

An appraisal of raw materials for the blast-furnace

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A BETTER UNDERSTANDING of the influence of raw material quality on furnace performance has formed the basis of most of the recent developments in ironmaking. Increasing emphasis on higher production rates with lower consumption of fuel, consistent with uniform quality of hot metal, has made it necessary to examine fully the qualities of all the raw materials, as this alone can lay the foundation for a sound scheme of burden preparation and burden control. With this in view, a comprehensive programme has been initiated in the research laboratory to study the characteristics of the various ores, fluxes, and coke; some of the results of this investigation are discussed in this paper. An attempt is also made to highlight some of the special features that characterize blast-furnace operation at Jamshedpur in so far as they are related to raw material quality.

GENERAL PATTERN OF RAW MATERIALS

Before proceeding to the evaluation of the detailed properties of individual raw materials, it is worthwhile to emphasize the combined effect of all the ingredients. Obviously, the quality of an iron ore cannot be assessed without reference to the qualities of the flux and fuel to be used for smelting. Similarly, the influence of changes in the ash content of coke can only be studied in relation to the slag contributions made by other raw materials. Taking the instance of local practice, the iron ores are high in iron i.e. 59–63% in the prepared burden, yet the slag volume is about 600–650 kg/tonne owing to the high (21–24%) ash content of the coke and the presence of as much as 6–10% of insolubles in the limestone. And even with this large contribution of slag by flux and coke ash, the effect of the high proportion of alumina in the ore gangue is not completely overcome; the slag contains 24–26% Al_2O_3 .

Reference to the difficulties caused by the high concentration of alumina has been made on many previous occasions.^{1–4} Briefly, the slag tends to be viscous and promotes the reduction of silicon while hindering desulphurization. Owing to the ease with which silicon is reduced, the operator tries to run the furnace on the cold side so that he can control the silicon around 1.4–1.5%. The metal temperature is usually 1350–1390°C. This, however, interferes seriously with desulphurization. The partition coefficient for sulphur rarely exceeds 22 and the control of sulphur becomes difficult owing to the relatively high sulphur load, i.e. about 6.5 kg/tonne hot metal.

The adverse influence of alumina in slag can be overcome in two ways: first, by the addition of sufficient dolomite to reduce the viscosity of the slag, and secondly, by the dilution of the alumina by adding quartzite with corresponding increments in flux and coke. Both methods have been tried. The use of up to 20–25% dolomite in the flux gives very satisfactory operation,² but this has to be restricted because the slag made with dolomite additions to the flux does not meet the requirements for slag cement.

SYNOPSIS

The blast-furnace operators at Jamshedpur face a peculiar set of problems arising from the qualities of the available raw materials. The basic problem is the high alumina content of the blast-furnace slag; attempts to overcome it involve increases in coke and flux requirements with consequent loss of productivity. The details can be analysed completely by a set of nomograms. Turning to ore quality, a study of the varieties of ores reveals a wide divergence in reducibility. Moreover, some of the ores are prone to disintegration during handling and decrepitation by heating or exposure to carbon monoxide. Details of test results show that the quality of ores can be appraised only from a large number of different tests. Similar tests are also required for limestone. The quality of coke is best judged by ash content as fluctuations in ash present the most important problem.

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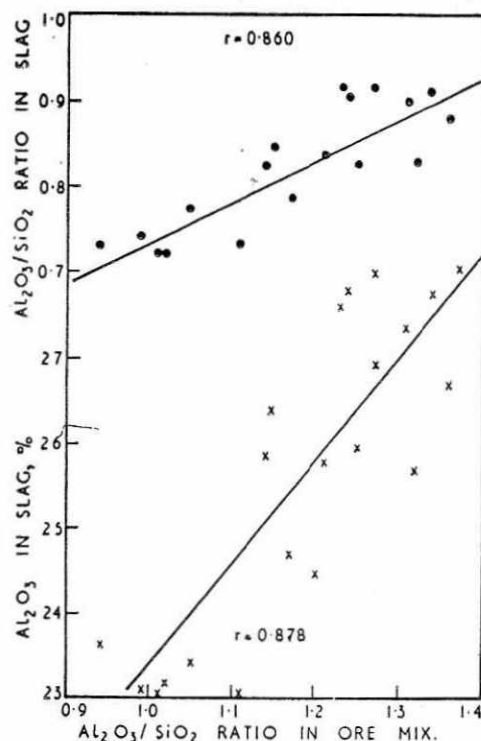
Further, the magnesia-bearing slags are not as effective desulphurizers, so the CaO/SiO_2 ratio has to be maintained around 1.2 to control sulphur; this raises the flux requirement with a corresponding extra for coke. Using quartzite to dilute the alumina content of slag gives satisfactory results but the slag basicity cannot be maintained at 1.3 ($CaO+MgO/SiO_2$) without a very large increase in flux and coke rates; attempts were, therefore, made to run one furnace on a 19–20% Al_2O_3 slag with a basicity index around 1.2 and the results showed that while the slag characteristics and silicons were better, sulphur removal was inadequate. Even with this sacrifice, about 90 kg of quartzite were required per ton of hot metal and the increments in coke and flux rates were 40 and 170 kg/tonne hot metal respectively.

The above comments on the effects of the high alumina content of slag and the methods of countering the difficulties are made specially to emphasize the peculiar set of conditions that the available raw materials impose on the local blast-furnace operators. Any solution to the alumina problem involves increased consumption of flux and coke, and a corresponding loss of productivity. An analysis of operational data shows that the changes in coke rate arising from alteration in chemistry can be fairly well predicted by the relation:

$$\text{Carbon Base required} = \text{Base requirement} + 0.40(\text{slag rate}) + 0.23(\text{flux rate})$$

The base requirement is calculated as a constant for a given mode of operation, i.e. constant wind rate, moisture content of blast, blast temperature, metal analyses, etc. The flux requirements can be computed for a constant basicity ratio; the value $CaO+MgO/SiO_2=1.3$ is found to be most suitable for local practice. The effects of changes in the qualities of the three principal materials predicted on this basis are summarized in Table I.

The values given in Table I show that the effect of a given change in one variable depends on the levels of ash and gangue. Thus a 1% increase in gangue is seen to be more harmful when the coke ash is high than when the coke is low in ash. Further, an increase in the gangue content by 1% is more harmful than a similar increase in the ash



1 Effect of alumina/silica ratio in the ore mix on slag analysis

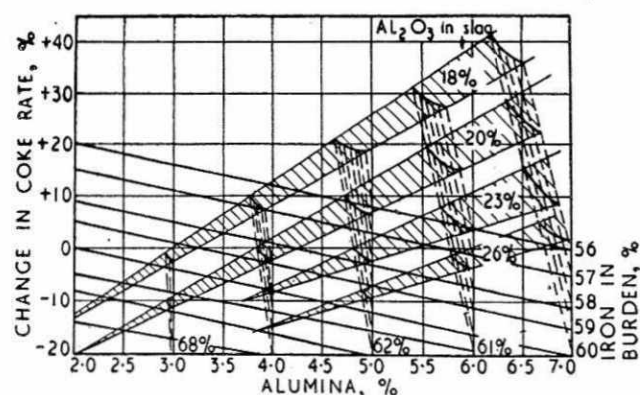
content as far as the increase in coke and flux requirements and slag make are concerned. The calculation does not take account of the operator's difficulties when handling high ash coke to which a reference is made later. The calculation can be extended to take into consideration the use of quartzite for controlling the alumina content of the slag. In fact, it has been possible to use a series of nomograms to calculate all the burden changes for variations in the analyses of ore, flux and fuel as also additions of quartzite and alterations in practice which shift the base carbon requirement.

Turning to productivity, the slag make is a rough yardstick. Analysis of monthly statistics showed that the production rate is lowered by 1% for every 10 kg increase in slag rate, in the range of 450 to 750 kg/tonne. This can be used to convert the figures in Table I into productivity indices so that the effect of alteration in the raw materials can be fully assessed.

The effect of beneficiation on the quality of the product can also be appraised by the use of detailed burden calculations. Here, it is worthwhile to mention that washing

TABLE I Overall effects of alterations in the analyses of ore, flux, and fuel

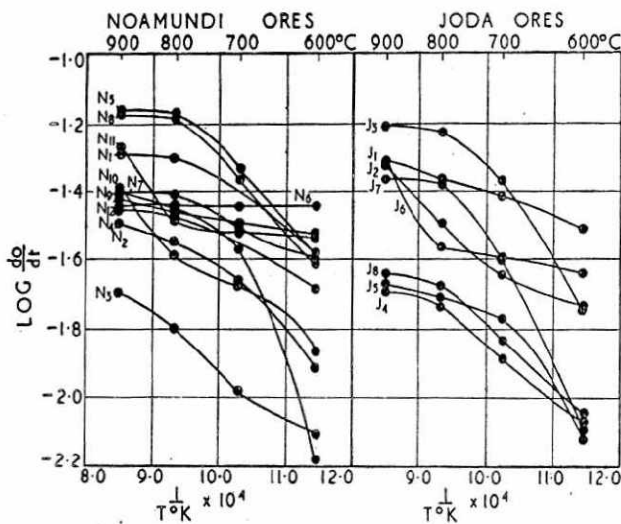
1% increase in		Extras, kg/tonne		
		coke	flux	slag
gangue in ore	at ash, %			
	19	26	30	38
	21	30	30	39
ash in coke	at gangue, %			
	5	25	16	20
	9	28	18	23
silica in flux	at ash, % and gangue, %			
	13	32	20	26
	19	5	8	9
	21	5	11	9
	23	5	12	9
	19	9	13	10
	21	9	15	11
	23	12	17	13



2 Overall rating of ore quality in terms of alumina and iron content as related to the slag characteristics and coke rate

alone can appreciably improve the grade of the iron ores. With a mixture of ores from the Gorumahisani, Badampahar and Joda East mines, operation with a scrubber and wet screening can, for example, raise the iron content of the $\frac{+3}{-20}$ in product by 0.2–0.5% and decrease the gangue by about 0.6–1.0%. The $\frac{-3}{-20}$ in fraction is upgraded from about 56–57% Fe, 9% SiO_2 , and 8% Al_2O_3 to about 59.5–60.5% Fe, 6.5% SiO_2 , and 6.9% Al_2O_3 . The reduction in total gangue by 3.5% is appreciable in view of the changes in coke and flux rates listed in Table I. Not all ores respond similarly; the ores from the Noamundi mine tend to lose their silica content preferentially with the result that the alumina/silica ratio is raised after washing. This can cause a rise in the alumina content of slag unless the ratio is adjusted by either blending with ores having a favourable $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio of unity or less or by mixing quartzite. The concept of judging the quality of the ore in terms of the $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio has found favour with local operators since it gives an indication of the alumina content of the slag,² as shown by Fig. 1. Some believe that the ratio is an incorrect measure of ore quality since the natural proportions can always be compensated by additions of quartzite. This approach is not wholly correct, as an addition of quartzite has to be made to bring down the net $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio to about 1.2 and this entails an increase in the effective gangue content and a fall in the iron content of the ore-quartzite mixture.

A detailed evaluation of the quality of the iron ore can, therefore, be made only after taking account of the nature of the slag. A series of burden calculations for coke rate are summarized in Fig. 2 which shows the variations in coke requirements for various levels of iron and alumina in the ore. The slag basicity is kept constant at 1.3. The full lines depict the values for straight ore burdens. The dotted lines show the alterations in coke rate that would be necessary if the alumina content of the slag is brought down by additions of quartzite. An examination of the diagram leads to three important conclusions. First, an increase in iron content at constant alumina in the ore brings down the coke rate but raises the alumina content of the slag since the silica contribution from the ore is reduced. Secondly, the coke rate is lowered by an increase in the alumina content of the ore at any given iron level because the slag make is decreased; but the alumina content of the slag rises, so that the benefit of lower coke rate can be had only up to a critical alumina concentration in the ore. Thirdly, the dilution of alumina by quartzite addition raises the coke requirement, the extra being proportional to the magnitude of the change in the alumina content of slag. Similar diagrams can be constructed for the effects of



3 Effect of temperature on the rate of oxygen removal; ore lump size: $-\frac{1}{4} + \frac{1}{2}$ in

ore chemistry on slag volume and flux rate and these also lead to the same conclusions.

DETAILS OF ORE QUALITY

It is not enough to know the chemical composition of the ore since this does not give any clue regarding its behaviour in the furnace. For this purpose, samples representative of all the varieties of iron ores that are likely to be used at Jamshedpur in the next few years were collected by the geological department and these were tested for reducibility,⁵ porosity,⁶ size stability during handling⁷ and heating,⁸ and fusion points. The results are interesting as they not only illustrate the widely divergent pro-

perties of various ores but also focus attention on the influence of structure on the behaviour of the ore.

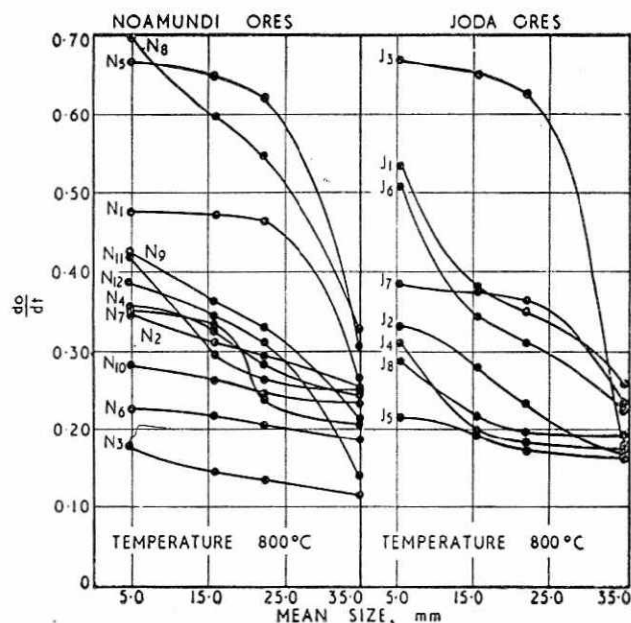
Particulars of the samples are listed in Table II, which includes the megascopic description and the range of chemical analyses. Usually the higher iron and lower gangue contents are found in the larger size fractions while the lowest iron and highest gangue occur in the fines.

Reducibility tests were conducted on four different size fractions: 3.2-6.4, 12.7-19.0, 19.0-25.4, and 31.8-38.1 mm, and at four temperatures: 600°, 700°, 800°, and 900°C, to assess the effect of size and temperature. Purified and dried hydrogen was passed over 75 g of sample at 1500 ml/min and the water vapour formed by reduction of iron oxide was continuously collected to determine the time dependence of reduction. The resulting data were analysed to rate the reducibilities of the ores in four different ways: the time required for 80% reduction, for 90% reduction, the % reduction after 100 min, and finally the rate of removal of oxygen, g/min per 100 g Fe, at 50% reduction. The rankings of the different ores by all these four criteria could be satisfactorily correlated; the correlation coefficients varied from 0.93 to 0.98 which shows that any one of these methods is quite adequate.

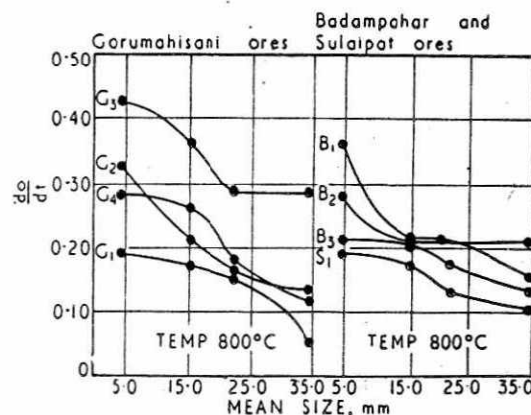
The effect of temperature on the rate of oxygen removal, at 50% reduction, is summarized in Fig. 3 to bring out the divergence in the characteristics of the different ores. The spread in the logarithmic graph shows that the rate of oxygen removal varies by a factor of two between the most easily reducible ore and the ore most difficult to reduce. While the expected trend of lower rate at lower temperatures is found in most ores, the results for N6, N11, and J7 are specially peculiar. The first ore is relatively little affected by changes in temperature; in the other two (N11 and J7), the rate of oxygen removal rises sharply only beyond 800°C.

TABLE II Particulars of iron ore samples

Designation	Mine	Megascopic description	Range of chemical composition, %		
			Fe	SiO ₂	Al ₂ O ₃
N1	Noamundi	Steel grey laminated ore	68.7-69.2	0.25-0.76	0.40-1.08
N2	"	Brecciated hard ore	68.1-68.6	0.24-1.28	0.50-0.91
N3	"	Massive bluish grey hard ore	67.9-68.4	0.40-0.68	0.66-1.25
N4	"	Biscuity soft ore	66.3-67.5	0.52-1.0	0.75-1.09
N5	"	Lateritized laminated soft ore	63.8-67.0	0.52-0.80	1.08-4.36
N6	"	Massive soft ore	63.0-66.8	0.32-0.88	1.54-4.87
N7	"	Limonitic and goethitic ore	58.4-67.0	0.60-0.92	2.66-3.23
N8	"	Spongy soft ore	57.5-65.8	0.40-0.60	2.60-11.70
N9	"	Shaly ore	55.0-59.9	4.92-8.92	4.18-10.13
N10	"	Soft highly ochreous ore	52.8-55.6	0.08-0.48	6.64-10.37
N11	"	Goethitic ore	52.4-54.0	0.28-0.52	8.87-10.76
N12	"	Lateritic ore	36.6-45.6	4.12-16.18	20.17-24.27
J1	Joda East	Massive ore	68.5-68.8	0.33-0.67	0.8-1.08
J2	"	Flaky friable ore	67.4	1.4	0.58
J3	"	Hard foliated ore	65.8-67.0	2.68-3.04	1.34-2.61
J4	"	Foliated ore	62.2-67.0	1.72-4.28	1.59-4.02
J5	"	Hard massive ore	61.8-66.0	1.84-3.76	1.09-3.78
J6	"	Hard laminated ore	66.2-66.4	1.32-1.56	0.58-1.5
J7	"	Flaky ore	64.0-67.5	1.24-3.36	0.5-2.76
J8	"	Spongy lateritized soft ore	62.8-64.5	0.2-0.58	2.52-4.54
G1	Gorumahisani	Hard bluish grey ore	59.2-66.0	0.16-2.04	0.6-1.44
G2	"	Banded friable dark-grey ore	57.4-63.8	2.6-4.8	0.25-3.96
G3	"	Soft massive greyish brown ore with rare patches of ochre	59.2-62.2	1.24-2.60	0.17-3.90
G4	"	Greyish brown ochreous ore	58.2-62.4	1.22-1.8	0.33-2.04
B1	Badampahar	Greyish brown laminated ore with ochreous patches	57.0-64.2	1.46-1.84	0.17-1.19
B2	"	Massive lateritized soft ore	54.4-65.6	1.48-3.80	0.60-3.90
B3	"	Flaky ore	53.4-60.6	0.84-1.60	0.33-1.68
SI	Sulaipat	Hard ore	65.4-67.8	0.4-1.76	0.16-0.35



4 Effect of lump size on reducibility, Noamundi and Joda East ores



5 Effect of lump size on reducibility, Gorumahisani, Badampahar, and Sulripat ores

tumbler, decrepitation, and carbon-monoxide cracking tests reveal the following:

—12.7 mm fraction, %, caused by:

Ore	Shatter	Tumbler	Decrepiation in air	Bursting in CO
N1	1.2	2.8	—	52.3
N5	9.2	16.7	0.2–3.2	23.1
N9	2.6	11.5	1.0–1.9	13.6
J7	Extremely friable, could not be tested	—	8.4	—
J3	4.7	1.6	63.0–74.6	—
G1	1.5	4.4	0.7	—

It is seen that, with the exception of the hard bluish grey Gorumahisani ore (G1), all the other five undergo appreciable degradation in size due to handling and decrepitation. Thus, these ores need not be crushed much below 50 mm, as determined at the sizing plant, because the effective size for reduction in the blast-furnaces would be much smaller.

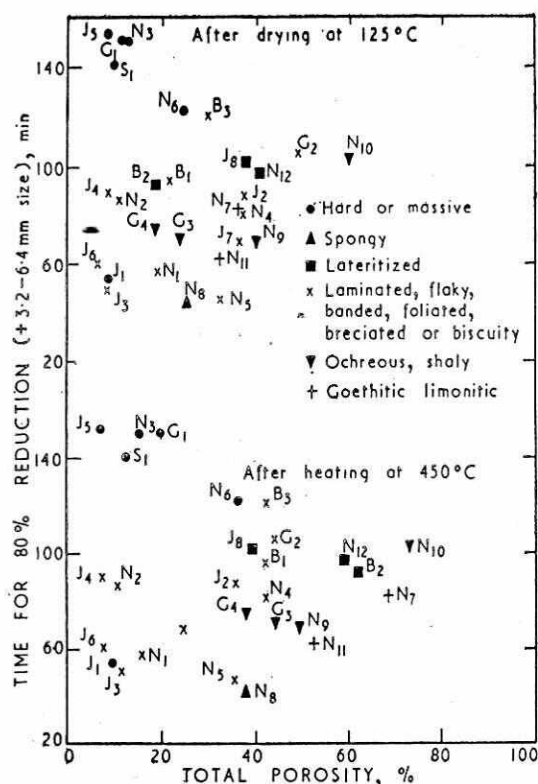
Investigations into the size degradation during handling led to some interesting conclusions. For example, the ranking of the different ores in accordance with the percentage of —3.2 mm fines produced in shatter and tumbler tests did not follow the same order; the coefficient of rank correlation was about 0.88. Further, the minimum crushing load criteria gave a still different ranking; the correlation of this rank with those based on shatter and tumbler indices was only just significant ($r=0.60-0.64$). Finally, the crushing load of laminated ores (N1, N4, J4, G4, and B3) varied by a factor of 2–4 depending on the direction of the load relative to the plane of lamination.

Results of decrepitation tests showed that the tendency towards decrepitation is not strictly related to the moisture content. For example, ores N10, N11, N12, B1, and B2 with more than 9.0% loss of weight on ignition exhibit very little break-up due to heating, whereas the ores J1 and J6 containing only 0.03% moisture produced up to 88.7–99.8% of —12.5 mm and 18.0–44.0% of —3.2 mm fractions. However, pre-drying to 150°C completely removed the susceptibility to decrepitation and pre-wetting generally increased it. Further, it was found that the foliated and laminated ores were most susceptible to decrepitation. Thus it appears that the structure of the ore plays the predominant role in the tendency towards decrepitation and the presence of moisture only increases the susceptibility.

It is common to relate the reducibility of an ore to its micro- and macro-porosity. Results on the 28 different ores (Fig. 6) do not support the earlier conclusions.¹¹ Apparently, the influence of structure is so pronounced that the laminated, foliated and spongy ores are reduced

The size effect is summarized in Figs. 4 and 5, showing the rate of oxygen removal as a function of the mean particle size. Here again, the spread of reducibility is obvious; this divergence is greater the smaller the diameter of the particle. Apparently the limiting factor in the smaller size is the ease with which the reduction front can advance and thus a small difference in the limiting factor can cause a greater alteration in the ratio of oxygen removal from smaller particles of ore than from the bigger lumps. The results also show that the overall laws governing the size dependence of reducibility^{9,10} are not always followed. The ores J4 and J5 can be cited as examples; in this case, the rate of oxygen removal is lowered by an increase in particle size only up to about 22 mm, beyond which the rate of reduction is little affected by a further increase in size. This observation is quite contrary to the general trend of decreasing rate of oxygen removal with increasing particle size. The explanation for this behaviour is to be found in the disintegration of the bigger lumps by decrepitation. Separate decrepitation tests on the ores showed that the sizes over 25 mm produce as much as 48.1–98.9% of —12.7 mm fractions after heating to 450°C, and this tendency towards disintegration is almost absent in sizes below 12.7 mm. Thus, it is obvious that ore lumps which undergo a size change due to disintegration cannot be expected to follow the usual pattern of lower reducibility with increasing size. A detailed analysis showed that the lumps of all the ores showing even a slightly peculiar behaviour: N3, N4, N6, N11, N12, J4, J5, G3, and B2, undergo size degradation due to decrepitation and disintegration by the reduction process.

Another aspect of the size effect on reducibility is the determination of the optimum top size of ore lumps to be charged in the furnace. Using the plots in Figs. 4 and 5, one can conclude that only six (N1, N5, N9, J7, J3, and G1) of the 28 different ores need be crushed below about 40–45 mm to ensure good reducibility; all the others are easily reduced even when the lumps are of 50 mm size. One has, however, to consider whether the top size in the ore crushing plant really represents the top size of the ore as reduced in the furnace; obviously, any size degradation during handling or heating can decrease the effective size of the ore. Results of shatter,



6 Relationship between reducibility and total porosity

faster than hard massive ores having the same porosity. Further, the porosity tests are usually conducted on pre-dried samples and the values can change markedly if the ores are heated to say 450°C as shown in the lower part of Fig. 6. It is felt that the latter set of values give a better correlation for a given type of ore structure.

Turning finally to the softening and fusion points of the ore, only pyrometric cone tests were performed. But even these results show the following interesting relationships:

$$\text{Softening temperature } ^\circ\text{C} = 1\,200 + 4.425\% \text{Fe}; r = 0.64$$

$$\text{Fusion temperature } ^\circ\text{C} = 1\,318 + 3.36\% \text{Fe}; r = 0.61$$

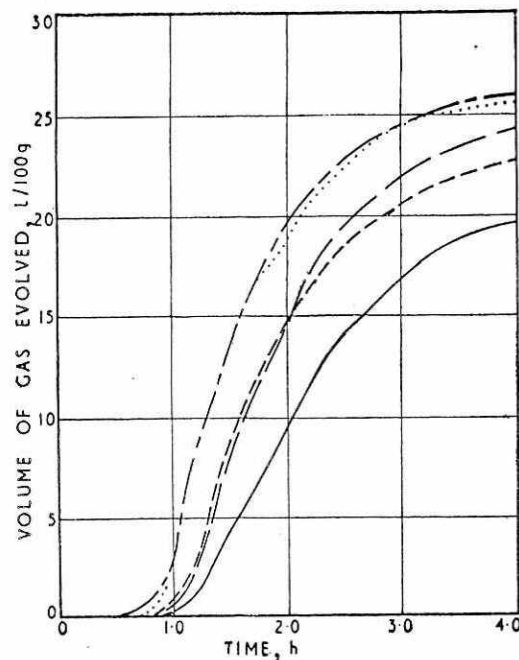
Thus the ores with high gangue content soften early. Further tests under reducing atmospheres are in progress.

QUALITY OF FLUX

The gangue content of the limestone varies from 6–10%, as stated earlier. In addition to this index of quality, it is also necessary to examine the calcination characteristics of different grades as they determine the level at which the carbon dioxide is released in the blast-furnace. Preliminary tests results on four limestones and one sample of

TABLE III Effect of sudden changes in the ash content of coke; initial condition: 22% ash, 9% gangue in ore with $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio 1.05

Ash %	Final slag change, kg/tonne	Al_2O_3 %	Basicity	Bosh change, kg/tonne	Slag Al_2O_3 %	Basicity
19	-22	25.85	1.405	-4	22.3	1.715
20	-15	25.97	1.367	-2	22.4	1.705
21	-8	26.10	1.328	-1	22.5	1.695
22	(initial)	26.12	1.300	-	22.7	1.655
23	+8	26.20	1.271	+4	22.6	1.635
24	+15	26.23	1.239	+6	22.7	1.625
25	+21	26.30	1.222	+9	22.7	1.605
26	+31	26.40	1.182	+11	22.7	1.585


7 Amount of CO_2 given out by different types of limestone against time; calcination temperature, 950+5°C

calcite are summarized in Fig. 7 which shows the divergence in the behaviour of different lots. The samples attained the test temperature of 950°C in about 55–65 min and they were maintained at this temperature until the end of the run. It is obvious that both the rate of evolution and the extent of calcination vary widely. The calcite sample shows the lowest rate of calcination in spite of its high purity. It is felt that tests of this type can better appraise the quality of the flux.

QUALITY OF COKE

The average shatter index of coke used at Jamshedpur is 85% over 2in and 90% over 1½in after four drops and the tumbler index measured by the Breslau drum test is 78–81% over 40 mm. The coke is screened to remove any nut size. The only real difficulty with the quality of the coke is the high ash content referred to above and the fluctuations in ash content. It is considered worthwhile to discuss the latter aspect in some detail.

If the ash content of the coke changes without advance notice, it alters the amount and nature of both the bosh and tap slags. It is possible to compute the effect on the basis of local operation data for the percentage of coke burnt at the tuyeres, and an initial condition of 22% ash in coke with 9% gangue in the ore burden. The results are summarized in Table III. The bosh slag analyses are calculated only for the quaternary system $\text{CaO-MgO-SiO}_2\text{-Al}_2\text{O}_3$ since it is not possible to estimate the amounts of iron and manganese oxides present in the first formed slag. However, the calculations show the magnitude of the change caused by fluctuating ash content. A sudden increase in ash content can thus be expected to make the bosh slag less basic and more fluid and these characteristics would be maintained even after the coke ash is liberated at the tuyeres; further, the increase in slag make would raise the thermal load. Therefore, the slag would be an inefficient desulphurizer. It is thus clear that the sudden swings in ash content, encountered in local practice, further vitiate the control on iron quality already rather difficult in view of the overall quality of the slag.

CONCLUSION

The quality of iron ores, flux, or coke cannot be fully appraised by chemical analysis alone. The size factor also determines the behaviour of these materials and hence it becomes necessary to measure several additional properties. The test results on different ore samples prove the necessity of this approach to the problem of appraising the quality of raw materials for the iron blast-furnace.

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