermogram was obtained upto 550 ^{0}C at a heating rate of 30 ^{0}C per minute with oxygen as purge gas at a rate of 20 cc per minute.

The above procedure was followed to obtain the DSC thermograms for all the 31 coal samples. It was observed from all the thermograms that initially the endothermic reaction dominates followed by the exothermic reactions. The temperature of initiation of the exothermic reaction can be considered as an indicator of spontaneous heating susceptibility of coal samples, which is known as the onset temperature. The lower is this temperature, higher is the spontaneous heating susceptibility. To determine the onset temperature or characteristics temperature (T_o) of exothermic reaction, first a tangent is drawn at the inflexion point of the pre-transition. Then a second tangent is drawn at the greatest slope of the first exothermic reaction. The intersection of the two tangents gives the characteristics or onset temperature. In DSC-7 calorimeter the onset temperature is determined by selecting the point (temperature) at which the tangents are to be drawn. The onset temperature is read out (displayed) directly from the intersection of the tangents.

4.5 Results of Susceptibility Indices

The results of different susceptibility indices obtained by the above experiments are presented in Table 2.

Table 2: Results of different susceptibility indices of coal samples

Sample No.	**CPT (^{0}C)**	**DTA T_c (^{0}C)**	**CAB (litre/min)**	**DSC T_0 (^{0}C)**
1	149	171.87	0.54	249.37
2	149	136.47	0.57	235.21
3	146	137.33	0.58	240.76
4	148	124.82	0.57	240.02
5	147	153.34	0.65	234.30
6	148	157.89	0.97	236.39
7	155	158.46	1.06	225.40
8	150	127.69	1.03	233.22
9	148	160.00	0.59	236.96
10	147	146.25	0.59	229.17
11	144	145.88	0.56	229.89
12	144	148.33	0.41	226.66
13	150	135.88	0.66	240.79
14	151	140.67	0.63	242.75

15	142	155.71	0.72	233.89
16	150	165.71	0.96	237.77
17	148	178.46	0.53	245.63
18	141	168.33	0.75	245.84
19	143	146.25	0.62	248.90
20	154	152.94	0.70	245.75
21	180	188.98	2.47	286.02
22	155	128.38	1.04	235.20
23	160	169.66	1.27	259.46
24	152	162.30	0.44	230.91
25	150	129.33	0.79	217.61
26	144	132.94	0.63	225.94
27	152.5	136.87	0.79	216.28
28	155	145.33	0.48	224.14
29	150	128.00	0.17	222.06
30	138	122.67	0.33	235.32
31	173	149.23	0.25	262.44

5. CORRELATION BETWEEN SUSCEPTIBILITY INDICES AND INTRINSIC PROPERTIES

The correlation studies have been carried out between the different susceptibility indices and the coal characteristics as obtained from proximate, ultimate and petrographic analyses. The susceptibility indices are taken as dependent variables and each constituent obtained from the proximate, ultimate and petrographic analyses as an independent variable. The correlation coefficients obtained in all cases are presented in Table 3.

Table 3: Correlation coefficients between different susceptibility indices and constituents obtained from proximate, ultimate and petrographic analyses

Sl. No.	**Susceptibility Indices → Intrinsic Characteristics ↓**	**CPT (^{0}C)**	**DTA T_c (^{0}C)**	**CAB (litre/min)**	**DSC T_0 (^{0}C)**
1.	M	0.76	0.33	0.68	0.69
2.	VM	0.65	0.72	0.80	0.74
3.	A	0.50	0.39	0.28	0.43
4.	C	0.47	0.51	0.55	0.56
5.	H	0.45	0.31	0.40	0.06
6.	O	0.79	0.38	0.85	0.63
7.	V	0.45	0.33	0.46	0.26
8.	L	0.36	0.72	0.39	0.24
9.	I	0.49	0.39	0.30	0.32

It can be observed from the above correlation study that

- CPT, transition temperature (T_c) obtained from DTA thermogram and the onset temperature (T_0) obtained from DSC thermogram show better correlation with the constituents of proximate analysis than that of ultimate and petrographic analyses.
- CAB value shows better correlation with M and VM of proximate analysis, and C and H of ultimate analysis than other constituents.

Since in most of the cases the constituents of proximate analysis show a better correlation with the different susceptibility indices, an attempt has been made to study the combined influence of moisture, volatile matter and ash on different susceptibility indices by multivariable analysis and the results have been presented in Table 4.

Table 4: Correlation between the constituents of proximate analysis and different susceptibility indices

Sl. No.	Dependent variable	Empirical relation	Correlation coefficient
1	CPT	$146.7262M^{-0.027} + 7417.875\ VM^{-2.056} + 353.6539A^{-1.925}$	0.76
2	T_c	$0.379M + 3.786VM+1.659A$	0.96
3	CAB	$0.878M^{-0.406}+8021VM^{-3.111} -2.5A^{-2.623}$	0.79
4	T_o	$103M^{-0.037} + 609.6461VM^{0.443} + 1638.623A^{-2.996}$	0.85

It may be observed from Table 4 that

- The correlation coefficients between the different susceptibility indices, viz. CPT, transition temperature obtained from DTA thermogram, CAB value and onset temperature of DSC thermogram; and the constituents of proximate analysis taken together have improved considerably.
- This reveals that moisture, ash and volatile matter jointly influence the susceptibility indices.
- Therefore, for classification of Indian coals the following four susceptibility indices, viz. Crossing point temperature (CPT), transition temperature (T_c) of DTA thermogram, Critical air blast (CAB) value and Onset temperature (T_o) of DSC thermogram have been chosen along with moisture, volatile matter and ash content obtained from proximate analysis.

6. K-MEANS CLUSTERING

Clustering is the process of partitioning or grouping a given set of patterns into disjoint clusters. This is done such that patterns in the same cluster are alike and patterns belonging to two different clusters are different. Clustering is a search for hidden patterns that may exist in datasets. Clustering techniques are applied in many application areas such as data analyses, pattern recognition, image processing, and information retrieval (Zalik, 2008).

The k-means method has been shown to be effective in producing good clustering results for many practical applications. It is attractive in practice, because it is simple and it is generally very fast. It partitions the input dataset into k clusters. Each cluster is represented by an adaptively-changing centroid (also called cluster centre), starting from some initial values named seed-points. k-Means computes the squared distances between the inputs (also called input data points) and centroids, and assigns inputs to the nearest centroid. An algorithm for clustering N input data points $x_1,x_2, . . . ,x_N$ into k disjoint subsets C_i, i = 1,. . . ,k, each containing n_i data points, $0 < n_i < N$, minimizes the following mean-square-error (MSE) cost-function:

$$J_{MSE} = \sum_{i=1}^{k} \sum_{x_t \in c_i} \| x_t - c_i \|^2 \qquad (1)$$

x_t is a vector representing the t-th data point in the cluster Ci, and ci is the geometric centroid of the cluster Ci. Finally, this algorithm aims at minimizing an objective function, in this case a squared-error function, where $\| x_t - c_i \|^2$ is a chosen distance measurement (norm) between data point x_t and the cluster centre c_i. This criterion tries to make the resulting k clusters as compact and as separate as possible.

The k-means algorithm assigns an input data point x_t into the *i*th cluster if the cluster membership function *I* (x_t, i) is 1, where

$$I(x_t, i) = \left\{ \begin{array}{lll} 1 & \text{if I = arg min } (\| x_t - c_i \|^2) & j = 1, \ldots\ldots, k \\ 0 & \text{Otherwise} & \end{array} \right\} \qquad (2)$$

Here c_1, c_2, . . . c_j, , . . . , c_k are called cluster centres which are learned by the following steps:

Step 1: Initialize k cluster centres c_1, c_2, . . . , c_k by some initial values called seed-points, using random sampling.
For each input data point x_t and all k clusters, repeat steps 2 and 3 until all centres converge.
Step 2: Calculate cluster membership function I (x_t, i) by Equation (2) and decide the membership of each input data point in one of the k clusters whose cluster centre is closest to that point.
Step 3: For all k cluster centres, set c_i to be the centre of mass of all points in cluster C_i.

Determination of number of clusters

In k-means algorithm the number of clusters required to group the sample has to be pre-determined and fixed. This can be done on the basis of previous knowledge about the data or following different other approaches. In the present case the number of clusters has been determined by finding out the knee in an evaluation graph as suggested by Salvador and Chan (2004). The evaluation graph is a two dimensional plot where the x-axis is the number of clusters and y-axis is a measure of the quality of error of a clustering consisting of x clusters. The y-axis values in the evaluation graph can be any evaluation metric, such as distance, similarity error, or quality. In the present case the minimum Euclidean distance between the samples has been taken into consideration for evaluation. In order to determine the location of the transition area or knee of the evaluation graph, a pair of lines are required to be drawn that most closely fit the curve, their point of intersection being the knee of the curve and the value of the x-axis at the knee is used as the number of clusters present in the data set. Each line must contain at least two data points and must start at either end of the data.

An evaluation graph for determination of the knee for constituents of proximate analysis along with CPT has been presented in Figure 2. The number of clusters and Euclidean distance has been determined using the SPSS version 10.0 software. From the evaluation graph, it was found that there are 4 clusters present in the data set. Therefore, it was decided to determine four clusters for all cases.

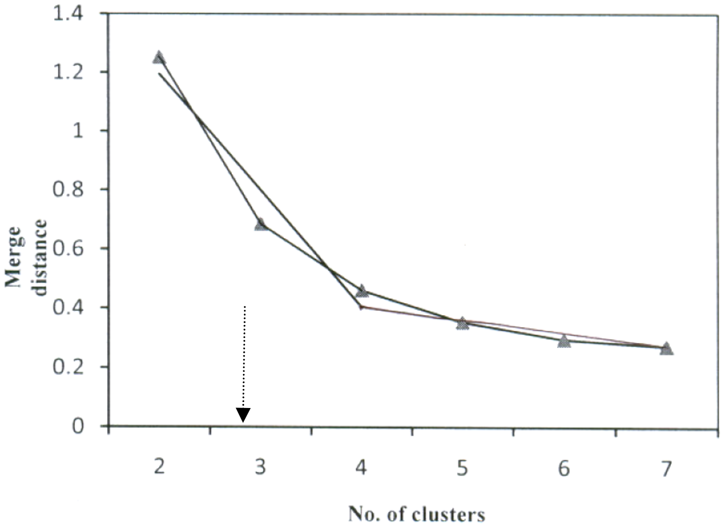

Figure 2: Evaluation plot for determining the knee of the curve

The clustering of all the 31 samples into four clusters was determined using the software SPSS version 10.0. The program presents the details of clusters with sample numbers in tabular format and the results of one such case of CPT with the constituents of proximate analysis is presented in Table 5. It may be mentioned here that the results in other three cases of susceptibility indices with the constituents of proximate analysis are the same as presented in Table 5 except in case of one sample (sample no. 24) of DTA and CAB, which in other cases occurs in cluster no. 2 instead of cluster no. 1.

Table 5: Clustering of coal samples using M, VM, A and CPT

Cluster no.	Number of sample	Sample numbers
1	3	21, 23, 24
2	16	2, 4, 5, 7, 8, 10, 11, 12, 22, 25, 26, 27, 28, 29, 30
3	11	1, 3, 6, 9, 13, 14, 15, 16, 17, 18, 19, 20
4	1	31

7. DISCUSSION AND CONCLUSION

The order of cluster number does not necessarily represent the degree of susceptibility of the coal samples. It only indicates the similarity in spontaneous heating tendencies of coal seams in a particular cluster.

A review of the status of fire as observed in the field and mentioned in Section 3 indicates that,

- The lignite of Neyveli occurs in aquifers and it catches fire within a very short time as soon as it is excavated from the benches and stacked. The field observations indicate clearly that the Neyveli lignite is more susceptible to spontaneous heating as compared to coal samples collected from all other seams and the hierarchical clustering has placed it in a separate cluster, i.e. cluster no. 4 (Table 5). Therefore, it can be termed as very highly susceptible.
- Sample nos. 24, 25, 26 and 30 are also known for their high susceptibility in Indian Coalfields, which take more time to catch fire than Neyveli lignite and these have been placed along with some samples in cluster no. 2, which may be termed as highly susceptible.
- Sample nos. 21 and 23 are placed in cluster 1 and as mentioned in the field experience of fires, these are the least susceptible, and therefore termed as poorly susceptible.
- A few cases of fires have been observed in seams with sample nos. 6 and 17, and these are in cluster no. 3 with a few other samples. It may be termed as moderately susceptible.

Finally, it may be concluded that by knowing the susceptibility of a few samples in each cluster and applying the hierarchical clustering the coal seams have been categorized into four classes and these are as follows:

Class No.	**Category**	**Cluster No.**	**Sample No.**
1	Very highly susceptible	4	31
2	Highly susceptible	2	2, 4, 5, 7, 8, 10, 11, 12, 22, 24, 25, 26, 27, 28, 29, 30
3	Moderately susceptible	1	1, 3, 6, 9, 13, 14, 15, 16, 17, 18, 19, 20
4	Poorly susceptible	3	21, 23

It may be mentioned here that by using all four susceptibility indices separately with the results of proximate analysis, there is no change in sample numbers in different clusters, which confirms the consistency and authenticity of the total classification system. Any new coal seam can be placed in any one of these categories by knowing the constituents of proximate analysis and any one of the aforementioned susceptibility indices in the laboratory. The present approach has the advantage of being supported by available commercial software programs in order to facilitate industrial applications and it has the flexibility in allowing the user to identify the required number of clusters in advance, or consider it as a dependent variable.

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