CHARACTERISTICS OF INDIAN NON-COKING COALS AND IRON ORE REDUCTION BY THEIR CHARS FOR DIRECTLY REDUCED IRON PRODUCTION

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ABSTRACT

Studies on chemical and physical properties (proximate analysis, sulphur content, reactivity, iron ore reduction potential, caking index and ash fusion temperatures) of coals, procured from sixteen different mines of Orissa, were undertaken for their judicial selection in Indian sponge iron plants. These coals were found to have low sulphur (range : 0.40 – 0.66 %) and moderate to high ash (range : 22 – 53 %) contents. The results indicated no caking characteristic in all the coals except Basundhara. Majority of the studied coal ashes were found to have higher fusion temperatures (ST: 1349 – 1547^{0}C; HT: 1500 – 1663^{0}C; and FT: 1510 – 1701^{0}C). An increase in fixed carbon content in the coal char, in general, led to decrease in its reactivity towards CO_2, and majority of the chars exhibited significantly higher reactivities (> 4.0 cc of CO/g.sec). Further reduction studies in coal chars at 900^{0}C indicated an increase in the degree of reduction of fired hematite iron ore pellets with increase of char reactivity and reduction time. The authors recommend the utilization of majority of the studied coals as such and some of them (Lakhanpur, Samleshwari, Orient OC– 4 and Dhera coals) after blending or beneficiation.

***Keywords**:* ash fusion temperatures, caking index, coals and chars, composition, , iron ore, reactivity, reduction

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1. INTRODUCTION

Prospects of demand for steel in India and its rich mineral resources, liberalized economic policy of the nation and globalization of market have attracted many foreign and national steel magnates to invest in steel sector of the country. At present, the annual steel production in India is about 42 MT and is expected to reach up to the level of 110 MT by 2020 (Patnaik 2006). Steel manufacturing through blast furnace route faces many problems, such as scarcity of coking coal (particularly in India), large emission of air pollutants, high investment cost, poor flexibility in production capacity, etc.. In view of abundant and easy availability of low grade (D, E, F and G) non-coking coals in India, more attention is being paid in recent years towards their utilization in direct reduction processes. Over the last few years, coal-based (rotary kiln) direct reduction processes have gained importance as the potential alternative route of ironmaking in India. Moreover, this sponge ironmaking technology has received higher economic viability by its ability to generate a considerable amount of electricity through the use of hot waste gases and char. The quality of coal/char is one of the most important problems to be solved in order to use them more effectively in these processes. For successful utilization of coal in sponge ironmaking, the properties which need to be well understood are fixed carbon, volatile matter, ash and sulphur contents, caking and swelling indices, ash fusion temperatures, char reactivity and its strength, bulk density, etc..

The present article reports the findings of some laboratory studies on the above mentioned properties of 16 different types of low grade (D, E and F) non-coking coals (obtained from different mines of Orissa) and reduction potentials of their chars. The objectives were : (i) to ascertain the behaviour of these non-coking coals in advance, and (ii) to provide sufficient technical information to the sponge iron plants, particularly to those which do not have R&D facilities. The authors also wish to investigate the relationships between (i) measured reactivity values and ash contents of selected coals, and (ii) reactivities of chars and their iron ore reduction potentials. This work may help in assessing the cost and selection of coal for a particular sponge iron plant.

2. FUTURE OF DRI INDUSTRY IN INDIA

Sponge iron industry has emerged as a front line player in national economy and India has become the largest producer of sponge iron in the world. Sponge iron has now succeeded in becoming a preferred raw material in secondary steelmaking, and electric arc furnaces are happily looking forward for the use of 70% DRI. At present, the country has about 209 operating units and 106 units are in various stages of completion. Table 1 shows the trend of growth of sponge iron production in India (Patnaik 2006, SIMA 2007). It has been estimated that the production of sponge iron in India will exceed 25 MT/year by 2011 (Patnaik 2006) and thus the prospect of this industry in India is bright. Out of the total production of 16.28 MT of sponge iron in 2006–07, 11.01 MT was based on non-coking coal and rest on gas (SIMA 2007). In India, there is no scope of increasing the production of sponge iron through gas-based plants because of limited availability of natural gas. Hence, the future expansion in sponge iron production has to depend on coal-based plants.

The sponge iron industry is quite comfortable so far the reserves of iron ore and coal are concerned. Total recoverable resources of iron ore in the country account for about 9% of the world’s reserves and the major deposits are located in the states of Orissa (34%), Jharkhand (27%), Chhatisgarh (18%), etc. (Tripathy 2007). Grade-wise total proved reserves of non-coking coal in India have been outlined in Table 2 (Jena 2007).

The gradation of Indian non-coking coals has been carried out on the basis of useful heat value (UHV) and is shown in Table 3 (Government of India 2007). As per the present system of coal linkage in India, about 80% of the production of high grade coals (A, B and C) goes to the power sector and the balance 20% to other industrial sectors including sponge iron plants (Jena 2007). These data clearly indicate that measures must be taken to utilize D, E, F and G grade coals through better process control.

3. EXPERIMENTAL

3.1. Materials Selection

In the present investigation, sixteen types of non-coking coal samples of grades D, E and F were collected from different mines of Orissa, India. Hematite iron ore, used in the reduction studies, was obtained from BPJ OMC Ltd. No. 6 mine of Orissa and its chemical and physical properties have been reported in our previous paper (Kumar et al. 2008).

3.2. Coal Char Preparation

In order to produce chars for the reactivity and iron ore reduction studies, all the selected coal samples (size : 1–3 mm) were carbonized in a stainless steel reactor at a temperature of 950 ± 5^0C, as per standard method (Indian Standard : 12381 1994). During carbonization, the coal sample was heated from room temperature to 950^0C at the rate of about 7^0C min^{-1} and charred at this temperature for 3 h followed by furnace cooling. The resulting chars were then processed for their proximate analysis and reactivity studies.

3.3. Determination of Caking Index

The caking indices of coals were determined according to the standard test method (Indian Standard : 1353 1993) by the maximum sand to coal ratio in a mixture of 25g which, after carbonization at 920^0C for seven minutes, gives a coherent mass capable of supporting a 500g weight and generating less than 5% of loose powder.

3.4. Determination of Chemical Properties

3.4.1. Proximate Analysis and Sulphur Content

Proximate analysis (Indian Standard : 1350 1969) of coals and chars was carried out on samples ground to pass through a 72 mesh B.S. test sieve, while sulphur contents in coals were determined by X-ray Fluorescence Spectrometer at Rourkela Steel Plant.

3.4.2. Reactivity Measurement

Reactivity values of chars to carbon dioxide gas were determined as per standard method (Indian Standard : 12381 1994), which simulates the conditions in a rotary kiln based sponge iron plants. In this laboratory test, 5g of dried char sample of size 0.5 to 1.0 mm was held in a perforated crucible made of 100 mesh stainless steel screen and so kept in a silica reaction tube of the tubular furnace that the sample was in uniform temperature zone. The test sample was brought to the required temperature of 1000^0C under nitrogen atmosphere (50 cc min^{-1}). After the stabilization of temperature, a stream of dry carbon dioxide gas was admitted to the reactor at a flow rate of 100 cc min^{-1} for 25 min. The power was then switched off and the sample was cooled to 150^0C in nitrogen atmosphere. The reacted char sample was then weighed and the reactivity was calculated by using the following equation (Indian Standard : 12381 1994):

Reactivity = 11.61 x W ⁄ (5 x C_{fix} – W/2) cc of CO gas / g . sec

Where, W denotes the weight loss in char and C_{fix} is the fraction of fixed carbon in the char before reaction.

3.5. Determination of Ash Fusion Temperatures

The fusion temperatures of coal ashes were determined according to the German standard test method (DIN : 51730 1984). This ash fusion test consisted of observing deformation, shrinkage and flow in cubic shaped (size: 3 mm) ash samples in a Leitz high temperature microscope (equipped with a heating system) up to the temperature of 1700^0C in air. The heating rate was 10^0C min^{-1}. The four characteristic ash fusion temperatures were identified as : (i) initial deformation temperature (IDT) – first sign of change in shape; (ii) softening temperature (ST) – rounding of the corners of the cube and shrinkage; (iii) hemispherical temperature (HT) – deformation of cube to a hemispherical shape; and (iv) fluid temperature (FT) – flow of the fused mass in a nearly flat layer.

3.6. Procedure for Reduction Studies of Iron Ore Pellets

Experiments on reduction of weighed amounts of fired (at 1200^0C for 1 h) iron ore pellets (15 mm approximate diameter), embedded centrally on a packed bed of coal char powder (–72 mesh size) in stainless steel reactors, were carried out by heating the reactors from room temperature to the predetermined temperature of 900^0C at a rate of about 7^0C min^{-1}. The pellets were soaked at the final temperature for 60 and 90 min, and the reactors were then taken out and cooled in air. Similar reduction experiments were performed in all the coal chars. The pellets thus reduced were weighed and the degree of reduction was expressed as the wt.% of oxygen removed from each of them.

4. RESULTS AND DISCUSSION

The chemical compositions, caking index and ash fusion temperatures of coals under investigation have been listed in Table 4, while Table 5 presents the results of char reactivity and iron ore reduction experiments.

4.1. General Characteristics of Studied Coals

Quality of coal affects the economy, output and efficiency of the kiln operation. Fixed carbon indicates about the availability of carbon during reduction of iron ore. The gases generated from low volatile (< 27%) coals are insufficient to contribute in the reduction of iron ore inside the kiln. On the other hand, a high volatile matter (> 30%) causes various problems in the kiln, such as reduction in kiln temperature, high oxygen and coal requirements, high carbon dioxide concentration in the reducing gas, reduction in the degree of DRI metallization and more tarry materials in the gas (Ghorai et al. 2001). A high ash content (a dead load occupying kiln volume) in the coal increases slag volume and SPM emission, causes poor drainage through the char bed and adversely affects the thermal requirement and productivity of the kiln. High sulphur content increases flux and fuel requirements in the process. Caking index of coal is also of direct relevance to the kiln operation. As reported in the literature (Patnaik 2006), a high caking index causes sintering, reduces char reactivity and leads to accretion formation in the kiln. Therefore, caking index of coal should be preferably below one (however, acceptable up to three).

From the proximate analysis results of the studied coals (Table 4), the values of volatile matter, ash and fixed carbon contents appear to fall in three groups of data range : (i) 27–39%, 22–33% and 40–45% for Basundhara, Lingaraj and Bharatpur coals; (ii) 21–

32%, 36–49% and 30–35% for Belpahar, Orient OC–2, Jagannath, RKC, Ananta, Nandira and Kalinga coals; and (iii) 22–27%, 47–53% and 23–27% for Lakhanpur, Samleshwari, Orient OC–4 and Dhera coals. This variation in chemical composition of these coals appears to be associated with the difference in contents of their petrographic constituents. As outlined in the literature (Stach et al. 1982), these coals are rich in mineral matters due to their drifted origin. The results (Table 4) also indicate that the distinction between these coals with respect to sulphur content is less pronounced and all of them are having lower sulphur content in the range 0.40–0.66 %. However, the relative sulphur contents are higher in the high ash coals. Furthermore, the results obtained (Table 4) established no caking characteristics in all of them except Basundhara coals, most probably due to the dominance of inert components (fusinite, semifusinite, mineral matter, etc.). Almost all the studied coals are of Gondwana system and the literature (Stach et al. 1982. Narasimhan and Mukherjee 1999) indicates very high inertinite (mainly fusinite and semifusinite) contents (50–80% on mineral matter free basis) in them. The vitrinite content seldom exceeds 40%. This may be the reason for no caking index in these coals. Secondly, all the studied coals exhibited higher reactivities towards CO_2 gas for their chars (Table 5) and this appears to be an indication of presence of substantial amounts of inertinites in them, as suggested by Choudhury et al. (2007). From the point of view of coal petrology, the caking power of coal comes from its active/fusible components (vitrinite, exinite, liptinite and 1/3 of semivitrinite) (Chen 1989). The caking index of vitrinite (93) has been reported to be much higher than that of the inertinite (13–19) and approximately equal to that of the exinite concentrate (92) (Chen 1989). Semivitrinite is considered to be a weakly caking maceral. The weakly caked (caking index: 2) Basundhara coals appear to contain some amount of fusible components.

4.2. Coal Ash Fusion Temperatures

Ash fusion t+emperatures (AFTs) are widely used as a measure of coal ash fusibility and its agglomeration characteristics, and give prior information to the designers and operators about the likely ring formation in the rotary kilns. During rotary kiln operation, the coal ash having low AFT melts and partially adheres to the char surface reducing its reactivity and forms agglomerated mass. In order to ensure no ring formation or agglomeration inside the rotary kiln, the initial deformation temperature (IDT) of coal ash should be at least 130 – 150^0C more than the operating temperature of the kiln and softening temperature must exceed 1300^0C (Tripathy 2007). As pointed out in the literature (Vassilev et al. 1995), the progression from initial deformation to fluid temperature is due principally to various stages of mineral transformations, reactions, softening, partial and complete melting, and solutions. Softening temperature (ST) corresponds to a considerable initial deformation in the sample as a result of phase transformations, solid – state reactions, and localized softening and melting of some minerals. Hemispherical temperature (HT) corresponds to a considerable melting of most of the ash constituents and sluggish flow. Fluid temperature (FT) is related to the rate of solution of most refractory minerals and their products, as well as to the intensive flow of the liquid.

As outlined in the literature (Vassilev et al. 1995), the contents of Al_2O_3, SiO_2, TiO_2 and K_2O increase, while the quantities of Fe_2 O_3, CaO, MgO, Na_2O and SO_3 commonly decrease the ash fusion temperatures. The relative influence of these oxides in increasing AFT is normally $TiO_2 > Al_2O_3 > SiO_2 > K_2O$, and for decreasing AFT is SO_3

> CaO > MgO > Fe_2O_3 > Na_2O. However, the dominant ash forming constituents like Al_2O_3, SiO_2, Fe_2O_3 and CaO have a main contribution on the AFT values. As suggested by Vassilev et al. (1995), the high AFT is more characteristic of sialic (SiO_2 and Al_2O_3) ashes, while the low AFT is typical of calsialic (CaO, SiO_2 and Al_2O_3), ferricalsialic (Fe_2O_3, CaO, SiO_2 and Al_2O_3) and ferrisialic (Fe_2O_3, SiO_2 and Al_2O_3) ashes.

The results, listed in Table 4, indicate that majority of the studied coal ashes are of approximately similar nature and possess higher fusion temperatures (ST : 1349 – 1547^0C; HT: 1500 – 1663^0C; and FT : 1560 - 1701^0C). Higher AFTs are expected to be related to an increased contents of SiO_2, Al_2O_3 and Kaolinite (Al_2O_3, $2SiO_2$, 2 H_2O) in these coals. Basundhara (E), Dhera (F) and Bharatpur (E) coal ashes were found to have somewhat lower IDT, ST, HT and FT values (Table 4). This is most probably because of relatively higher iron oxide (Fe_2O_3) and calcium oxide contents in them. The iron oxide appears to react with silica and lime to form low melting fayalite (M. P. – 1205^0C) and Fe – Ca oxides (M. P. – 1225 to 1325^0C), as suggested by Vassilev et al. (1995). As can be seen in Table 4, the studied coal ashes, in general, exhibited longer fusion intervals (>40^0C) between their HT and FT values, and thus appear to have high concentrations of Al_2O_3 and SiO_2 and a low solution activity, as referred by Vassilev et al. (1995).

4.3. Assessment of Coal Char Reactivity

The carbon dioxide reactivity of coal char (a measure of its iron ore reduction potential) is important to optimize the operational conditions of rotary kilns. The reactivities of chars under rotary kiln conditions and their impact on iron ore reduction have not been extensively addressed in the literature. This has, therefore, brought about a need to understand the reactivity of coal char better. As reported in the literature (Patnaik 2006), the use of highly reactive coal allows the kiln operation at relatively lower temperature with enhanced productivity and decreased tendency for ring formation.

Data, summarized in Table 5, indicate that the reactivities of the studied coal chars are significantly higher (i.e. > 2 c c of CO / g. sec) than that required for sponge ironmaking. Fig. 1 shows the correlation of reactivity of coal chars with their fixed carbon and ash contents, and indicate that the proximate analysis results can be used to predict the reactivity of chars. As evidenced by Fig.1, the reactivity of coal char, in general, decreased with increase of its fixed carbon content, while the ash content had the opposite effect. The fall in char reactivity with increase of its fixed carbon / decrease of ash content is believed to be due to the combined effects of more closeness of carbon atoms, growth of carbon microcrystallites, improvement in structural ordering and reduction in the number of reaction and catalytic sites, as suggested by Kashiwaya and Ishii (1991), Kumar and Gupta (1994), and Sahu et al. (1988). On the other hand, it is expected that in the char matrix, the extent of discontinuity in the arrangement of carbon atoms, number of active sites and catalytic effect increase with ash content and all these factors enhance the reactivities of chars. The aforesaid variation in reactivity with ash content could also be ascribed, at least in part, to the higher concentration of inertinites (highly reactive maceral constituents) in coals having more mineral matter contents, as suggested by Choudhury et al. (2007) and Narasimhan and Mukherjee (1999).

4.4. Assessment of Iron Ore Reduction Potentials of Coal Chars

The findings of the present investigation have shown that the degree of reduction of fired iron ore pellet is strongly influenced by the reactivity of coal char used. Table 5 shows the results of experiments carried out for the reduction of fired hematite iron ore pellets in sixteen different types of coal chars at a temperature of 900^0C for 60 and 90 min time durations. The overall % reduction data, cited in Table 5, include reduction during pre – heating period (time consumed in heating from room temperature to 900^0C) also. Weight loss in pellets during heating at 900^0C is expected mainly due to reduction reactions by CO gas and fixed carbon of the coal char, the volatile matter being present in very small amounts (2 – 4 wt.%) in chars appears to have negligible effect.

Fig. 2 depicts the correlation between the degree of reduction (%) of fired hematite iron ore pellets and carbon dioxide reactivity of coal chars. It could be seen in this figure that despite considerable scatter in the data, the degree of reduction, in general, improved greatly with increasing coal char reactivity for both the studied heating time durations (at 900^0C) of 60 and 90 min. This is because higher reactivity enhances the rate of CO gas formation and consequently gives more reduction of iron ore. Secondly, the effect of reactivity in increasing the degree of reduction was slightly more prominent for 90 min heating duration at 900^0C than for 60 min (Fig. 2). The results (Table 5) also established that the degree of reduction at 900^0C increased with increase of heating time from 60 to 90 min, but at the retarded rate. This retardation in reduction rate could be ascribed to the combined effects of an increase in product metallic layer thickness, formation of wustite relics and pasty slag, and sintering of pores and reduced iron, which offer greater resistance in the diffusion of carbon and CO gas to the surface of unreduced iron oxide.

4.5. Prospects of the Studied Coals in Sponge Ironmaking

The efficiency and effectiveness of DR processes are very sensitive to coal characteristics. Under Indian conditions, the recommended chemical and physical properties of coal to be used in sponge ironmaking are (i) volatile matter, ash and fixed carbon contents : 27–32, 21–25 and 30–42 wt.%; (ii) sulphur content : < 1.0 wt.%; (iii) reactivity : > 2.0 cc of CO/g.sec; (iv) ash softening temperature : $\geq 1300^0$C; (v) caking index : < 3.0; (vi) swelling index : < 1.0; and (vii) bulk density : ≥ 800 kg/m^3. Majority of Indian coals, particularly available in Orissa, are fulfilling these requirements partially. However, sponge iron manufacturers are forced to use them.

Data listed in Tables 4 and 5 reveal that some of the properties (e.g. reactivity, sulphur content, caking index and ash fusion temperatures) of currently studied coals are very much favourable for their use in rotary kilns, while ash and fixed carbon contents render some of them (e.g. Lakhanpur, Samleshwari, Orient OC–4 and Dhera coals) unsuitable. Higher ash and lower fixed carbon contents increase the coal consumption and cause accretion problem, but do not pose any serious operational problem inside the rotary kiln. As outlined in the literature (Raja and Pal 2006), coal requirements per ton of sponge iron produced in India are approximately 1.2 tons for B/C grade coals and 2.5 tons for D/E/F grade coals. It is worthy to note here that the high ash coals yielded chars having much higher reactivities (Table 5) than that required for sponge iron plants, and this characteristic could be exploited to reduce the reduction temperature and time and thus the energy consumption. Secondly, it may also be preferred to blend the high ash coals (e.g. Lakhanpur, Samleshwari, Orient OC–4, Dhera, etc.) with high grade coals in order to maintain a moderate ash content in the blend.

5. CONCLUSIONS

On the basis of the results of the present investigation, the following conclusions have been drawn :

i) The proximate analysis results categorize the studied coals in three groups on the basis of their volatile matter, ash and fixed carbon contents and recommend Lakhanpur, Samleshwari, Orient OC–4 and Dhera coals unsuitable for sponge iron plants.

ii) Almost all the coals were found to have no caking characteristics and sulphur contents in them varied in the range 0.40–0.66 wt.%.

iii) Majority of the studied coal ashes exhibited higher fusion temperatures and ensured for no chance of ring formation inside the rotary kilns.

iv) The carbon dioxide reactivities of all the studied coal chars have been reported to be significantly higher than that required for coal-based DR processes.

v) The reactivity of coal char, in general, increased with increase of its ash content, owing to an increased number of active and catalytic sites.

vi) Increase in heating time from 60 to 90 min at 900^0C enhanced the degree of reduction of fired iron ore pellet in coal char, but reduced the reduction rate (% degree of reduction per unit time).

vii) Increased coal char reactivity, in general, enhanced the degree of reduction in fired iron ore pellet and thus decreased the time of reduction.

viii) Caking index, sulphur content, reactivity and ash fusion temperatures results indicate that all the studied coals are extremely useful for their industrial exploitation in the manufacture of sponge iron.

ix) Altogether, it appears that majority of the studied coals could be used individually and some of them (Lakhanpur, Samleshwari, Orient OC–4 and Dhera coals) after blending with high grade coals or beneficiation.

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Table 1. Trend of growth in sponge iron production in India

Year	1989-1990	1991-1992	1994-1995	1996-1997	1999-2000	2002-2003	2003-2004	2004-2005	2005-2006	2006-2007
Production (million tonne)	0.20	1.30	3.40	5.00	5.30	6.90	8.10	10.06	11.82	16.28

Table 2. Grade-wise proved coal reserves in India

Coal grade	High			Intermediate	Low	Total
	A	B	C	D	E, F & G	
Reserves (million tonne)	961	2,341	7,197	6,216	21,783	38,498

Table 3. Gradation of Indian non-coking coals

Grade	Useful heat value (UHV) (Kcal / kg) UHV = 8900 – 138(A+M)	Corresponding (A+M) at 60% RH & 40^0 C	Gross calorific value (GCV) (Kcal / kg) at 5% moisture level
A	> 6200	≤ 19.5	> 6454
B	5601 − 6200	19.6 − 23.8	6050 − 6454
C	4941 − 5600	23.9 − 28.6	5598 − 6049
D	4201 − 4940	28.7 − 34.0	5090 − 5597
E	3361 − 4200	34.1 − 40.0	4325 − 5089
F	2401 − 3360	40.1 − 47.0	3866 − 4324
G	1301 − 2400	47.1 − 55.0	3114 − 3865

A − % Ash ; M − % Moisture

Table 4. Chemical composition, caking index and ash fusion temperatures of non-coking coals obtained from different mines of Orissa

Coal mine	Caking index	Proximate analysis (wt.%, dry basis)			Sulphur content (wt.%)	Ash fusion temperatures(^{0}C)			
		Volatile matter	Ash	Fixed carbon		IDT	ST	HT	FT
Lakhanpur (F)	Nil	22.58	50.54	26.88	0.64	1138	1421	1585	1638
Belpahar (F)	Nil	25.98	39.13	34.89	0.52	1242	1349	1538	1582
Samleshwari (F)	Nil	26.74	46.74	26.52	0.55	1317	1493	1614	1689
Orient open cast-2 (F)	Nil	28.43	37.89	33.68	0.48	1296	1492	1511	1558
Orient open cast-4 (F)	Nil	23.44	53.13	23.43	0.66	1317	1547	1663	1699
RKC (F)	Nil	20.73	48.96	30.31	0.61	1219	1446	1568	1652
Basundhara phase -2 (E)	2.0	27.26	32.63	40.11	0.48	1253	1428	1524	1600
Basundhara phase -7 (E)	2.0	29.90	29.59	40.51	0.45	1189	1355	1451	1509
Jagannath (F)	Nil	31.60	36.17	32.23	0.41	1262	1541	1614	1653
Ananta (F)	Nil	25.26	43.16	31.58	0.45	1310	1500	1602	1646
Lingaraj (D)	1.0	39.12	15.93	44.95	0.40	1205	1410	1513	1600
Bharatpur (D)	Nil	34.67	21.74	43.59	0.43	1255	1540	1661	1701
Bharatpur (E)	Nil	31.44	28.87	39.69	0.44	1218	1266	1379	1435
Nandira (F)	Nil	26.70	39.18	34.12	0.49	1310	1475	1545	1617
Dhera (F)	Nil	24.69	52.04	23.27	0.63	1223	1365	1495	1540
Kalinga (F)	Nil	21.88	46.35	31.77	0.53	1170	1426	1579	1633

D, E and F are coal grades. IDT – Initial deformation temperature; ST – Softening temperature; HT – Hemispherical temperature; FT – Flow temperature.

Table 5. Chemical properties of studied coal chars and degree of reduction values of fired hematite iron ore pellets reduced in these chars at 900^0C

Coal char	Proximate analysis (wt.%, dry basis)			Reactivity (cc of CO/g of C. sec)	Reduction time (min)	
					60	90
	Volatile matter	Ash	Fixed carbon		Degree of reduction (%)	
Lakhanpur	3.00	62.60	34.40	9.30	67.89	82.90
Belpahar	3.30	50.30	46.40	4.67	58.85	67.37
Samleshwari	3.20	59.50	37.30	6.39	65.80	78.30
Orient open cast-2	2.70	57.00	40.30	5.17	59.75	69.02
Orient open cast-4	2.90	67.90	29.20	12.36	41.38	60.21
RKC	3.60	52.10	44.30	3.66	48.05	58.33
Basundhara phase-2	3.40	45.50	51.10	4.41	58.57	72.35
Basundhara phase-7	3.20	44.00	52.80	3.62	41.73	53.53
Jagannath	3.30	47.75	48.95	3.16	49.14	57.10
Ananta	2.10	62.40	35.50	5.88	57.69	81.03
Lingaraj	3.00	33.25	63.75	3.50	65.61	76.42
Bharatpur (D)	3.10	38.05	58.85	5.44	50.50	79.78
Bharatpur (E)	2.40	45.80	51.80	4.77	55.10	69.80
Nandira	3.30	41.15	55.55	3.12	40.85	46.43
Dhera	3.40	52.00	44.60	7.81	53.85	64.03
Kalinga	2.30	56.50	41.20	7.79	66.50	78.60

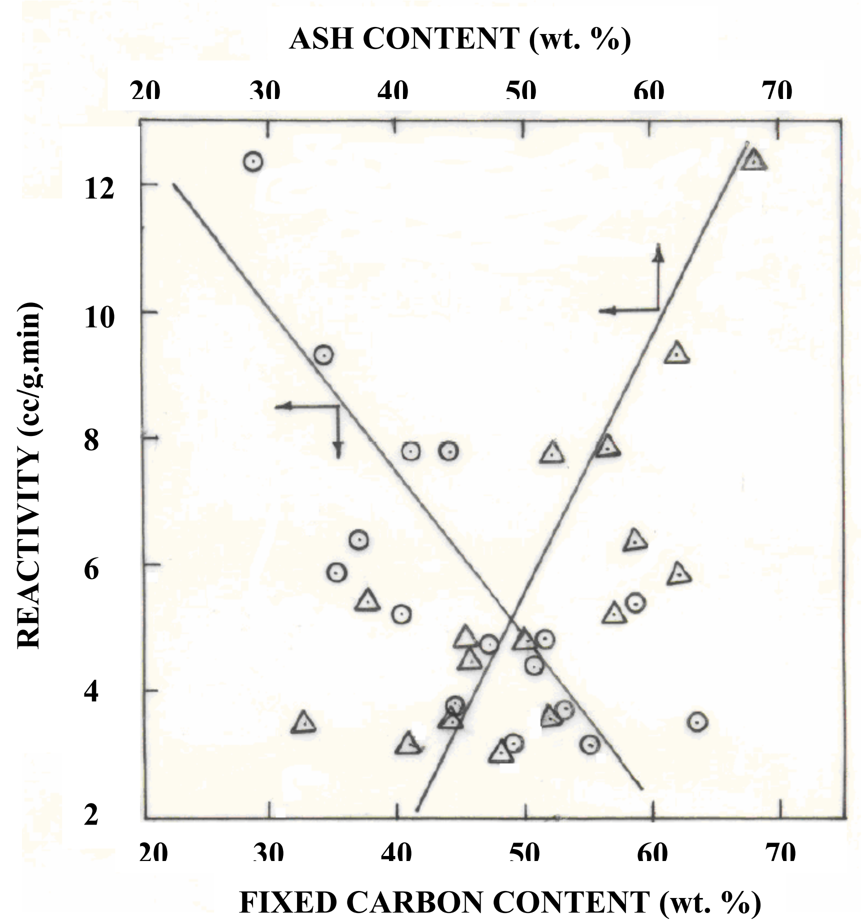

Fig.1. Correlation of reactivity with fixed carbon and ash contents

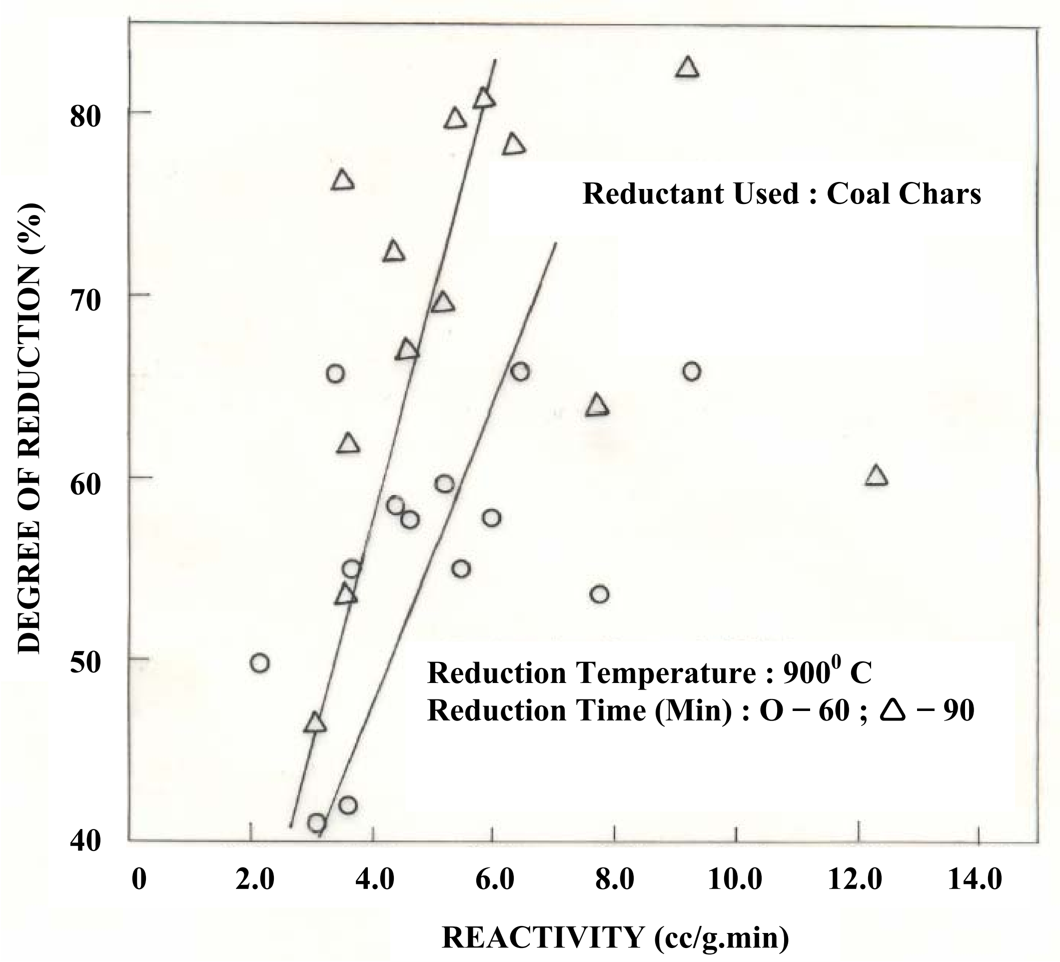

Fig.2. Relationship between degree of reduction (%) and reactivity of coal chars