The Journal of CPRI,
Vol. 12, No. 3, September 2016 pp. 579-590

Characteristics of different Indonesian coals blended with a high ash Indian coal

Arun Kumar K H*, Saravanan V** and Shekhar Kumar M***

Two Indonesian coals from different mines were blended with a high ash representative Indian coal obtained from South Eastern Coalfield Limited (SECL) mines at different proportions like 10/90, 20/80, 30/70 and 50/50. These blends were characterized for the qualitative and quantitative parameters based on additive rule. The additive/non-additive behavior of these blend proportions were studied comparing the experimentally obtained value with the calculated values based on additive rule. The results obtained indicate that the quantitative parameters like proximate and ultimate parameters were found to be additive and the qualitative parameters like ash fusion temperature and Hardgrove Grindability Index (HGI) were found to have deviation from the calculated values. Among the two different blends one blend showed additive characteristics on the HGI values while the other one showed non-additive characteristics. The Ash Fusion Temperature (AFT) was found to be non-additive in both the blends.

Keywords: *Blending, Indonesian coal, additive rule, AFT, HGI, boiler performance parameters.*

1.0 INTRODUCTION

Coal-based power accounts for over 83% of India's thermal power capacity. The power sector being poised for higher growth rate will have more and more dependence on coal in the foreseeable future. In view of coal being a financially viable option for long-term power generation and renewable energy not expected to cope with it significantly, coal remains as the mainstay of the energy sector. However, the coal industry has been unable to keep up the domestic production with the growing demand from the power sector. One of the immediate choices is to import coal from foreign countries and blend with Indian coals (Dry beneficiation) and use the blended coal for power generation. This is being practiced in India presently. However, the blending of coals of different origin has other adverse effects in respect of the overall combustion behavior due to the differential burning combustion characteristics of the individual coals. Sometimes the blended coal is worse than the constituent coals in respect of the boiler parameters viz. combustion behavior, slagging and fouling and pollutant formation. There are many literatures [1-8] indicating that when the coals of different types are blended together, the resultant blended coal may behave different to that of the individual coals as some of the characteristics of the blended coal are not additive and the same cannot be predicted from the proportions of the individual coals.

The behavior of the coals towards combustion, pollution formation, slagging/fouling propensity and grindability are generally being evaluated from proximate and ultimate parameters, ash composition, ash fusion temperature and HGI

* SRF, Materials Technology Division, Central Power Research Institute, Bengaluru-560080, India. E-mail:arunkhmtech@gmail.com
**Joint Director, Materials Technology Division, Central Power Research Institute, Bengaluru-560080, India. E-mail: saran_cpri@cpri.in
*** Additional Director (Retd.), Materials Technology Division, Central Power Research Institute, Bengaluru-560080, India.

respectively. It is reported that while blending high sulphur bituminous coal with sub-bituminous coal, the ash content was found to be higher than the predicted value by additive rule due to the reason that the evolution of sulphur oxides from bituminous coal is captured by the alkaline elements in the sub-bituminous coals to form sulphates and retained in the ash [9, 10]. Similarly, the ash fusion temperature of certain coal blends was found to be lesser than the constituent coals due to the formation of low melting constituents by the reaction of different elements between constituent coals. Similarly the grindability behavior also vary from blend to blend. Some have reported the HGI was additive [11, 12 and 13] and some researchers have reported the HGI was non-additive [9, 14].

In India most of the power plants are blending high ash Indian coals with the coals of Indonesian origin. The Indonesian coals are having high calorific value and high volatile content. Indian thermal power plants are procuring Indonesian coals from different mines. As explained earlier, the blending of coals from different origins may pose additive characteristics for some of the properties and non-additive characteristics for other properties, it is imperative that the coal blends are to be evaluated in the laboratory scale before utilizing the same in the power plant boilers to prevent adverse effects and economic loses. In the present work two different varieties of Indonesian coals blended with a high ash content Indian coal from South Eastern Coalfield Ltd (SECL) and the blended coal characteristics are studied at laboratory scale and reported for their additive and non-additive nature.

2.0 EXPERIMENTAL WORK

The Indonesian coals of two different varieties designated as “Imp-1” and “Imp-2” and an Indian coal from SECL designated as “Ind”were separately prepared to -250 microns. The Imp-1/ Ind coals and Imp-2 / Ind coals were then blended to 10/90, 20/80, 30/70 and 50/50 weighted average compositions. The compositions and the code are given in Table 1. The parent coals and the blends were further assessed for proximate and ultimate parameters. The ashes were prepared from the parent coals and the blends by heating the samples to 750 ^{o}C and the ashes were subjected to ash fusion temperature measurements. For the HGI analysis, the parent coals were reduced to 0.6mm to 1.18mm size and blended at this size to 10/90, 20/80, 30/70 and 50/50 weighted average compositions. These samples were subjected to HGI analysis.

TABLE 1

COMPOSITIONS AND CODES FOR THE COALS

SL. NO.	COMPOSITION, %			CODE
	IMPORTED COAL-1	IMPORTED COAL-2	INDIAN COAL	
1	100	0	0	IMP-1
2	0	100	0	IMP-2
3	0	0	100	IND
4	10	0	90	10 IMP -1
5	20	0	80	20 IMP -1
6	30	0	70	30 IMP -1
7	50	0	50	50 IMP -1
8	0	10	90	10 IMP -2
9	0	20	80	20 IMP -2
10	0	30	70	30 IMP -2
11	0	50	50	50 IMP -2

The brief description about the experimental procedure for proximate, ultimate, ash fusion temperature and HGI are given as below:

2.1 Proximate Analysis

Proximate analysis is the determination of moisture, volatile matter, ash content and fixed carbon present in the coal. It is basically a thermo gravimetric analysis in which the sample is heated from ambient temperature to elevated temperature and the weight loss is observed with respect to temperature. The LECO TGA-701™ proximate analyzer was used for obtaining the proximate parameters and the guideline standard used was ASTM D 5142-02a [16].

The moisture was determined as the weight loss at 108°C and the volatile matter was determined as the weight loss for 7 minutes at 950°C in nitrogen environment. The ash is determined as the weight of the remaining non-combustible residue after combusting "char" (left out mass after the release of moisture and volatile matter) at 750°C in oxygen environment. The fixed carbon is calculated as the value remaining after deducting moisture, volatile matter and ash from 100.

2.2 Ultimate Analysis

The ultimate analysis is the determination of the elemental composition constituting the combustible and noncombustible portion of coal. In this analysis carbon, hydrogen, nitrogen, sulphur and oxygen which constitutes the organic phase and also the ash and moisture constituting the inorganic phase of the material are assessed. Among these, the moisture and ash was determined through LECO TGA-701™ equipment as part of proximate analysis and the carbon, hydrogen, nitrogen and sulphur were determined using LECO Truspec CHNS™analyzer using ASTM D 5373 [17] and 4239 [18] as guideline standards. The carbon, hydrogen and sulphur presented in the coal were converted to their oxides by combusting the coal in oxygen environment and quantified through IR spectroscopy, the nitrogen oxide formed was reconverted to nitrogen and quantified through thermal conductivity measurement.

2.3 Gross Calorific Value (GCV)

The GCV gives the measure of the gross heat released by unit mass of coal. The GCV is generally determined using a Bomb Calorimeter. In the bomb calorimeter, the known weight (about 1g) of sample is combusted in a pressure vessel (constant volume) at a pressure of about 3.1 M Pain oxygen environment. The pressure vessel is surrounded by known weight of water (2 kg) at temperature T_1. The heat released (heat of reaction) during the combustion of coal transferred to the surrounding water will increase the temperature of the water to T_2. The increase in temperature (T_2-T_1) multiplied with the mass and specific heat of surrounding water gives the amount of total heat released by the coal. Knowing the mass of the coal, the gross heat released by unit mass of the coal is estimated. It is very important to estimate accurately the heat loss during this process to obtain the accurate value of GCV. There are many types of advanced bomb calorimetric technologies available present day viz. adiabatic, is operibol, etc. which are using microprocessor devices to estimate the heat loss during the process to obtain accurate value of GCV. In the present work LECO AC-350™ make, is operibol type bomb calorimeter was used for the estimation of the GCV of parent coals and blends. The guideline standard used for this work was ASTM D 5865 [19].

2.4 Ash Fusion Temperature (AFT)

The ash fusion temperature is used for predicting the slagging and fouling tendencies of coal. The ash fusibility characteristics depend largely on the mineralogical composition of the ash and the type of atmosphere prevailing during combustion in the boiler. This can range from reducing to oxidizing atmospheres depending on the precise location in the boiler [1]. Interactions between the minerals in the different coals that make up the blend may occur, leading to the difficulty in predicting ash fusion temperature of the blend form the individual coals.

As coal ash is not a pure substance and it is the heterogeneous mixture of various mineral oxides, it does not possess single melting point unlike pure substances. The AFT is the empirical determination of the melting characteristics of ash through a specially devised method by ASTM-D 1857-03 [20]. In this method, the coal ash is made in the form of triangular pyramidusing dextrin binder and heated from ambience to 1500°C. The standard describes four successive stages of deformation of the pyramid at four successive temperatures, which are called Initial Deformation Temperature (IDT), Softening Temperature (ST), Hemispherical Temperature (HT) and Fluid Temperature (FT). The temperature at which the first rounding of the apex of the pyramid happening is observed as Initial Deformation Temperature (IDT).Softening Temperature (ST) is the temperature at which the pyramid has fused down to a spherical lump in which the height is equal to the width at the base. The temperature at which the pyramid has fused down to a hemispherical lump in which the height is one half the width of the base is observed as Hemispherical Temperature (HT). Fluid Temperature (FT) is the temperature at which the fused mass has spread out in a nearly flat layer with a maximum height of 1.6 mm.

2.5 Hardgrove Grindability Index

The HGI is done as per IS4433 -1979 [21]. In this analysis 50g of coal sample of size range between 0.6 mm to 1.18 mm was ground in the bowl mill of the HGI machine (The design of HGI machine is given in BIS:4433 [21]) for 60 revolutions. The ground coal sample is further sieved in 75 µm mesh for longer duration so that all the -75 µm particles pass through the mesh. In the present work, the sieving was done for 20 minutes with intermittent gap. The weight of the sample passing through -75 µm is noted (M) and the HGI value is calculated as

$$HGI = 13 + 6.93\,M \quad \text{....(1)}$$

The experimental results of the proximate, ultimate, GCV, ash fusion temperature and HGI of the parent coals and blends are given in are given in Table 2 and 3. In parallel, the values of the above parameters for the blended coals are theoretically calculated using the additive rule

$$M=(1-x_2)\,M_1+ x_2\,M_2 \quad \text{....(2)}$$

Where, M is the blend value of any parameter (say "ash content") investigated and M_1 and M_2 are the parameters of parent coals 1 and 2. The x_2 is the weight fraction of coal 2 in the blend. The values calculated using the additive rule are given in brackets in the Table2 and 3.

The experimentally obtained values and the values calculated using the additive rule are compared for the proximate, ultimate, GCV, ash fusion temperature and HGI parameters as given in Figures 1 to 18.

3.0 RESULTS AND DISCUSSIONS

The Indian power plants are designed for using the Indian coals of ash content about an average of 35%. Blending imported coal with Indian coal may affect the boiler parameters. The blending is the physical mixture of the constituent coals. However, within the boiler when they undergo combustion one may influence the other one. This has been reported by several researchers [7]. In the present work, while comparing the experimentally obtained values with the values calculated using additive rule, it was found that some of the parameters are showing additive characteristics and some are showing non-additive characteristics. The details are given in subsequent sections.

3.1 Proximate and ultimate parameters

The proximate and ultimate parameters of the blended samples were compared on moisture free basis, as moisture is not a stable parameter with the environmental conditions and this may introduce uncertainty in the results. The volatile matter is generally an additive property for coal blends. However the report made by Riley and others [9] indicate that the dry volatile matter for the blends were generally higher than the predicted values using additive rule. They also reported that the greatest differences between the measured and predicted values generally occurred for blending between widely differing ranks (determined by calculating GCV on moist mineral matter free basis (mmmf)) [23] and also for the 50:50 blends of closer ranks. In the present work for both the blends Imp-1/Ind and Imp-2/Ind, as shown in Figure 1 and Figure 2 the volatile matter was found to be additive in all the blend proportion ranges. This might be due to the reason that the kinetics of volatile release rate might be similar in both the parent coals as the determination of volatile is a time dependent process. The power plants directly or indirectly in respect of ash handling and also the problems like slagging and fouling. Riley and others [9, 12] found that the obtainedash content value for the blends were found to be more than the calculated values for the constituent coals with widely differing rank for 50:50 blends. Artos and scaroni [10] made the similar report that the ash content of the mixture of high volatile bituminous and sub-bituminous coals showed higher value due to the reason that the increase of sulphate in the ash from sulphur oxides (released by bituminous coal) trapped by the alkaline minerals in the low rank coals.

TABLE 2

PROXIMATE, ULTIMATE AND GROSS CALORIFIC VALUES OF INDIVIDUAL AND BLENDED COALS

SAMPLE CODE	PROXIMATE ANALYSIS, %, (DRY BASIS)			ULTIMATE ANALYSIS, %, (DRY BASIS)				GROSS CALORIFIC VALUE, MJ/KG
	VOLATILE MATTER	ASH	FIXED CARBON	CARBON	HYDROGEN	SULFUR	NITROGEN	
IND	25.9	41.4	32.7	44.1	3.15	0.52	1.18	17.6
IMP-1	51.9	11.9	36.2	69.4	5.58	1.32	1.45	28.8
IMP-2	52.0	5.4	42.6	66.5	4.55	0.07	0.3	26.7
10 IMP-1	26.7 (28.5)	40.0 (38.4)	33.4 (33.1)	46.2 (46.7)	3.30 (3.39)	0.57 (0.6)	0.82 (1.21)	18.5 (18.7)
20 IMP-1	30.0 (31.1)	36.9 (35.5)	33.5 (33.4)	48.5 (49.2)	3.88 (3.64)	0.74 (0.68)	0.72 (1.23)	19.5 (19.8)
30 IMP-1	32.0 (33.7)	34.0 (32.5)	34.0 (33.8)	51.0 (51.7)	4.09 (3.88)	0.80 (0.76)	1.00 (1.26)	20.7 (21.0)
50 IMP-1	37.2 (38.9)	28.0 (26.7)	34.8 (34.5)	55.0 (56.8)	4.52 (4.37)	0.98 (0.92)	0.68 (1.32)	23.0 (23.2)
10 IMP-2	27.0 (28.5)	40.0 (37.8)	33.2 (33.7)	46.2 (46.4)	3.41 (3.29)	0.45 (0.48)	0.76 (1.10)	18.3 (18.5)
20 IMP-2	29.0 (31.1)	36.4 (34.2)	34.5 (34.7)	48.6 (48.6)	3.60 (3.43)	0.39 (0.43)	0.67 (1.00)	19.0 (19.4)
30 IMP-2	32.0 (33.7)	33.0 (30.6)	35.2 (35.7)	51.9 (50.8)	3.77 (3.57)	0.36 (0.39)	0.91 (0.92)	19.8 (20.3)
50 IMP-2	38.0 (38.9)	25.0 (23.4)	37.6 (37.7)	56.2 (55.3)	3.99 (3.85)	0.28 (0.30)	1.00 (0.74)	21.4 (22.1)

Note: The values given in bracket are calculated as per additive rule

TABLE 3

HARDGROVE GRINDABILITY INDEX AND ASH FUSION TEMPERATURES OF INDIVIDUAL AND BLENDED COALS.

SL. NO.	SAMPLE CODE	HARDGROVE GRINDABILITY INDEX	ASH FUSION TEMPERATURES		
			INITIAL DEFORMATION TEMPERATURE, ^{o}C	SOFTENING TEMPERATURE, ^{o}C	HEMISPHERICAL TEMPERATURE, ^{o}C
1	IND	63	1160	1500	>1500
2	IMP-1	55	1160	1400	1480
3	IMP-2	69	1050	1220	1230
4	10 IMP-1	62 (62)	1080 (1160)	1460 (1490)	>1500

5	20 IMP-1	63 (61)	1100 (1160)	1410 (1480)	>1500
6	30 IMP-1	65 (61)	1030 (1160)	1420 (1470)	>1500
7	50 IMP-1	66 (59)	1060 (1160)	1410 (1450)	>1500
8	10 IMP-2	62 (64)	1100 (1149)	1460 (1472)	>1500
9	20 IMP-2	64 (64)	1090 (1138)	1440 (1444)	1490
10	30 IMP-2	65 (65)	1100 (1127)	1410 (1416)	1460
11	50 IMP-2	66 (66)	1090 (1105)	1340 (1360)	>1500
Note: The values given in bracket are calculated as per additive rule					

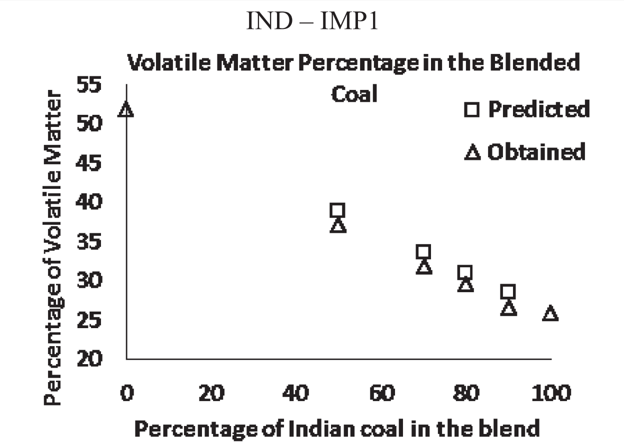

FIG. 1. VOALTILE MATTER OF IND – IMP1

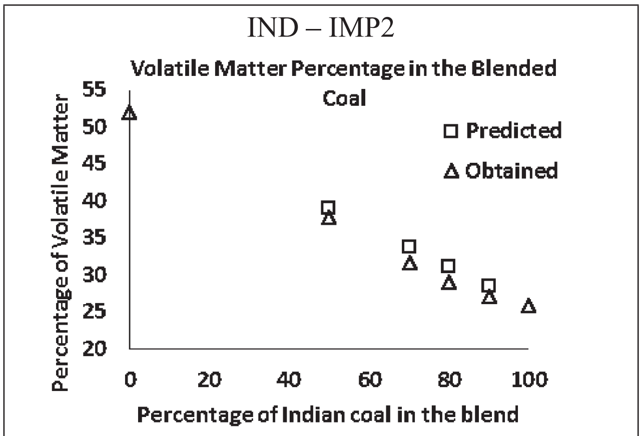

FIG. 2. VOLATILE MATTER OF IND- IMP2

This indicates that there are no sulphur-alkali reactions as alkali content in the Indian coal is relatively low. The ultimate analysis parameters are generally additive. As reported by Riley and others [9, 11] the carbon, hydrogen and sulphur are found to be additive for both the coal blends Imp-1/Ind and Imp-2/Ind in the present work at all proportions (Figure 5 to 10).

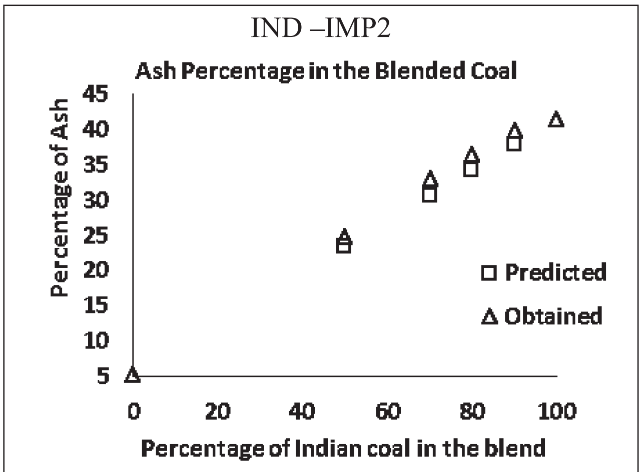

FIG. 3. ASH OF IND- IMP2

In the present work as similar to the volatile content the ash content was found additive (Figure 3 and Figure 4) in all ranges or both the blends Imp-1/Ind and Imp-2/Ind.

IND – IMP1

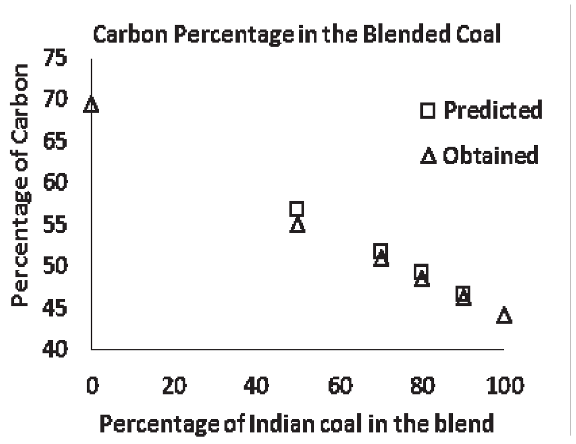

FIG. 4. CARBON OFIND- IMP1

IND – IMP2

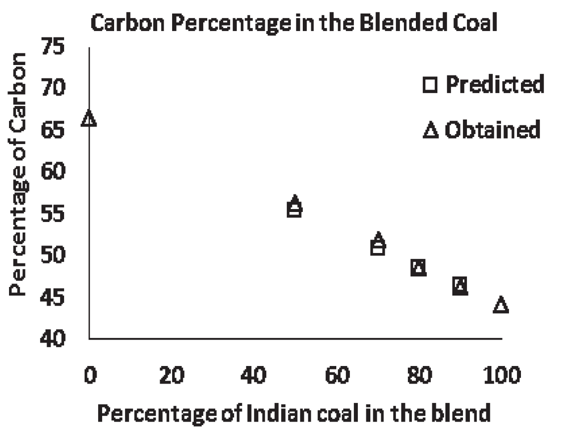

FIG. 5. CARBON OF IND- IMP2

IND – IMP1

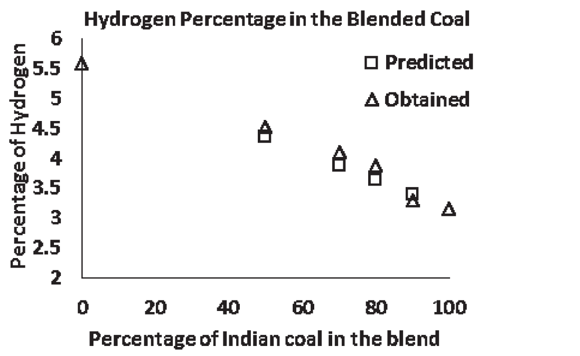

FIG. 6. HYDROGEN OFIND- IMP1

3.2 Ash Fusion Temperature

It is observed that the trend of ash fusion temperature from IDT to FT in the case of Imp-2 coal is found to be relatively lower than Ind and Imp-1 coals which is attributable to the high iron content [22]. The IDT and ST of Imp-1/Ind and Imp-2/Indwere found to be lower than the calculated values (Figure 15 to 18) for all the proportions. The reduction in IDT value for the proportions 10/90, 20/80 and 30/70 is attributed to the internal reactions between the minerals of both the coals, forming a low melting component which melts at lower IDTs.It is reported that [1], coal contains high levels of organically associated cations such as Na, Ca and Mg, upon combustion form small particles that are very reactive fluxing agents and reduce the viscosity of liquid phases responsible for slagging and fouling problems. The Imp-1 and Imp-2 are found to have high calcium and magnesium contents compared to Indian coal. The elemental composition of the constituent coals are given in Table 4. The fluxing action of the high calcium and magnesium contents of the imported coals responsible for the reduction in the IDT and ST of the blends than the predicted value.

IND – IMP2

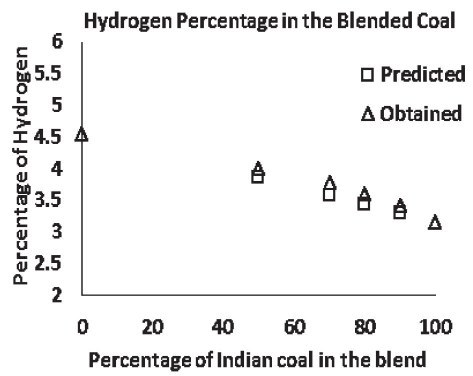

FIG. 7. HYDROGEN OF IND- IMP2

IND – IMP1

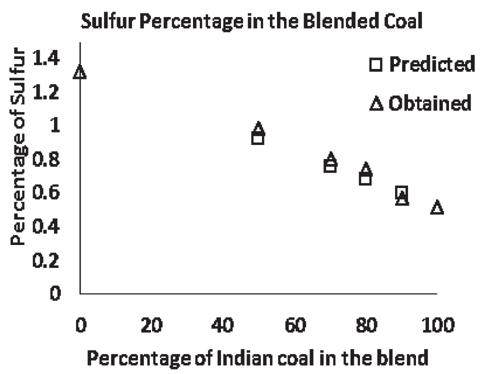

FIG. 8. SULFUR OFIND- IMP1

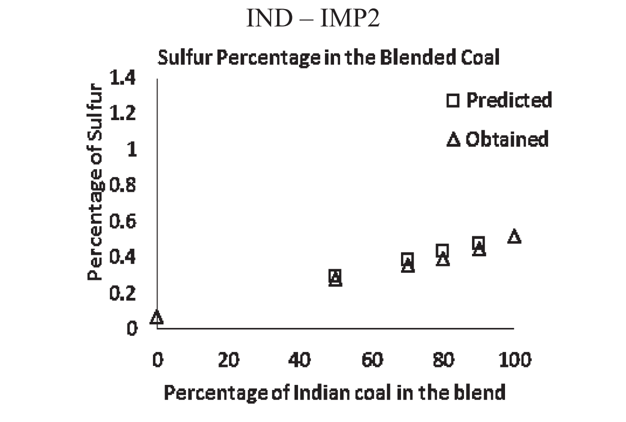

FIG. 9. SULFUR OF IND- IMP2

3.3 Gross Calorific Value

The GCV of coal is the amount of heat released from the combustible portion of coal. As the proximate and ultimate parameters were found to be additive,the GCV also trail the additive rule. The same is depicted in Figure 11 and 12.

3.4 Grindability

The HGI provides a measure or ease of pulverization of a coal in comparison with coals used as standards. Higher index indicates that the coal is easier to grind. The coal mills in the power plants are generally designed for the fineness of the pulverized coal (design coal) should be 70% pass through 75 microns size and not more than 1% retained on the 300 microns size. If the HGI value of the coal blend is lower than the design coal, then the mill capacity will be reduced. This can lead to boiler load limitations and lead to boiler derating [1]. Some workers reported that the HGI was additive [6]

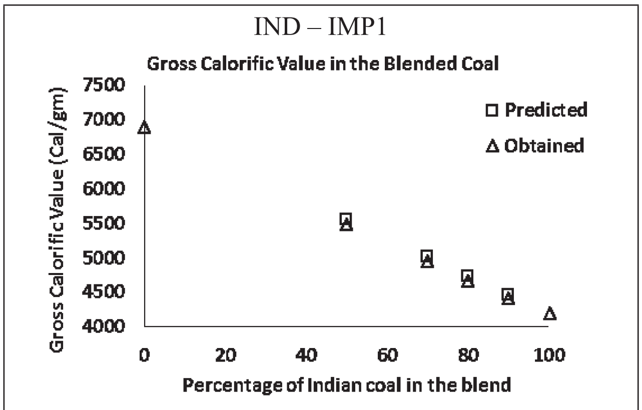

FIG. 10. GROSS CALORIFIC VALUE OFIND- IMP1

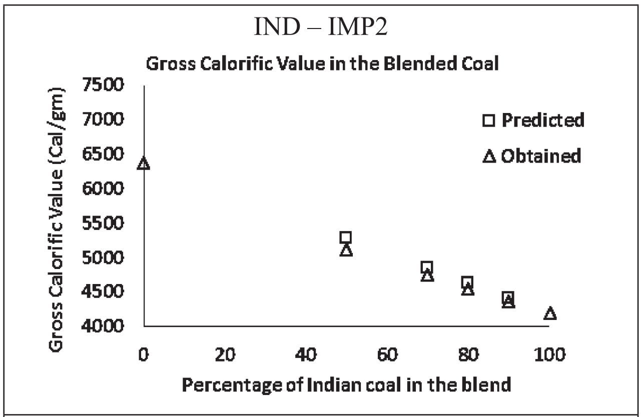

FIG. 11. GROSS CALORIFIC VALUE OF IND- IMP2

and some have reported that HGI is non-additive for containing coals with very different HGI values [8]. If the values are not additive, disproportion might occur in the resultant pulverized coal and this affects the combustion behavior in the boiler.

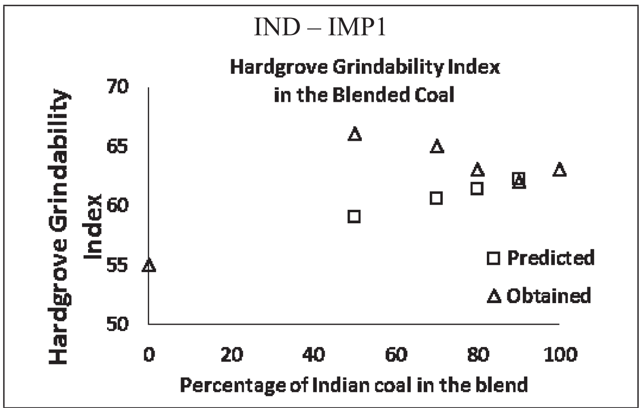

FIG. 12. HGI OF IND- IMP1

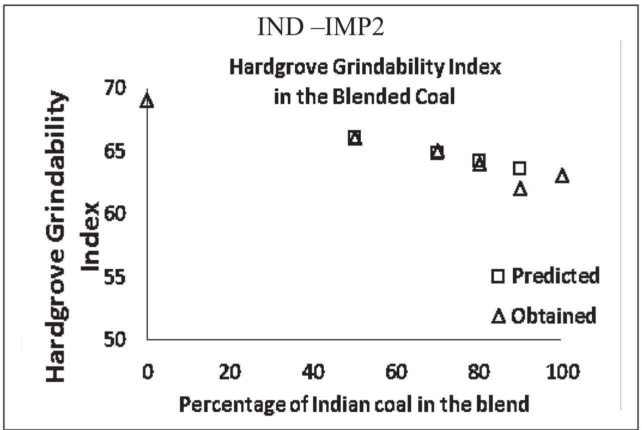

FIG. 13. HGI OF IND- IMP2

In the present work, the HGI values obtained for the Imp-1, Imp-2 and Ind coal are 55, 69 and 63 respectively. In the present work,the Imp-1/ Ind blends are showing non-additive behavior (Figure 13) and Imp-2/Ind blends are showing additive behavior (Figure 14). This indicates the unpredictability of HGI values of the blends from its component coals. This is in line with the results reported by Riley and others [9], Sliger [13], and waters [14] on the unpredictable nature of HGI for the blended coals from the values of Individual coals. However, some researchers [15, 26] indicated that the rank of the constituent coals are having impact on the HGI of the blended coal. The iso-rank coals

IND – IMP1

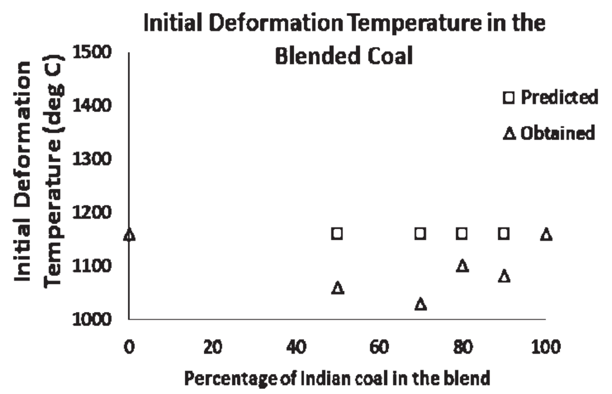

FIG. 14. INITIAL DEFROMATION TEMPERATURE OFIND- IMP1

IND – IMP2

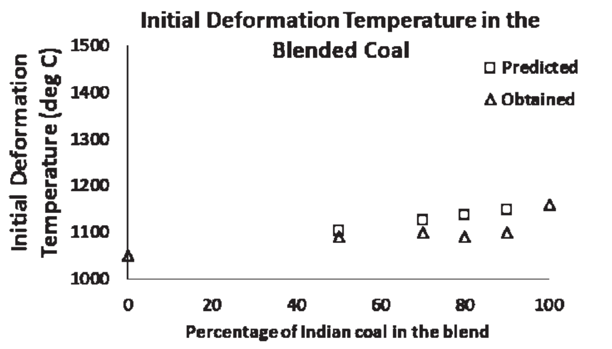

FIG. 15. INITIAL DEFORMATION TEMPERATURE OF IND- IMP2

IND – IMP1

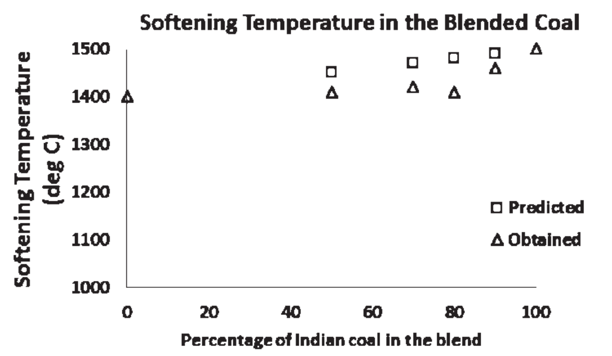

FIG. 16. SOFTENING TEMPEARTURE OFIND- IMP1

IND – IMP2

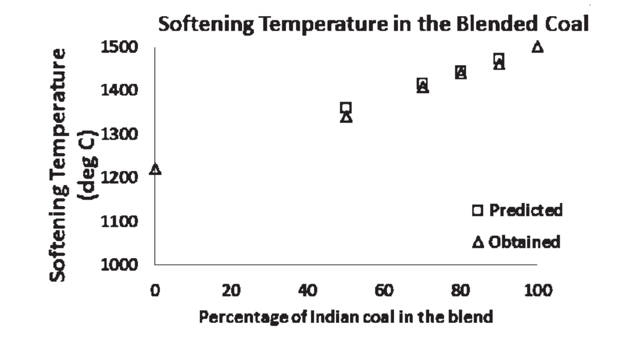

FIG. 17. SOFTENING TEMPERATURE OF IND- IMP2

are generally additive and the coals of different ranks show non-additive behavior. In the present work, the Indian coal and the Imp-2 are having the same rank (High Volatile B bituminous) and Imp-1 is having different rank (High Volatile A bituminous)compared to other two coals. The rank of the coals determined as per ASTM D 388-99 [23] is given in the Table 5. The additive behavior of Ind-Imp2 and the non-additive behavior of Ind-Imp 1 may be attributable to the blending of similar and dissimilar rank coals respectively.

TABLE 4

ASH ELEMENTAL OXIDES, %

OXIDES	SAMPLE		
	IND	IMP 1	IMP 2
SILICON DI-OXIDE	61.46	52.72	35.69
ALUMINIUM OXIDE	30.65	32.02	14.66
CALCIUM OXIDE	1.34	5.69	25.21
MAGNESIUM OXIDE	0.19	1.48	3.23
MANGANESE OXIDE	0.01	0.02	0.37
TITANIUM DI-OXIDE	0.48	0.85	2.3
SODIUM OXIDE	0.01	0.01	0.01
POTASSIUM OXIDE	0.93	0.29	0.55
IRON OXIDE	4.47	4.84	14.43
PHOSPHORUS PENTOXIDE	0.31	0.01	0.01
SULPHUR TRI-OXIDE	0.15	2.07	3.54

TABLE 5			
RANK OF COAL			
Sl. No.	SAMPLE	GCV mmmf, MJ/kg	RANK OF COAL
1	IND	31.9	High Volatile B Bituminous
2	IMP-1	33.1	High Volatile B Bituminous
3	IMP-2	28.4	High Volatile A Bituminous

4.0 CONCLUSIONS

1. The volatile matter and ash content were found to be additive in all the blends. The additive characteristics of volatile matter observed might be attributable to the similarity inthe kinetics of volatile release rate in both the component coals. The ash additivity indicates that there were no internal reactions between the sulphur content of one coal to the alkaline minerals of other coal as Indian coal was having less alkali content (sodium and potassium)
2. The ultimate analysis parameters and GCV were found to be additive as reported by other researchers.
3. The ash fusion temperature was found to be lower for blended coals compared to component coals and this is due to the effect of high calcium and magnesium in the imported coals which are acting as fluxing agents.
4. The HGI values were found to be additive for one combination of imported and Indian coal blends (Imp2-Ind) and non-additive for another combination (Imp1-Ind). The non additivity is due to the rank effect as the Indian coal and Imported coal are having different ranks.

The above observations indicate that the properties of coal blends cannot always be predicted from the component coal properties. It is imperative that every coal blend to be assessed for their properties in respect of proximate, ultimate, grindability, ash fusion characteristics etc. The constituent coals with similar characteristics like volatile release rate, rank, etc. may be chosen as the parameters for blending to avoid unanticipated complexities during combustion.

However, even the blend of similar rank coals sometimes show non-additive characteristics due to the internal reactions of constituent coals during combustion (example: the fluxing action of high level of calcium and magnesium). In the present study Ind-Imp-1 blends are found to be relatively better than Ind-Imp-2 in respect of proximate, GCV and AFT. However, Ind-Imp-1 shows non additive characteristics in respect of HGI and also have high sulphur value. The non-additive characteristics of HGI may lead to the disproportionation in the mill if both the coals are being ground together. This can be overcome by using separate mills for Indian and imported coals (tier blending). The high sulphur also can be tackled by applying Flue gas De-sulphurisation techniques.

REFERENCES

[1] A M Carpenter, Coal blending for power stations, International Energy Agency (IEA) Coal Research/64 1993, pp. 5-100,1995.

[2] W Moron, W Rybak, Combustion characteristics of blended coals, Third European Combustion Meeting (ECM), Mediterranean agronomic institute of Chania, Crete, Greece 11th -13th April, pp. 5-40, 2007.

[3] V Saravanan, R K Kumar, Ramakrishna, SSeetharamu, Combustion characterization of a pulverized coal 210 MW boiler through Computational Fluid Dynamics approach, The Journal of CPRI, Vol.9, No. 1, pp.63-70, 2004.

[4] W P Pan, and Y Gan, A study of thermal analytical values for coal blends burned in an air atmosphere, Thermochimica Acta, Vol.180, pp. 203-217, 1991.

[5] J Qiu, FLi, H Zeng, B Yao, and Y Ma, Determination of Optimum blending ratio

during coal blends combustion, Combustion Science and Technology, Vol.157, No .1, pp. 167-184, 2000.

[6] S Sua, J H Pohla, D Holcombeb, and J A Hartc, Techniques to determine Ignition, flame stability and burnout of blended coals in P.F. power station boilers, Progress in Energy and Combustion Science, Vol.27, pp. 75–98, 2001.

[7] S Biswas, N Choudhury, P Sarkar, A Mukherjee, S G Sahu, P Boral, and A Choudhury, Studies on the combustion behaviour of blends of Indian coals by TGA and Drop Tube Furnace, Fuel Processing Technology, Vol.87, pp. 191 – 199, 2006.

[8] J T Gilleland, S R Forsythe, R F Graham and H D Hayes, Non-additive analytical values for coal blends, In: Proceedings of the 7th International Conference on coal testing, Charleston, WV, USA, pp. 21-23, 1989.

[9] G Riley, J Wells, and J Williamson, Interactions between coal-ash and burner quarls. Part 2: Resistance of different refractory materials to slag attack in a combustion test facility, Fuel, Vol. 82, Issues 15–17, pp. 1867–1873, 2003.

[10] V Artos, and A W Scaroni, T.G.A. and drop-tube reactor studies of the combustion of coal blends, Fuel, Vol. 72, No.7, pp. 927-933, 1993.

[11] O Williams, C Eastwicka, S Kingmana, D Giddingsa, S Lormorb, and Edward Lester, Investigation into the applicability of Bond Work Index (BWI) and Hardgrove Grindability Index (HGI) tests for several biomasses compared to Colombian La Loma coal, Fuel, Vol.158, No. 15, pp. 379-387, 2015.

[12] J C Hower, Additivity of Hardgrove grindability: A case study, International Journal of Coal Geology, Vol. 7, pp. 68-70, 1988.

[13] J Sligar, Coal pulverizing mill section, an intensive course on the characterization of steaming coals, Newcastle, New South Wales: Newcastle, University of Newcastle, Institute of Coal Research, Vol.22, No.2, pp. 20–22, 1985,

[14] A Waters, The additive relationship of the Hardgrove Grindability Index, Journal of Coal Quality, Vol. 5, No. 1, pp. 33-34, 1986.

[15] A P Conroy, Grinding behavior of hard coals, Australian Combustion Technology Center (ACTC) Combustion News, Issue No. 5, pp. 1-4, 1998.

[16] Standard test methods for proximate analysis of the analysis sample of coal and coke by Instrumental procedures, ASTM D 5142 - 02a, West Conshohocken, P 19428-2959,USA.

[17] Standard test methods for instrumental determination of carbon, hydrogen and nitrogen in laboratory samples of coal and coke, ASTM D 5373 -02, West Conshohocken, P 19428-2959, USA.

[18] Standard test methods for sulfur in the analysis sample of coal and coke using high temperature tube furnace combustion methods, ASTM D 4239 -02a, West Conshohocken, P 19428-2959,USA.

[19] Standard test method for Gross Calorific Value of coal and coke, ASTM D 5865 – 03a, West Conshohocken, P 19428-2959, USA.

[20] Standard test method for fusibility of coal and coke ash, ASTM D 1857 -03, Conshohocken, P 19428-2959, USA.

[21] Indian standard method for determination of Hardgrove Grindability Index of coal, IS 4433 – 1979, Manak Bhavan, Bahadur Shah Zafar Marg, New Delhi-110002,India.

[22] Steam its generation and use, Edition 41, ISBN 0-9634570-1-2, Library of congress catalog number. pp. 21-6 to 21-12.

[23] Standard Classification of Coals by Rank, ASTM D 388-99, West Conshohocken, P 19428-2959, USA.

[24] A P Conroy, L A Juniper and D Phong-anant, The Impact of coal pulverizing

characteristics on power plant performance, International Conference on coal science, Tokyo, Japan, 23-27 Oct 1989, New Energy and Industrial Technology Development Organization (NEDO), vol. 2, pp. 1003-1006, 1989.

[25] J F Unsworth,D J Barratt, P T Roberts, Coalquality and Combustion performance: An International perspective, Amsterdam, the Netherlands, Elsevier Science Publishers, pp.640 -649, 1991.

[26] http://www.acarp.com.au/Media/ACARP-WP-5-Hardgrove Grindability Index.pdf