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Efficient utilization of Indian Coking Coal: Opportunities and challenges

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Abstract. The preservation of coking coal and the reduction of coke cost are gaining much importance in iron and steel industry. An effort is being made worldwide to maximize the use of inferior quality of coking coal in cokemaking without sacrificing the coke quality to minimize the coke cost. In general, Indian coking coals contain lower content of vitrinite ($\leq 50\%$) and higher content of ash ($\geq 15\%$) as compared to imported coking coal. Indian coking coals have poor washability characteristics also. Therefore, for making coal blend for coke making, selection of an appropriate proportion of Indian coking coals with imported coking coals is a major challenge for Indian steel industries. Proper selection of Indian coal not only reduces the coking coal import but also minimizes the coal blend cost with added benefits of the increase in the captive mine life. This paper touches the opportunities and challenges for efficient utilization of Indian coking coal as a component in the coal blend to produce the desired quality of coke.

Keywords: Indian coking coal / whasability / coking potential / cokemaking / coke quality

1 Introduction

The resources of prime coking coal in India is relatively small, therefore, to reduce the cost of coal blend, semi-soft coking coal and poor coking coal need to be used in coal blend. The quality of coal is a major issue that must be addressed by the coke producers holistically and inclusively. In iron making, coking coal is an important area to be addressed both for enhancement of its production and its optimum use to maximize the yield of good quality coke that meet the requirements of steel plants. Low volatile and medium volatile coking coals are being mined in India, and they are used in coking process, up to certain level, because the required heat is also an essential parameter for carbonization. In India, incremental increase in coke production for self-sufficiency in coke, for hot metal production is met mainly through imported low ash coking coal. This is because of the limited availability of high ash Indian coking coal and poor washability. Due to this peculiar behaviour, utilization of Indian coking coal in cokemaking is a challenge for iron and steel industries. Also, increase the higher slag volume generation compare to low ash coke which leads to an increase in hot metal cost. The challenges and opportunities of Indian coking coals is briefly described in Figure 1.

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Efforts have also focused on maximizing Indian medium coking coal in cokemaking to produce the quality of coke. But most of the Indian coals are the non-coking types which are found in eighteen major coal-fields spread over India. The deposits of Indian coals belong to two principal's viz., Lower Gondwana coals of Permian age and Tertiary coals of Eocene to Oligocene age. Out of them, the Lower Gondwana coals are more important for their distribution, quality, and deposition. The tertiary coals, though not of much significance in the context of their share in the total production area but it is much economic importance in the region where they occur. The main outcrops of Gondwana rocks are restricted mainly to the Indian Peninsula and along three linear tracts corresponding roughly to Damodar–Sone–Narmada Valley, Mahanadi Valley, and Wardha–Godavari Valley. Besides, they also occur in Chhattisgarh, Satpura, Sikkim, Andhra Pradesh, etc.

Gondwana coals of India are commonly richer in the inertinite group of macerals, with vitrinite in some cases, forming only a relatively minor component. The wide variation and fluctuation in different maceral assemblage reflect deposition in a cooler and drier climate and a more terrestrial environment than the Carboniferous coals of Europe or North America. The Gondwana coals show much variation in their petrographic properties due to postdepositional geological activities and multiple igneous intrusions in the form of dykes and sills. Both vitrinite-rich and inertinite-rich coals may occur in close proximity, and

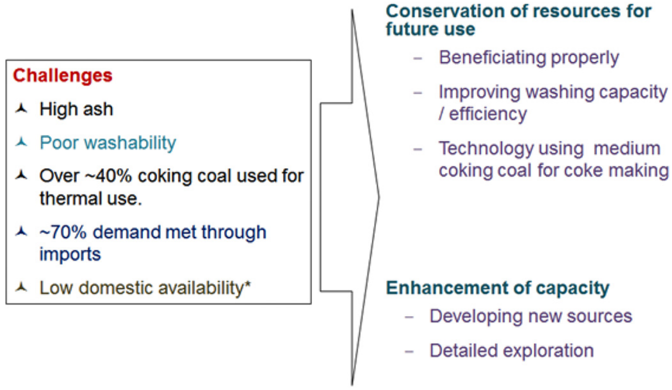

Fig. 1. Challenge for utilization of Indian reserve coking coal.

even as different parts of the same coal seam. Thus, it is important to understand the behaviour of inertinite in such coals from cokemaking perspective, which is full of complexity.

Most of the Indian coking coals are medium coking and of high ash content. Beneficiation of these coals is a must for their utilization in cokemaking. During washing, while the ash content of the coal is reduced, the same is expected to affect the reactive-inert maceral ratio. This will change the coking behaviour, including the expansion characteristics, of such coal. An increase in the expansion behaviour of coal increases wall pressure. Therefore, close monitoring of coking properties along with a drop in ash is necessary for smooth use of the coal in coke blend. An effort is, therefore, essential to understanding the impact of washing on coking properties. However, the final selection of coal for cokemaking depends not only on the coke quality requirements and the coal processing conditions but also on any restrictions which may be imposed by safe coke oven operation [1–20].

Significant effort has been focused on preserving the natural prime hard coking coals reserve by partly utilizing/replacing with high ash Indian coking coal and or maximization of inferior grade coals in the coal blend. It is well known that a good coal blend can result in inferior coke if proper care is not taken at the cokemaking plant. Similarly, techniques have now evolved for improving the quality of coke from inferior coal blend. With the above in view, it was felt necessary to optimize the ash percentage of clean coal of captive coals in stamp charged coal blend without affecting the cost and quality of coke. 1% increase in coal ash lead to approximately 4% increase in clean coal yield and thus cost reduction by replacing imported coal. Since Indian reserve coals are having different mineralogy and traditionally have high ash and poor petrographic properties but having good coking potential in terms of coke quality, especially coke CSR. Hence, a detailed study was taken to compare the overall coking potential of Indian low volatile matter content of coking coals (Gondwana region) with low volatile matter imported prime hard coking coals.

2 Methodology

Total of twenty-four coal samples was taken for the study. Eleven Indian coals belong to low volatile bituminous rank, one medium volatile medium coking coal and twelve imported prime coking coals (ten prime hard coking coals and two semi-soft coking coals). All the coal samples were tested with an objective to assess the coking potential. Different tests include proximate, chemical, rheological and petrographic were conducted based on the standard methods.

2.1 Washability of Indian coal samples

The washability characteristic of any ROM coal plays a vital role to decide the quality and productivity. The cost of the imported coal is always fluctuating and to ensure raw material security and minimize the impact of volatility in coal prices, it is desirable to try for augmentation of Indigenous coking coal through various routes and technologies and supply it to steel industries.

Syngenetic minerals occur either as finely disseminated mineral particles or in the form of larger species intimately intergrown with coal macerals. Coals with fine syngenetic minerals will produce relatively equal amounts of light density clean coal, middling and high-density rejects when subjected to gravity separation which is mainly used for coal washing in India. About 80% of raw coal is treated in dense media cyclone (gravity separation process) to produce clean coal. In contrast, the rest 20% treated in flotation or other gravity separation process based on coal characteristics. In this case liberation of the mineral matter can only be achieved by fine grinding. Coarser syngenetic minerals display much better washability characteristics. Better washing characteristics are mainly due to the greater degree of liberation of coarse minerals from coal.

Six coals, namely IND-A, IND-B, IND-C, IND-E, IND-H and IND-I were considered for washability studies. The proximate analysis of ROM is shown in Table 1.

Ash content of the head sample of IND-H was 23.68%, and an ash content of IND-A was 38.50% which is lowest and highest respectively among the six coals considered for washability. Sink-float analysis of IND-H showed a very high yield of about 85% at 18% ash whereas IND-A showed a very low yield of about 22% at 18% ash. IND-E having an ash content of the head sample was 29.58% showed a yield of about 28% at 18% ash. Coal IND-I of ash content 28.97% showed a yield of about 38% at 18% ash. Coal IND-C and IND-B having head sample ash as 38.50% and 31.90% yield of 32% and 55% at 18% ash level respectively.

IND-H has maximum clean coal yield of 85%, and both IND-A and IND-E have a low yield of 22% and 28% respectively.

After washing the coals, larger minerals and epigenetic minerals get washed out while the disseminated minerals, smaller in size remains within the matrix. Among quartz and kaolinite, after washing, the percentage of quartz increases while clay mineral decreases. Washability depends on the nature of occurrence of mineral, its size and its specific gravity.

2.2 Characterization of coal samples

The selected coal samples were characterized through proximate analysis, chemical analysis, free swelling index

Table 1. Properties of raw coals.

Coal ID	IND-A	IND-B	IND-C	IND-E	IND-H	IND-I
Ash, %	35.84	31.09	38.50	29.58	23.68	28.97
VM, %	19.21	17.06	17.69	18.06	19.69	20.35
IM, %	1.17	1.12	1.10	1.15	1.2	1.12
FC, %	43.78	50.73	42.71	51.21	55.43	49.56

Table 2. Chemical analysis of imported coking coals.

Coal ID	IMP-1	IMP-2	IMP-3	IMP-4	IMP-5	IMP-6	IMP-7	IMP-8	IMP-9	IMP-10	IMP-11	IMP-12
IM, %	0.9	1.0	1.2	1.1	1.34	1.14	1.68	1.90	1.74	1.57	1.75	2.35
Ash, %	9.90	10.0	8.74	9.25	8.09	8.90	10.77	9.89	8.93	9.40	9.03	5.91
VM, %	17.3	18.7	19.01	19.5	21.24	22.71	23.34	23.51	24.24	24.69	19.85	32.7
Sulfur, %	0.65	0.62	0.71	0.86	0.43	0.37	0.58	0.49	0.44	0.47	0.90	1.17
Phosphorus, %	0.045	0.03	0.039	0.035	0.06	0.057	0.055	0.046	0.069	0.058	0.122	0.02
SiO_2, %	47.93	48.44	54.94	51.50	53.89	58.96	59.93	54.23	54.29	59.05	59.35	56.98
Al_2O_3, %	26.32	28.13	31.03	29.50	38.82	28.73	29.01	32.04	36.24	32.65	24.42	28.49
Fe(T), %	9.08	9.84	5.98	7.60	3.02	3.24	4.40	5.15	4.80	2.61	6.75	5.62
CaO, %	5.65	3.86	2.64	2.00	0.63	3.24	2.71	4.35	0.88	1.49	3.51	1.55
MgO, %	2.27	1.14	1.15	0.60	0.38	0.86	1.13	0.57	0.25	0.56	1.56	0.78
MnO, %	0.04	Trace	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TiO_2, %	1.02	1.82	1.61	1.40	1.13	2.27	1.58	1.72	0.88	2.05	2.47	3.49
Na_2O, %	2.49	0.60	0.34	0.50	0.25	0.22	0.68	1.37	0.13	0.19	0.65	0.58
K_2O, %	0.44	1.42	2.299	2.25	1.884	2.484	0.564	0.572	2.525	1.399	1.299	2.519
Basicity Index	0.268	0.220	0.144	0.160	0.066	0.115	0.107	0.139	0.095	0.068	0.164	0.129

(FSI), low temperature grey-king assay (LTGK) test, Gieseler fluidity analysis and dilatation analysis test (Audibert-Arnu method – ASTM D 5515 and ISO Standard 349) as per the standard methodology.

Microscopic analysis of coal which includes determination of maceral composition, mean random reflectance of vitrinite was carried out based on the standard procedure (maceral composition of coal: ASTM D2799-05a, and Mean Random Reflectance of vitrinite: ASTM D2798-11a). Coal petrography has been done for all selected coal samples. Polished pellets were prepared for petrographic studies as per from minus 1 mm size of representative coal samples using a cold setting compound (ASTM D2797/2797M 11a). Pellets were studied under 50X oil immersion lens, and 10X objective lens using Leica DMRX reflected light microscope. Point counting method (500 counts per pellet) was used to quantify different maceral groups in coal and different carbon forms in coke. Vitrinite mean random reflectance (Ro) were measured in monochromatic light, and V-step distribution was calculated.

2.3 Carbonization study

The carbonization tests were conducted in a 7-kg carbolite oven. The construction and operation of the 7-kg electrically heated oven (370 length × 115 width × 305 height, mm) are based on the recommendations of the British Carbonisation Research Association (BCRA). The operating parameters like bulk density, oven temperature, moisture, granulometry and carbonization time was maintained constant for all the tests.

The coal samples to be used for making the coal blends were crushed to 3.0 mm below 90% and 0.5 mm below 48–50%. The coal cake was made inside a cardboard box by adding desired moisture content (10 ± 1%) and maintaining a bulk density of 1.15 t/m^3 (wet basis). Prepared coal cake was charged into the oven, which was preheated at a temperature of 900 ± 10 °C. After completion of carbonization (5 hrs), hot coke was pushed out and quenched with water. The quality of coke in terms of coke CSR and coke CRI was determined by using the Nippon Steel Corporation (NSC) method.

3 Result and discussion

3.1 Proximate analysis

Proximate analysis of all the imported coking coals and Indian coking coals is presented in Tables 2 and 3. Results show that imported coking coals having a lower content of ash (5.91–10.77%) and compared to Indian coking coals (15.20–21.31%). Ash content of all Indian coals is nearly 18% while three coals, IND-B, IND-I and IND-F, have higher ash content (20.5–21.3%). Inherent moisture (IM) is maximum (1.18%) in IND-E and lowest (0.57%) in IND-C.

Table 3. Chemical analysis of Indian coking coals.

Coal ID	IND-A	IND-B	IND-C	IND-D	IND-E	IND-F	IND-G	IND-H	IND-I	IND-J	IND-K	IND-L
IM, %	1.04	1.09	0.67	1.09	1.18	1.40	1.11	0.70	0.57	1.50	1.56	1.18
Ash, %	18.3	20.5	17.8	20.39	17.4	21.31	19.2	17.5	20.5	16.53	15.76	15.2
VM, %	17.2	17.7	17.9	18.52	18.7	18.73	18.75	19.3	19.4	21.32	22.21	24.8
Sulfur, %	0.68	0.87	1.02	0.82	0.79	1.00	0.66	1.01	0.79	0.62	0.63	0.90
Phosphorus, %	0.12	0.01	0.05	0.11	0.01	0.12	0.11	0.23	0.01	0.11	0.13	0.12
SiO_2, %	61.02	68.65	65.82	66.22	67.47	66.30	66.01	60.25	72.49	61.85	61.06	56.53
Al_2O_3, %	29.83	25.78	27.11	25.39	26.45	25.96	25.78	27.98	21.29	27.39	25.87	29.75
Fe(T), %	3.45	1.57	1.93	2.79	1.99	0.93	2.83	2.02	2.30	3.41	5.02	4.28
CaO, %	1.07	0.16	1.81	1.48	0.12	1.54	1.47	4.88	0.31	2.08	2.84	2.54
MgO, %	0.45	0.27	0.30	0.84	0.42	1.03	0.62	0.78	0.41	0.95	0.92	0.87
MnO, %	0.00	0.00	0.06	0.05	0.06	0.05	0.06	0.07	0.05	0.06	0.00	0.00
TiO_2, %	3.11	2.49	1.63	1.48	1.93	2.29	1.47	1.95	1.68	2.34	2.44	3.77
Na_2O, %	0.28	0.11	0.48	0.23	0.24	0.17	0.27	0.85	0.20	0.28	0.20	0.22
K_2O, %	0.791	0.973	0.845	1.528	1.325	1.728	1.473	1.236	1.276	1.641	1.650	2.032
Basicity Index	0.067	0.033	0.058	0.075	0.044	0.059	0.073	0.111	0.048	0.094	0.122	0.115

Table 4. Rheological analysis of imported coking coals.

Coal ID	IMP-1	IMP-2	IMP-3	IMP-4	IMP-5	IMP-6	IMP-7	IMP-8	IMP-9	IMP-10	IMP-11	IMP-12
FSI	9	$8\frac{1}{2}$	9	$8\frac{1}{2}$	9	7	8	$7\frac{1}{2}$	9	7	$5\frac{1}{2}$	$6\frac{1}{2}$
LTGK	G6	G5	G6	G5	G5	G3	G4	G2	G5	G2	G	G1
Max. Fluidity, ddpm	100	160	618	130	1929	134	2003	1072	2489	98	2	119
Max. Contraction, %	20	20	23	26	28	23	24	22	23	20	18	24
Max. Expansion, %	55	65	91	60	175	6	94	36	120	0	NIL	10

Table 5. Rheological analysis of Indian coking coals.

Coal ID	IND-A	IND-B	IND-C	IND-D	IND-E	IND-F	IND-G	IND-H	IND-I	IND-J	IND-K	IND-L
FSI	5	5	6	$5\frac{1}{2}$	7	$5\frac{1}{2}$	$5\frac{1}{2}$	7	3	$5\frac{1}{2}$	6	$6\frac{1}{2}$
LTGK	G	G1	G1	G1	G	G	G1	G2	F	G2	G1	G1
Max. Fluidity, ddpm	166	1049	21	513	1732	553	775	391	192	1403	1649	4205
Max. Contraction, %	19	18	20	19	19	18	19	19	19	18.00	16.00	21
Max. Expansion, %	−15	7	−19	−2	21	−1	10	22	−17	39	34	66

Volatile matter (VM) content of the clean coal ranges between 17.22% to 19.36% as the coals belong to the low volatile bituminous rank.

3.2 Ash chemistry

Ash constituent of selected coals is shown in Tables 2 and 3. Analysis suggests major oxides present are silica and alumina in all the seams. The results show that the SiO_2 content of Indian coking coals is higher (47.93–59.93%) and compared to imported coking coals (56.53–72.49%). All the Indian coals show a predominance of silica and alumina, alkali content below 0.32%, sulphur less than or equal to 1 except for IMP-12. The basicity index of Indian coals is in the excellent range (0.033–0.112) as compared to low ash imported coals (0.068–0.268) even though Indian coals having a high ash content.

3.3 Rheological properties of coals

Rheological properties of twenty-four selected coals are depicted in Tables 4 and 5. The FSI value of all selected coals varies is in the range of 5 to 7.5 except IND-I (FSI: 3) whereas the FSI of imported coking coals varies in the range of 5.5 to 9. Coal IND-I is quite rich in quartz content, and also it is having higher ash content (20.5%) than other coals. The LTGK value of Indian coking coal vary in the range of F to G2 whereas imported coals varies from G to G6, respectively. Maximum fluidity varies from 21 ddpm to 1732 ddpm except for IND-L, i.e. 4205. These coals have good plastic range. The plastic range is an essential property for deciding blend proportion. Maximum contraction is almost similar for all the coals, whereas IND-A, IND-I and IND-C have negative expansion. Indian coal IND-L is a medium volatile medium coking coal With 15%

Table 6. Petrographic analysis of imported coking coals.

Coal ID	IMP-1	IMP-2	IMP-3	IMP-4	IMP-5	IMP-6	IMP-7	IMP-8	IMP-9	IMP-10	IMP-11	IMP-12
Vitrinite, %	74.0	67.0	77.5	80.0	68.5	65.8	63.4	41.7	60.5	66.5	52.4	82.2
Liptinite, %	–	–	–	–	2.0	1.2	0.3	–	2.3	1.4	–	1.9
Inertinite, %	21.8	29.0	17.4	14.6	24.8	28.1	31.8	52.1	32.0	26.3	42.3	12.5
MM, %	4.2	4.0	5.1	5.4	4.7	4.9	4.5	6.2	5.2	5.8	5.3	3.4
Ro (avg.), %	1.55	1.42	1.39	1.41	1.2	1.16	1.21	1.13	1.14	1.11	1.32	1.07

Table 7. Petrographic analysis of Indian coking coals.

Coal ID	IND-A	IND-B	IND-C	IND-D	IND-E	IND-F	IND-G	IND-H	IND-I	IND-J	IND-K	IND-L
Vitrinite, %	46.0	38.3	44.0	46.0	49.8	42.3	46.8	57.0	51.0	52.2	47.1	50.6
Liptinite, %	–	0.7	–	–	1.0	0.2	–	0.2	–	1.7	1.2	2.5
Inertinite, %	42.0	50.0	45.0	41.8	40.0	44.7	42.1	32.8	37.0	36.2	42.3	37.8
MM, %	12.0	11.0	11.0	12.2	9.2	12.8	11.1	10.0	12.0	9.9	9.4	9.1
Ro (avg.), %	1.40	1.30	1.40	1.29	1.32	1.29	1.28	1.40	1.20	1.12	1.16	1.06

ash. IND-L is rich in silica and alumina. Alkali and Fe(T) content of IND-L is higher compared to foreign coals. This coal has a high FSI (6.5) and very high fluidity along with high expansion. It's vitrinite-rich coal with a Ro of 1.06%. Imported coal IMP-7 is prime coking coal with FSI (7.5). It has high fluidity and expansion property. It is vitrinite-rich coal with a Ro of 1.16%. Imported coal IMP-12 coal is low ash, high VM coal with vitrinite content of 82% and Ro of 1.07%. The V-step distribution suggests this coal be a blended one with vitrinite of very low reflectance. As a result, it doesn't have high fluidity or expansion, but FSI is 6.5. Imported coal IMP-11is semisoft coal with low ash and low VM. It doesn't have expansion and fluidity, but FSI is 5.5. It is also vitrinite-rich coal with a Ro of 1.32%.

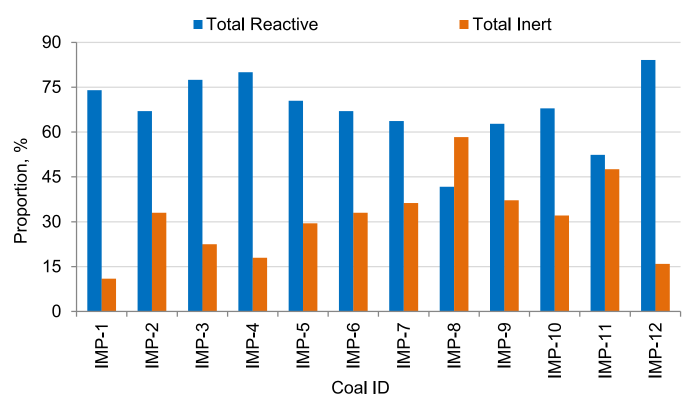

Fig. 2. Reactive and inert of different rank of imported coals.

3.4 Coal petrography

The petrographic analysis of twenty-four coals is presented in Tables 6 and 7. Results depict that the rank [Ro (avg.)] of all selected imported and Indian coking coals were tried to maintained almost the same band for batter comparison. The rank (Ro) of imported prime hard coking coal varies in the range of 1.07–1.55 whereas the Indian coking coals vary from 1.06–1.40. The result shows that all imported coals are having higher reactive macerals as compared to Indian coals except coal IMP-8. Indian coals are moderated reactive macerals whereas, coal, IND-B is inertinite-rich as compared to imported coals. Rankwise all selected Indian coking coals have a good band, and due to the overall coking potential, these coals generally falls in the category of medium to low volatile bituminous coal. The reactive macerals, inert macerals and v-step distribution of selected imported low ash prime coking coals and high ash Indian coking coals depict in Figures 2–5, respectively. Results show that imported coals having high dominant of V-11 and V-12 (Fig. 4) while the Indian coals having high dominant of V-12, V-13 and V-14 (Fig. 5).

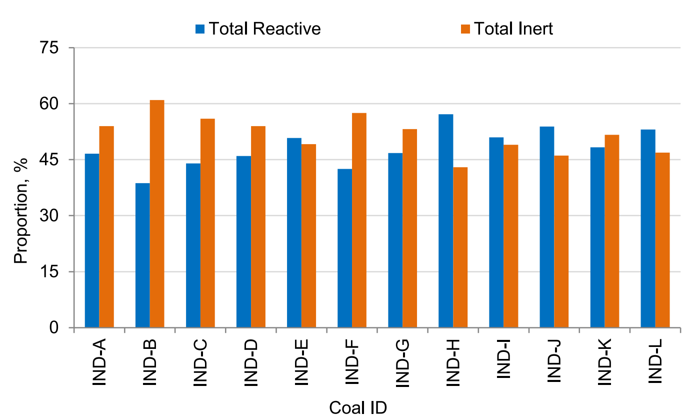

Fig. 3. Reactive and inert of different rank of Indian coals.

3.5 Carbonization study

3.5.1 Carbonization of individual coals

Total twenty-four individual coals (twelve imported coking coal and twelve Indian coking coal) with similar volatile matter content (17.20–24.80%) except coal IMP-12 have

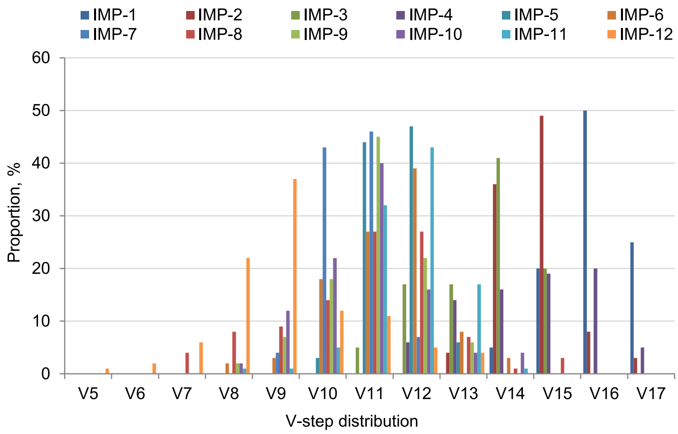

Fig. 4. V-step distribution of different rank of imported coals.

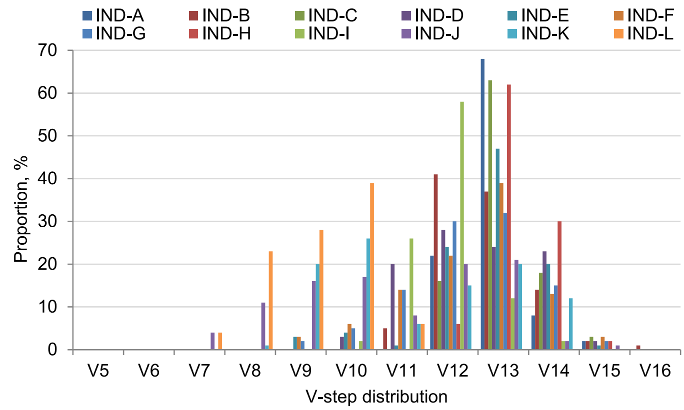

Fig. 5. V-step distribution of different rank of Indian coals.

Table 8. Carbonization study of Imported coking coals in laboratory ovens.

Coal ID	IMP-1	IMP-2	IMP-3	IMP-4	IMP-5	IMP-6	IMP-7	IMP-8	IMP-9	IMP-10	IMP-11	IMP-12
Moisture, %	10.0	10.1	10.2	10.1	10.0	10.1	9.9	10.1	9.9	10.2	10.1	10.0
Ash, %	9.9	10.0	8.7	9.3	8.1	8.9	10.8	9.9	8.9	9.4	9.0	5.9
VM, %	17.3	18.7	19.0	19.5	21.2	22.7	23.3	23.5	24.2	24.7	19.9	32.7
CI (−3.0 mm), %	90	89	90	91	90	90	90	90	90	90	89	90
CI (−0.5 mm), %	48	48	48	49	50	48	48	49	48	50	48	49
BD, t/m^3 (wet)	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Coking time, hrs	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Coke end temperature, °C	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050
Coke CSR	67.0	72.8	66.7	67.0	66.9	59.2	57.3	57.7	58.8	59.5	48.5	37.2
Coke CRI	23.5	20.2	23.0	24.2	24.4	32.0	32.3	33.1	32.1	30.0	40.6	42.1

been carbonized in a laboratory oven to assess the coking ability of the coals. Result of the carbonization test of individual coals under stamp charging conditions is given in Tables 8 and 9. The moisture content (10 ± 0.2%), crushing fines (90 ± 1% below 3 mm) and bulk density (1.15 t/m^3, wet basis) was maintained identical for all test. The result confirmed that all coals are having good coking ability quality of coke CSR (52.4–72.8). The coke CSR of selected imported prime hard coking coal and high ash Indian coals are presented in Figure 6. The result shows that high ash Indian coking coals produce an almost similar trend of coke CSR (52.4–71.9) as compare to similar volatile matter content of imported prime hard coking coals (57.3–72.8) even though Indian coals having poor vitrinite content and poor rheological properties (Tabs. 4–7). This may vary due to the lenticular mosaic structure of Indian coke [21]. As the literature suggests, such mosaic textures result from the carbonization of vitrinite of v-step from V12-V14 [20] but increase in lenticular mosaic texture than the respective vitrinite indicate the role of semifusinite in contributing toward the binder. The coke CSR of colas IMP-11 and IMP-12 were not plotted into the Figure 6 because both coals are fall into the semi-soft coking coal category (IMP-11 is having high rank whereas IMP-12 is lower rank) and hence the produced coke CSR is in the lower site (coke CSR of IMP-11 is 48.5 and IMP-12 is 37.5).

Results depict that due to variation in the inherent properties of selected Indian (Ash: 15.22–21.31%; basicity index: 0.033–0.112, FSI: 3–7; Ro: 1.06–1.40; Vitrinite: 38.0–57.0%) and imported coking coals (Ash: 5.91–10.77%; basicity index: 0.068–0.268, FSI: 5.5–9; Ro: 1.07–1.55; Vitrinite: 41.7–82.2%) the resultant coke CSR varied. Also, v-step distribution is different from coal to coal as compared to imported coals with similar rank and volatile matter content. It is confirmed from results that Indian coking coals have outstanding basicity index and coking potential even though it containing higher inert content.

3.5.2 Carbonization of coal blend

The coal blends in the proportions mentioned in Table 10 were carbonized in a laboratory oven. The results of carbonization test are presented in Table 10. It has been found that CSR with coals IND-E, IND-B, IND-C were better than coke CSR with coal blends of IND-A, IND-C and IND-I. CRI values also increased for all coals except IND-I with two different ash compositions (13.07 and 20.46%). This suggests that coal which produces a very high-quality coke individually will not necessarily improve the overall CSR of the blend. Coal forming a low CSR coke may improve the overall blend CSR on addition. Therefore,

Table 9. Carbonization test results of Indian coking coals in laboratory ovens.

Coal ID	IND-A	IND-B	IND-C	IND-D	IND-E	IND-F	IND-G	IND-H	IND-I	IND-J	IND-K	IND-L
Moisture, %	10.0	10.1	10.2	10.0	10.0	10.1	9.9	10.1	9.9	10.2	10.0	9.9
Ash, %	18.3	20.5	17.8	20.4	17.4	21.3	19.2	17.5	20.5	16.5	15.8	15.2
VM, %	17.2	17.7	17.9	18.5	18.7	18.7	18.8	19.3	19.4	21.3	22.2	24.8
CI (−3.0 mm), %	90	89	90	91	90	90	90	90	90	90	89	90
CI (−0.5 mm), %	48	48	48	49	50	48	48	49	48	50	48	49
BD, t/m^3 (wet)	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Coking time, hrs	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Coke end temperature, °C	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050
Coke CSR	64.5	52.8	71.9	61.6	61.5	52.4	63.7	65.0	55.0	55.0	54.5	54.4
Coke CRI	25.5	30.4	17.6	25.1	26.5	25.4	25.0	24.5	26.2	26.1	26.9	29.5

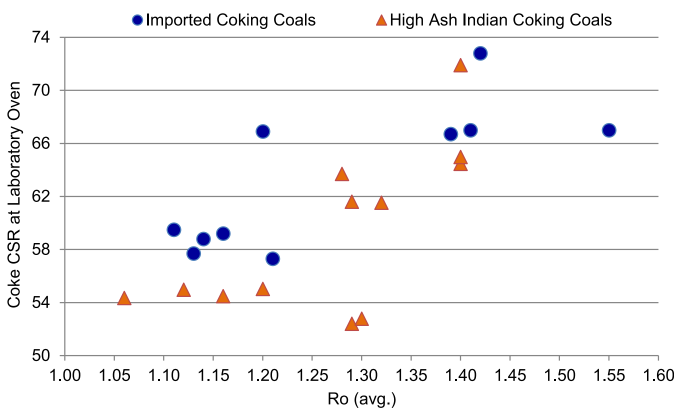

Fig. 6. Relation between Ro mean and coke CSR of imported and high ash Indian coking coals.

blending requires detailed knowledge of individual coal characteristics and properties.

Tables 8 and 9 summarize the results of coke made with 100% single coal in a laboratory-scale oven of both Indian and imported coal respectively. The ash, VM, Ro and FSI of imported coals varied in the range of 5.91–10.77%, 17.30–32.70%, 1.07–1.55 and 5.5–9 whereas for Indian coals 15.20–21.31%, 17.20–24.80%, 1.06–1.40 and 3–7 respectively. Results show that all imported coals can produce good coke CSR except coals IMP-11, IMP-12, IND-B and IND-F because IMP-11 is high-rank semisoft coal and IMP-12 is the low-rank semisoft coals whereas IND-B is high ash (20.50%), high inert component (62%) and IND-F is having high ash content (21.31%). The coke strength after reactivity (CSR) varies in the range of 37.2–72.8 for imported coals whereas for high ash Indian coking coals varies in the range of 52.40–71.90 respectively. The coal/coal blends yielding mini-oven coke of acceptable quality [coke strength after reaction (CSR) = 54 minimum] without excessive lateral expansion (8.2% maximum) were recommended for producing commercial oven coke with a CSR of 64 minimum [22]. It appears that Coals IMP-1, IMP-2, IMP-3, IMP-4, IMP-5, IMP-6, IMP-7, IMP-8, Imp-9 and IMP-10 and Indian coals IND-A, IND-C, IND-D, IND-E, IND-G, INDH, IND-I, IND-J, IND-K, AND IND-L can produce greater than 65 coke CSR in commercial coke oven.

The result depicts that mean vitrinite reflectance of Indian coals is in a narrow range (1.23–1.37%). Coal IND-I and IND-B have comparatively lower and wider v- step distribution, whereas others have narrow distribution. Coal IND-I with relatively low reflectance has an FSI - 3 and LTGK - F type in spite of having high vitrinite content. This suggests that vitrinite reflectance, i.e., the rank of the coal plays an important role. But the variation in coal properties of similar rank remains unaddressed. Maceral groups give a broader picture of coal and do not satisfy their characteristic properties to be used in coal preparation and utilization. A detailed analysis of individual maceral groups may give more insight into the coal.

For the present study, six coal blends have been prepared in which medium volatile medium coking coal, i.e. IND-L 35%, imported coals IMP-11, IMP-12, IMP-7 have proportions like 28%, 7% and 15% respectively. For each blend, six low volatile coals have been taken as a component of coal blend. The blend proportion has been selected in such a manner that cumulative vitrinite and Ro of the blend be in very close range. Results confirmed that there were significant variations in coke quality, especially in terms of coke CSR and CRI even keeping the vitrinite and reflectance in close range.

Table 10 depicts the results of carbonization tests of different coal blends which were carried out in a laboratory oven. The blending of coals was done based on the results of a straight carbonization test report. The results show that all designed coal blends were produced coke with CSR in the range of 54.25–61.43 with positive lateral dilation in range of 4.81–7.77%, which is suitable for stamp charging cokemaking. Both produce coke CSR and lateral expansion are acceptable to produce good quality of coke (≥ 65 coke CSR) with safer coke oven battery operation [22]. Hence, results confirmed that up to 50% high ash Indian coking coals may be easily used in the recovery stamp charge coal blends without sacrificing the coke quality.

4 Conclusion

The Indian medium coking coal having good coking potential but the washability of Indian coals is not good. Due to poor liberation, the Indian reserve coals is not better

Table 10. Carbonization test results of coal blends in laboratory ovens.

Coal blend composition, %	Vitrinite, %	Ro (avg), %	Bulk density, t/m^3 (wet)	Lateral Exp., %	Vertical Exp., %	Coke CSR	Coke CRI
IND-L: 35 IMP-1: 28 IMP-12: 07 IMP-3: 15 IND-K: 15	55.96	1.20	1150	+7.77	+2.59	56.83	30.03
IND-L: 35 IMP-1: 28 IMP-12: 07 IMP-3: 15 IND-H:15	55.96	1.20	1150	+7.77	+2.59	56.83	30.03
IND-L: 35 IMP-1: 28 IMP-12: 07 IMP-3: 15 IND-A: 15	54.31	1.19	1150	+7.70	+2.59	54.25	32.07
IND-L: 35 IMP-1: 28 IMP-12: 07 IMP-3: 15 IND-E: 15	54.88	1.19	1150	+5.33	+1.23	61.20	31.31
IND-L: 35 IMP-1: 28 IMP-12: 07 IMP-3: 15 IND-I: 15	55.00	1.17	1150	+5.18	+1.60	61.43	28.72
IND-L: 35 IMP-1: 28 IMP-12: 07 IMP-3: 15 IND-F: 15	53.06	1.19	1150	+4.81	+2.47	60.91	28.73

utilization in the steel industry and hence complex washery infrastructure with fine coal circuit to be designed for preparation of formidable of coals to the optimization of clean coal yield.

The study demonstrated that high ash Indian medium coking coals (15.2–21.3%) having the volatile matter content (17.2–24.8%), lower in vitrinite content (38–57%) and high Ro mean value (1.06–1.40%) whereas Imported coals have low ash (5.91–10.8%), almost similar volatile matter content (17.3–24.7%), rich vitrinite content (41.7–80.0%) and almost same Ro mean value (1.11–1.55%). The carbonization study confirmed that high ash Indian medium coking coals (Gondwana region) having peculiar behaviour to produce good quality of coke under stamp charged condition as compare to low ash premium imported coking coals. The study also confirms that coke CSR of coal blend contains 50% Indian coking coal (35% medium volatile matter and 15% low volatile matter) as a component of coal blend is acceptable to produce coke CSR ≥ 67 in Coke Plant.

Results confirmed that Indian medium coking coal having peculiar coking behaviour for producing the superior quality of coke as compare to low as imported coals. By the using of the high ash clean Indian coking coal (15.2–21.3%) can easily reduce the imported coal in the coal blend and that can be replaced by indigenous medium coking coal of low cost. Hence, the overall cost of the coal blend will be reduced without sacrificing the coke quality. It will also bring about the largest economy by replacing the imported prime hard coking coal and thereby reduced the cost of produced coke, thus the cost of hot metal. This also helps in overcoming the import of prime coking coals from the international market.

Abreviations

BD	Bulk density
CET	Coke end temperature
CI	Crushing index
CRI	Coke reactivity index
CSR	Coke reactivity index
Exp.	Expansion
FC	Fixed carbon
FSI	Free swelling index
IM	Inherent moisture
LTGK	Low temperature gray king assay
Max.	Maximum
MM	Mineral matter
ROM	Run of mine
VM	Volatile matter

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