The chemical composition of tertiary Indian coal ash and its combustion behaviour – a statistical approach: Part 2

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In Part 1 of the present investigation, 37 representative Eocene coal samples of Meghalaya, India were analyzed and their physico-chemical characteristics and the major oxides and minerals present in ash samples were studied for assessing the genesis of these coals. Various statistical tools were also applied to study their genesis. The datasets from Part 1 used in this investigation (Part 2) show the contribution of major oxides towards ash fusion temperatures (AFTs). The regression analysis of high temperature ash (HTA) composition and initial deformation temperature (IDT) show a definite increasing or decreasing trend, which has been used to determine the predictive indices for slagging, fouling, and abrasion propensities during combustion practices. The increase or decrease of IDT is influenced by the increase of Fe_2O_3, Al_2O_3, SiO_2, and CaO, respectively. Detrital-authigenic index (DAI) calculated from the ash composition and its relation with AFT indicates Sialoferric nature of these coals. The correlation analysis, Principal Component Analysis (PCA), and Hierarchical Cluster Analysis (HCA) were used to study the possible fouling, slagging, and abrasion potentials in boilers during the coal combustion processes. A positive relationship between slagging and heating values of the coal has been found in this study.

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1. Introduction

The organic components of coal are fundamental to define the nature of coal while the inorganic constituents contribute to the unwanted abrasion, slagging, and corrosion associated with coal combustion. The incorporated inorganic constituents (mineral matter) present in coal (Ward 2002) are responsible for most of the environmental problems associated with coal utilization. The characterization of coal ash for its tendency to form slag and foul has been related to the total mineral content, composition of coal, and ash fusion temperatures (AFTs) which are important parameters for the coal industry. The AFT partially reflects the extent of ash agglomeration during coal conversion, e.g., combustion, gasification, liquefaction, and ash-utilization processes. The formation of melts, sinters, and slag in combustion and gasification processes are responsible for significant operational and maintenance problems thereby increasing the cost and reducing the efficiency. A large number of studies have reported the relation of AFT with chemical and mineral composition of coal ash, and a relationship has been established to predict the melting behaviour of the ash (Vassilev *et al.* 1995; Vassileva and Vassilev 2002). The effects of major oxides, the ratio of silica-alumina

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(SiO_2/Al_2O_3) as well as acid and basic fluxes on the AFTs of coal ashes have been studied by different methods (Li *et al.* 2006; Song *et al.* 2009, 2010). Mineral conversion occurring in the process of fusion has a great impact on AFT (Yang *et al.* 2006). Many investigations have focused on the study of the coal ash fusibility to predict its behavior during thermal processes (Huffman *et al.* 1981; Benson *et al.* 1993; Lloyd *et al.* 1993). It is possible to make a reliable prediction of ash fusion characteristics on the basis of the major oxides in coal ash and its initial deformation temperature (IDT) in particular, having significant implications in marketing and furnace design. The abundance of hydroxides, sulphates, carbonates, phosphates, and trace elements present in coal may also affect the environment by contaminating the surface and subsoil water (Vassilev and Vassileva 2007) and become bio-available during conversion processes. Slagging and fouling inside a combustion boiler renders poor heat exchange and obstructs the gas flow, leading to load reduction and eventual shut down. Various laboratory tests such as sinter strength test (Final report, European Commission Directorate-General XIII Telecommunications, 1994) can be used to estimate the ash fouling propensities. MgO, CaO, and dolomite present may reduce ash fouling propensities under the test conditions.

The fuel additives can reduce the deposition and corrosion problems of the boiler by addition of MgO or $CaCO_3$; or by inducing crystal growth in liquid phases in a deposit to increase viscosity and thus reduce slagging (e.g., adding copper oxychloride); or help in removal of sulphur from coal (Final report, European Commission Directorate-General XIII Telecommunications, 1994).

Though tertiary Indian coals have been studied by several researchers (Mishra and Ghosh 1996; Singh and Singh 2000; Singh *et al.* 2012a, b, 2013),there is lack of information available on the fusibility of ash of these coals during combustion. Therefore, in this investigation, the Meghalaya coal ash samples were studied in terms of their chemical compositions, ash-fusion temperatures, and possible formation of slagging and fouling during utilization. The correlation trends between ash fusibility (IDT) and major oxides present in these coals have been discussed. In Part 1 of the present investigation, the genesis of the tertiary Indian coals with the help of major oxides of coal ash, ash yield and their relationship has been discussed using various statistical tools. The geology, coal occurrences of the studied area, the physico-chemical properties, and the coal ash compositions have also been reported in Part 1 of this investigation.

1.1 *Brief account of petrographic and chemical characteristics of northeast Indian coals*

The northeastern Indian coals are characterized by low ash, high sulphur, high volatile matter, low ash fusion temperature, and high tar yield in comparison to other Indian coals. The sulphur content in these coals is in the range of 2–8% where majority is organically bound to the coal structure (70–95%). It has been reported (Baruah 2008, 2009) that in northeastern Indian coals, the major minerals (>5%) are identified in the crystalline matter of coal are quartz, kaolin, illite, feldspar, calcite, pyrite, and gypsum. These tertiary coals are characterized by high vitrinite content (80% average), with the non-vitrinite fraction being predominantly inertinite which is low in proportion. The liptinite content is usually found to be less than 20% (Sharma *et al.* 2012).

The composition of major oxides found in the studied coal ashes are in the range of SiO_2 (37.78–68.18%), Fe_2O_3 (7.05–28.69%), Al_2O_3 (7.83–33.22%), CaO (0.11–0.96%), MgO (0.24–1.27%), TiO_2 (0.08–1.91%), SO_3 (0.15–1.48%), P_2O_5 (0.15–2.95%), and others (0.16–14.33% of K_2O and Na_2O). The minerals present in these coal samples are silicates, carbonates, phosphates, hydroxides, oxides, sulfates, and sulphides which have also been reported earlier (Nayak 2013). The minerals found in Meghalaya coals are shown in table 1.

2. Experimental

The 37 freshly mined coal samples from different coalfields of Meghalaya were subjected to proximate, ultimate analyses, done by proximate analyzer (TGA 701, Leco, USA), CHN analyzer (Truspec, Leco, USA) and Sulphur Determinator (S-144 DR, Leco, USA), respectively. The calorific values (CV) of all the coal samples have been determined by Automatic Bomb Calorimeter (Leco AC-350, USA) and the high temperature ash (HTA) analysis was carried out following standard methods (IS: 1355-1959) respectively. The complete data for chemical analysis are reported in Part 1 of this investigation. The studied coal samples are characterized by low to medium ash (4.1–26.9%), high volatile matter (22.8–38.89%), high sulphur (2.87–6.96%) content, and high calorific values (4035–6990 kcal/kg).

The ash fusion temperature (AFT) measurements were carried out as per Indian Standard procedure (IS: 12891-1990) using Leitz Wetzlar ash fusion point determination apparatus at maximum temperature of 1600°C. This experiment is carried out in a reducing environment at a

Table 1. *Mineral matters present in Meghalaya coal ash.*

Silicates	
Quartz	SiO_2
Mica	$KAl_2AlSi_3O_{10}(OH,F)_2$
Feldspar	$KAlSi_3O_8$
Kaolinite	$Al_2Si_2O_5[OH]_4$
Chlorite	$(Mg, Fe)_5Al_2Si_3O_{10}(OH)_8$
Sulfides	
Pyrite	FeS_2
Marcasite	FeS_2
Sphalertite	ZnS
Phosphates	
Apatite	$Ca_5F(PO_4)_3$
Monazite	$(Ce, La, Th, Nd)PO_4$
Carbonates	
Calcite	$CaCO_3$
Siderite	$FeCO_3$
Sulfates	
Gypsum	$CaSO_4 \cdot 2H_2O$
Barite	$BaSO_4$
Oxides	
Hematite	Fe_2O_3
Rutile	TiO_2
Hydroxides	
Gibbsite	$Al\ (OH)_3$
Geothite	FeOOH

rate of 10°C/min up to 1000°C, and then by changing the heating rate to 5°C/min. During the process, the initial deformation temperature (IDT), hemispherical temperature (HT), and final fusion temperature (FT) were recorded according to the specific shapes of the ash cylinder. The ash fusion temperature (AFT) of the individual coal samples was determined and reported in table 2.

The statistical analyses such as correlation coefficient, Principal Component Analysis (PCA), and Hierarchical Cluster Analysis (HCA) were performed using SPSS16 and XLSTATS software.

Table 2. *Ash fusion temperatures (AFT) of the Meghalaya coal ash samples.*

Coal samples	IDT (°C)	HT (°C)	FT (°C)
M1	1260	1480	1500
M2	1290	1440	1490
M3	1190	1490	1500
M4	1210	1490	1500
M5	1250	1500	1510
M6	1280	1490	1510
M7	1280	1480	1520
M8	1240	1450	1520
M9	1300	1465	1480
M10	1250	1475	1530
M11	1220	1452	1490
M12	1230	1435	1480
M13	1210	1425	1530
M14	1210	1405	1480
M15	1230	1470	1520
M16	1260	1430	1480
M17	1250	1480	1500
M18	1180	1475	1488
M19	1190	1480	1510
M20	1200	1480	1500
M21	1190	1470	1500
M22	1180	1490	1520
M23	1260	1520	1520
M24	1240	1475	1510
M25	1290	1390	1480
M26	1220	1480	1500
M27	1270	1490	1500
M28	1290	1485	1500
M29	1250	1500	1500
M30	1190	1460	1500
M31	1190	1475	1490
M32	1180	1470	1500
M33	1210	1440	1480
M34	1220	1480	1500
M35	1210	1500	1530
M36	1170	1480	1500
M37	1200	1500	1520

IDT: Initial deformation temperature, HT: hemispherical temperature, FT: final fusion temperature.

3. Results and discussions

3.1 *Relationship between major oxides and ash-fusion temperatures (AFT) of coals*

The initial deformation (ID), hemispherical (HT) and flow (FT) ash-fusion temperatures of the coals under study are shown in table 2 and found to be 1180°–1290°, 1425°–1520° and 1480°–1530°C, respectively. In this study, the observations are mostly made considering the initial deformation temperature (IDT), where most of the melting takes place in this temperature range and therefore low ash fusion temperatures are seen (table 2) and rarely does the final temperature exceed >1500°C. In this investigation, the HT and FT are not considered as they exhibit similar results when compared with the major oxides. The AFTs of coals largely depend upon the chemical composition of ash. The AFT is applied for understanding the fusion behaviour of the coal ashes and is based on the measurement of three key temperatures describing the softening and melting behaviour of ash.

The main constituents of coal ash are silica, alumina and iron oxides with small percentages of other oxides such as CaO, MgO, alkalies, etc. The ash fusibility is reported to be a function of these major oxides present in coal ash. The coal ash fusibility characteristics are difficult to determine precisely, partly because many of the coal ash components do not have a sharp melting point like a pure compound. The melting point of alumina and silica is around 1600°–1700°C (Dutta Roy 1940). The other components such as Fe_2O_3, CaO, MgO, and alkalies act as a flux upon Al_2O_3 and SiO_2 reducing the fusion point of ash. The fusion point generally varies according to the ratio between the acidic components and the bases ($SiO_2 + Al_2O_3 + TiO_2/Fe_2O_3 + CaO + MgO + K_2O + Na_2O$). Greater the ratio the higher is the fusion point (Dutta Roy 1940). It is reported that higher the SiO_2 concentrations, higher the melting point, but in this case (table 2), the fusion is lowered by the presence of other oxides like MgO, CaO and alkaline oxides. Moreover, the ratio between the acidic components and bases of these coals is found to be 3.23 indicating low ash fusion temperatures of these coals. The fusion temperature of these coals is comparatively lower than that of the Jharia and Raniganj coalfields range, from 9.50 to 3.26 (Dutta Roy 1940). The chemical composition of the major inorganic oxides present in the high temperature coal ash can be used for their classification as sialic, ferrisialic, ferricalcisialic, and calsialic (Vassilev and Vassileva 2009; Singh *et al.* 2011, 2012a, b). The studied coal samples belong to the high and medium acid groups of sialic, ferrisialic, and calsialic types of high temperature ash (figure 1).

The influence of the chemical composition of Meghalaya coal ash samples on their fusibility was assessed by the regression plots of coal ash composition with IDT (figure 2). Significant correlation is observed between the major oxides and AFTs separately. Positive correlations with IDT are shown by Fe_2O_3 ($R^2 = 0.529$) and Al_2O_3 ($R^2 = 0.5397$) (figure 2b, c) whereas SiO_2 ($R^2 = -0.7757$) and CaO ($R^2 = -0.6882$) are negatively correlated with IDT (figure 2a, d) respectively. From the literature study, it is found that SiO_2 and Al_2O_3 concentrations increase the AFTs but in our investigation the higher concentration of SiO_2 decreases the IDT, while IDT is moderately increased with higher concentration of Al_2O_3. Significant interpretation cannot be drawn from individual major oxides with AFT as their relation with fusibility is not found to be of a definite trend. If SiO_2 and Al_2O_3 are present alone, they increase the melting point of the coal ash. The other oxides such as Fe_2O_3, CaO, MgO, and other alkalis may affect the fusibility of ash by acting as a flux, which might be the cause for reduction in IDT. The presence of these oxides is also evidenced by the presence of the silicate minerals [quartz (SiO_2), feldspar ($KAlSi_3O_8$–$NaAlSi_3O_8$–$CaAl_2Si_2O_8$), chlorite ($(Mg, Fe)_5Al_2Si_3O_{10}(OH)_8$), and kaolinite ($Al_2Si_2O_5(OH)_4$)], carbonates [calcite ($CaCO_3$)], phosphates [monazite (Ce, La, Th, Nd) PO_4 and apatite ($Ca_5F(PO_4)_3$)], hydroxides [gibbsite $Al(OH)_3$], oxides [hematite

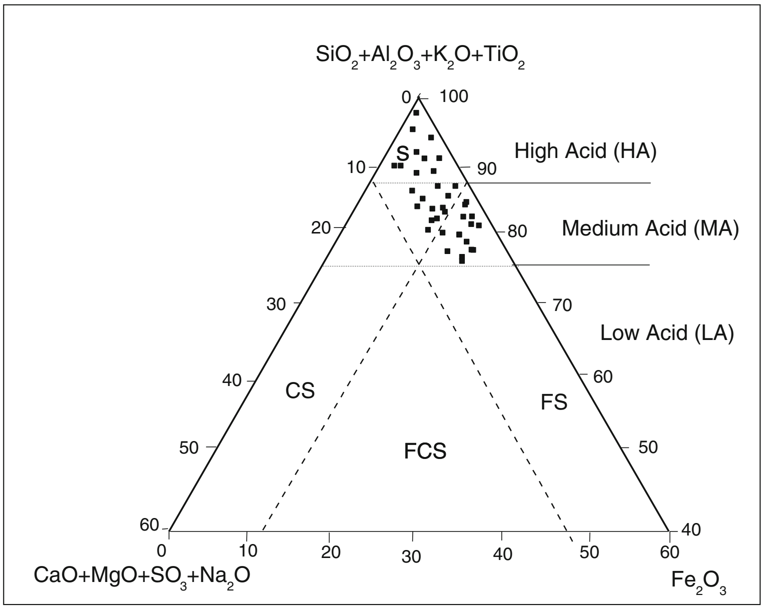

Figure 1. Chemical classification and genetic mineral classification systems of high temperature ash. (S: Sialic, FS: Ferrisialic, FCS: Ferricalsialic, CS: Calsialic.)

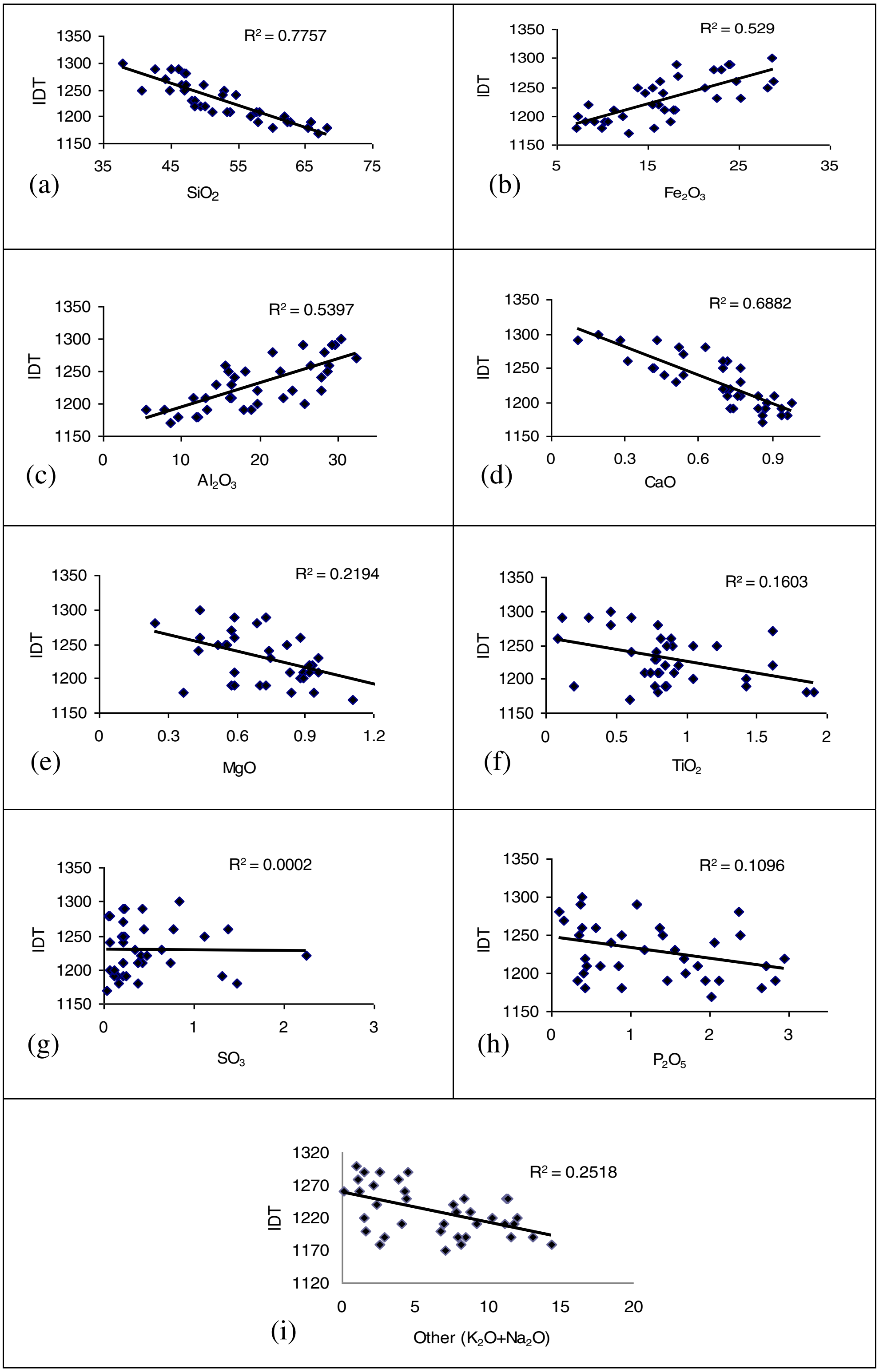

Figure 2. Correlation trends between initial deformation temperatures (ID) and (a) SiO_2, (b) Fe_2O_3, (c) Al_2O_3, (d) CaO, (e) MgO, (f) TiO_2, (g) SO_3, (h) P_2O_5, and (i) others ($K_2O + Na_2O$).

(Fe_2O_3) and rutile (TiO_2)], sulfates [gypsum ($CaSO_4 \cdot 2H_2O$)], and sulphides [pyrites (FeS_2), marcasites (FeS_2), and sphalerites (ZnS)] (Nayak 2013). The mineralogical data analysis has also evidenced the presence of higher concentration of major oxides of Fe_2O_3 and Al_2O_3, which may be responsible for the increase of the initial deformation temperature. However, from the study of major oxides of these coal ashes, it is found that the concentration of SiO_2 is more than Fe_2O_3 and

Al_2O_3 and as a result the IDT decreases with the increase of SiO_2. The thermo-mechanical analysis (TMA) of ash at high temperature (800°–1600°C) which has not been done here may also indicate the ash fusion characteristics. However, at higher temperatures, mineral and phase transformations are observed. TMA measurements provided the rapid fusion events during ash fusion identified by different peaks which are related to formation of eutectics shown by appropriate phase diagrams (Gupta *et al.* 1998). Different thermodynamic computer models also may give information on the thermo-chemistry of the main minerals present in the coal ash such as SiO_2–Al_2O_3–FeO–Fe_2O_3–CaO (Australian Coal Rev 1998) and transformation.

Coal ashes are normally classified as low melting (<1300°C), medium melting (1300°–1450°C), and high melting (>1450°C) AFT types according to the HT values (Vassilev *et al.* 1995). The coals under study have low to high melting ashes. According to the chemical classification systems for HTA (Vassilev *et al.* 1995; Vassilev and Vessileva 2009), a majority of the studied coal ash samples correspond to sialoferric type (figure 3). The studied low melting ashes of sialoferric type having higher proportion of Si, Al, Fe, Na, and K (mainly quartz, chlorite, kaolinite, pyrites and marcasites) and these oxides react with the silicates and probably form a large number of fluxing low temperature eutectic of Fe–Al–Na–K silicate phases that start to melt intensively at 1170°–1300°C. The abundance of silicate minerals in these coals also contributes significantly to the low melting of their ashes (Vassileva and Vassilev 2002).

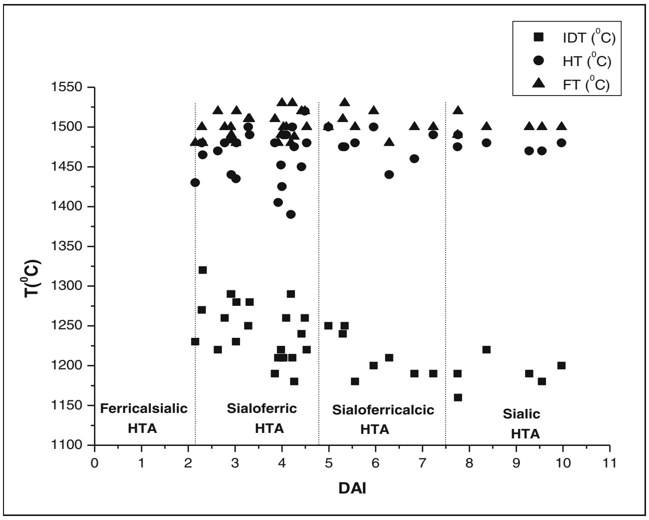

Figure 3. Correlation trends between detrital-authigenic indices (DAI) and ash-fusion temperatures (AFT) for Meghalaya coal ashes (37 numbers).

3.2 *Slagging, fouling and abrasion potentials of Meghalaya coal ash samples*

The fusion behaviour of coal ash is an important factor in determining the formation of slag deposits on the reactor surfaces. It may also have an influence on the nature of the fouling formation that can occur on surfaces during heat exchange. The slagging and fouling depositions cause corrosion and erosion of boiler tubes affecting heat transfer efficiency (Munir and Nimmo 2010). Most of the coal conversion technologies such as combustion and gasification face common challenges caused by slagging and fouling. The two essential factors controlling clinker formation, slagging, and fouling in coal conversion processes are: (a) operating conditions of the process and (b) the minerals that contain fluxing inorganic elements (K, Na, Ca, Fe, Mg, etc.) in the coal (Van Dyk *et al.* 2006). The major elements including alkali metals (K, Na), alkaline earth metals (Ca, Mg), silicon, chlorine, and sulphur are involved in reactions leading to ash slagging and fouling (Heinzel *et al.* 1998; Fryda *et al.* 2010). The alkali elements (Na, K) are particularly important in the initiation of slag formation and its growth (Barnes 2009). Quartz and to some extent pyrite are the main minerals associated with the abrasion deposits. The presence of coarse-grained nonspherical quartz may be responsible for abrasion or erosion hazards in gasifiers and combustion furnaces (Reifenstein 1999).

The presence of basic compounds in coal ash ($Fe_2O_3 + CaO + MgO + Na_2O + K_2O$) lowers the melting temperature while the acidic compounds ($SiO_2 + Al_2O_3 + TiO_2$) increase its melting temperature. The ratio of basic compounds to acidic compounds is considered as an index for slagging behaviour (Skorupska 1993; Vamvuka and Zografos 2004; Pronobis 2005; Kazagic and Smajevic 2007; Masia *et al.* 2007). The commonly used slagging and fouling indices have been reported below (Skorupska 1993; Vamvuka and Zografos 2004; Pronobis 2005).

Terms	Formula	Range
Slagging index	(Base/acid)X (S dry)	<0.6, low slagging; 0.6–2.0, medium; 2.0–2.6, high; >2.6, extremely high.
Fouling index	(Base/acid) X ($Na_2O + K_2O$)	$\leq$ 0.6, low fouling; 0.6–40, high; $\geq$ 40, extremely high.

Fe_2O_3 and CaO contents in coal ash are the important parameters for determining the slagging behaviour of coal. The slag formation is disturbed if the concentration of acid oxides in the coal samples is greater than the basic oxides (Akar and Itekoglu 2007). The coal samples under study show that the acid oxide contents (average 73.56%) are more than the basic oxide contents (average 24.72%), thereby having low slag forming potential. But as seen for these coals with high sulphur content, the slagging factor is found to be 1.51 (table 4), which is >0.6 (Akar and Itekoglu 2007).

The average slagging, fouling, and abrasion potentials of Meghalaya coal ash are 1.51, 0.15 and 3.37, respectively (table 3). Based on the ranges given above, it is found that the Meghalaya coals have medium slagging with low fouling potential. The presence of high sulphur (average 4.29%) in the studied coal samples also favours slag formation. In order to utilize these coals with slag

Table 3. *Slagging, fouling and abrasion parameters of Meghalaya coals.*

	Slagging potential				Fouling potential	
Coal samples	Base/acid ratio Base/acid	Fe/Ca Fe_2O_3/CaO	Silica ratio SiO_2/ SiFeCaMg	Slagging factor (Base/acid)X (S dry)	Fouling factor (Base/acid)X $(Na_2O + K_2O)$	Abrasion potential silica/alumina ratio SiO_2/Al_2O_3
M1	0.35	79.45	0.65	1.79	2.20	1.76
M2	0.39	85.71	0.65	2.68	0.15	1.81
M3	0.31	14.09	0.85	2.180	0.03	8.40
M4	0.41	24.99	0.75	2.34	0.04	5.02
M5	0.38	27.62	0.67	2.13	0.09	2.09
M6	0.32	35.33	0.67	1.90	0.31	1.67
M7	0.40	44.15	0.66	2.14	0.10	2.19
M8	0.35	30.96	0.75	2.26	0.05	3.26
M9	0.44	150.47	0.56	2.38	0.45	1.24
M10	0.37	19.76	0.77	2.09	0.03	2.94
M11	0.25	22.05	0.73	0.69	0.16	1.78
M12	0.50	44.29	0.67	1.85	0.06	2.93
M13	0.46	21.26	0.73	2.66	0.04	4.11
M14	0.31	23.17	0.75	1.81	0.07	3.53
M15	0.54	32.71	0.64	2.59	0.07	3.38
M16	0.54	39.85	0.61	2.79	0.13	3.05
M17	0.70	66.78	0.58	2.06	0.06	2.57
M18	0.26	16.30	0.79	1.01	0.10	5.42
M19	0.39	23.58	0.77	1.70	0.05	11.38
M20	0.12	8.25	0.87	0.34	0.07	2.40
M21	0.29	9.29	0.87	0.84	0.02	4.68
M22	0.24	10.47	0.86	0.89	0.03	7.10
M23	0.23	23.36	0.74	0.84	0.19	1.74
M24	0.22	31.85	0.77	0.76	0.09	1.90
M25	0.31	165.18	0.70	1.02	0.07	1.52
M26	0.29	11.89	0.83	1.06	0.02	2.08
M27	0.27	33.81	0.69	1.05	0.13	1.37
M28	0.37	55.58	0.63	1.07	0.24	1.45
M29	0.33	37.83	0.73	1.04	0.04	1.57
M30	0.26	11.28	0.82	1.06	0.03	3.05
M31	0.17	10.76	0.85	0.66	0.06	3.68
M32	0.31	8.19	0.87	1.17	0.02	5.10
M33	0.26	12.43	0.80	0.81	0.04	2.31
M34	0.39	22.06	0.74	1.40	0.04	2.47
M35	0.43	22.18	0.74	1.26	0.04	3.15
M36	0.29	15.02	0.82	0.86	0.04	7.89
M37	0.27	12.39	0.80	0.84	0.03	2.89
Avg. for (M1–M37)	0.34	35.25	0.74	1.51	0.15	3.37

1. Base = $Fe_2O_3 + CaO + MgO + K_2O + Na_2O$, 2. Acid = $SiO_2 + TiO_2 + Al_2O_3$, 3. SiFeCaMg = $SiO_2 + Fe_2O_3 + CaO + MgO$.

forming tendencies, fluidized bed combustion system would be the best choice to avoid slagging characteristics.

3.3 *Analysis of coal ash and its thermal behaviour*

3.3.1 *Correlation analysis*

Correlation coefficients have shown the interrelation among the coal ashes, calorific value, and the predictive indices. The Pearson correlations derived (table 4) for these datasets show that the slagging potential ($r = 0.55$) is positively correlated with the heating value of the coals. No other significant relation is found with the other characteristics of coal ash behaviour.

3.3.2 *Hierarchical clustering analysis (HCA)*

Cluster analysis is carried out to discriminate between ash and the thermal behaviour of these coals with mutually high similarity. In the dendrogram (figure 4), two major clusters are obtained. The first cluster comprises of two subsections including slagging potential, CV, and fouling potential, while the second cluster has one subsection including ash and abrasion potential. In this analysis, it is found that the slagging behaviour and calorific value of Meghalaya coals that have pairwise similarities form a common group and this grouping is continued until all of them are contained in a single group.

3.3.3 *Principal Component Analysis (PCA)*

The ash content, slagging potential, fouling potential, abrasion potential, and CV were selected for the principal component analysis due to their continuity of measurement in time scale. In the application of principal component analysis to these datasets, a correlation matrix was used. As Chatfield and Collin (1980) stated, the components with an eigen value of <1 should be eliminated

Table 4. *Bivariant analysis of ash behaviour of coal.*

Variables	Ash	Slagging potential	Fouling potential	Abrasion potential	CV
Ash	**1**	0.123	−0.166	0.042	−0.369
Slagging potential	0.123	**1**	−0.045	0.007	**0.545**
Fouling potential	−0.166	−0.045	**1**	−0.054	0.162
Abrasion potential	0.042	0.007	−0.054	**1**	−0.207
CV	−0.369	**0.545**	0.162	−0.207	**1**

* The significant r values at 99% confidence level are: ≥ 0.40 and ≤ -0.40 for 37 variables.

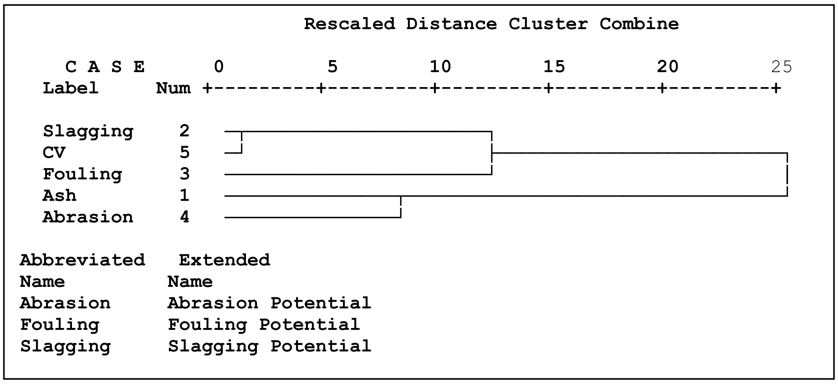

Figure 4. Hierarchical clustering analysis (HCA).

Table 5. *Eigen values and % variability by principal components.*

	F1	F2	F3	F4	F5
Eigen value	1.688	1.231	1.000	0.858	0.254
Variability (%)	33.767	24.626	19.367	17.159	5.080
Cumulative %	33.767	58.393	77.761	94.920	100.000

Table 6. *Results of principal component analysis.*

	F1	F2	F3
Ash	−0.483	**0.629**	−0.258
Slagging potential	**0.623**	**0.700**	0.130
Fouling potential	0.320	**−0.552**	0.169
Abrasion potential	−0.327	0.169	**0.941**
CV	**0.926**	0.107	0.052

so that fewer components are dealt with. The first two components are extracted and the other components are eliminated. When the percentages of the total variances of the three extracted components are accumulated, it can be seen that these three principal components account for 77.76% of the total variance of the original data (table 5). Only variables having loading more than 0.5 are considered to explain each factor (table 6).

From tables 5 and 6, the factor 1 accounts for 33.77% of total variance in the observed variables and is associated with slagging potential and CV. The high loading of CV reflects that slagging potential is related to it. HCA also shows the linkage between CV and slagging potential (figure 4). The major link between the CV and slagging index is coal ash oxides. It might be possible that increase in basic oxide as compared to acid oxide or sulphur content may cause the higher values of both. It is reported that sulphur may cause increase in the value of CV (Wynteri *et al.* 2004). The factor 2 accounts for 24.63% of the total variance with slagging potential, ash, and fouling potential (negatively). This factor indicates that ash and fouling potential are related to the slagging potential of the coal. The negative score of fouling potential indicates that with increase in slagging behaviour, the fouling potential of the Meghalaya coals decreases. Factor 3 accounts for 19.37% of the total variance with high loading of abrasion potentials. The graphical representation of the Principal Component Analysis shows samples with similar behaviour (M1, M2, M3, etc.) and variables (ash, abrasion potential, slagging potential, etc.) through the score (figure 5a) and loading plots (figure 5b), respectively. By comparing the score plot and loading plot, the relationships between samples and variables are identified. In the plots, close variables are seen to have high correlation and show similar results for close samples. The variables on the opposite side of the origin are significantly negatively correlated while orthogonal variables have no relation. Samples on the right of these plots are dominated by the variables on the right and vice versa. The relationship between the score plot and loading plot is illustrated in the bi-plot diagram (figure 5c).

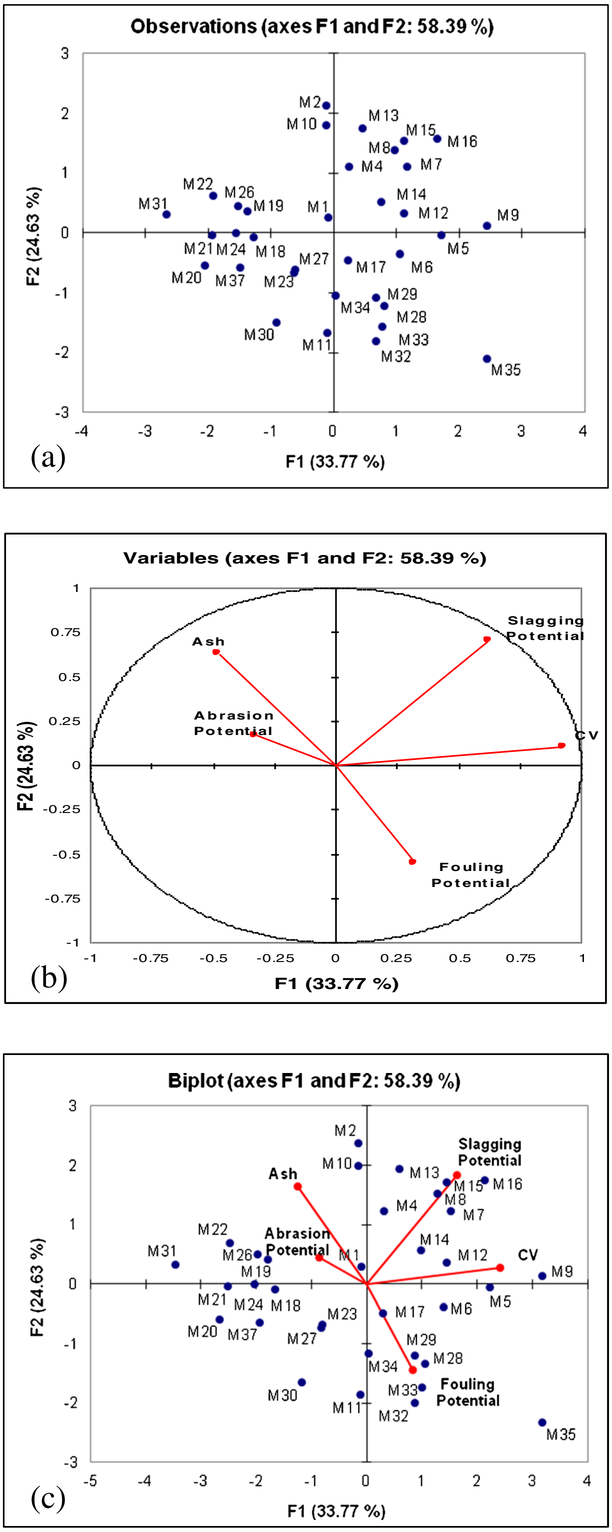

Figure 5. (a) Score plot, (b) loading plot and (c) bi-plot of principal component analysis (PCA).

4. Conclusion

The correlation trends between initial deformation temperature and the chemical composition of Meghalaya coal ash samples showed that the increase in the concentration of Fe_2O_3 and Al_2O_3

increases the IDT while the reverse is seen for SiO_2 and CaO. The presence of other oxides like MgO, P_2O_5, TiO_2, SO_3, Na_2O, and K_2O may also be significant for lower IDT. The coal samples belong to the high and medium acid groups of sialic, calsialic, and ferrisialic types of high temperature ash and are mostly low and high melting exhibiting sialoferric type. Based on the slagging and fouling ranges, it is found that the Meghalaya coals have medium slagging potential whereas these coals exhibit low fouling potentials. The study of correlation, HCA and PCA analyses among the ashes, calorific value, and predictive indices revealed that the slagging behaviour of the Meghalaya coals is found to correlate with the calorific values. The low ash fusibility of these coal ashes can be overcome in the combustion systems by adding fuel additives like MgO or $CaCO_3$, or inducing crystal growth to increase viscosity and reduce slagging.

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