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Analysis of Slag Flow in Blast Furnace during the Extraction of Iron

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***Abstract* - The project aim set measurement of flow characteristics of blast furnace slag. The industrial slag (actual slag from different blast furnace), synthetic slag prepared in the laboratory for pure oxides as obtained from market and iron bearing materials with various extents of reduction resembling that expected to be in the cohesive zone as per literature are chosen for measurement while the final slag obtained from the industry reveals shortness of the slag. The synthetic slag doesn't shown a clear trained, the iron bearing materials reveals variation of the characteristics temperature with variation in the extend of the reduction, SEM micrograph and XRD plots of the iron bearing material with different extended of reduction reveal compositional changes associated with structural changes.**

***Index Terms* – Blast Furnace, characteristics temperature, C/S ratio.**

I. INTRODUCTION

The iron making blast furnace is a complex high temperature counter current reactor in which iron bearing materials (ore, sinter /pellet) and coke are alternately charged along with a suitable flux to create a layered burden in the furnace. The iron bearing material layers start softening and melting in the cohesive zone under the influence of the fluxing agents at the prevailing temperature which greatly reduces the layer permeability that regulates the flow of materials (gas/solid) in the furnace. It is the zone in the furnace bound by softening of the iron bearing materials at the top and melting and flowing of the same at the bottom. A high softening temperature coupled with a relatively low flow temperature would form a narrow cohesive zone lower down the furnace. This would decrease the distance travelled by the liquid in the furnace there by decreasing the Silicon pick-up . On the other hand the final slag, which trickles down the Bosh region to the Hearth in the furnace, should be a short slag that starts flowing as soon as it softens. Thus fusion behaviour is an important parameter to evaluate the effectiveness of the B.F. slag. Fusion behaviour is described in terms of four characteristic temperatures; IDT, the initial deformation temperature symbolising surface stickiness, important for movement of the material in the solid state; ST, symbolising plastic distortion, indicating start of plastic distortion; HT, the liquidus temperature, symbolising sluggish flow, playing a significant role in the aerodynamics of the furnace and heat and mass transfer; and FT, the flow temperature, symbolising liquid mobility. The slag formed in the cohesive zone is the primary slag formed with FeO as the primary fluxing constituent; the solidus temperature, fusion temperature, solidus-fusion interval being significantly affected by FeO. This slag is completely different from the final slag where the fluxing is primarily caused due to the presence of basic constituents like CaO or MgO. While it is not possible to obtain primary slag from the industrial blast furnace, it is always possible to prepare a synthetic slag in the laboratory resembling the primary slag and study its flow characteristics. We have kept this venture for future studies and the present study limits itself to the study of flow characteristics of the final slag as obtained from the industry. However, it must be noted that from the process point of view the final slag should be a "Short Slag", a slag with a small difference between the ST and FT. Such a slag acquires liquid mobility and trickles down the furnace away from the site where it starts distorting plastically, as soon as possible. This action exposes fresh sites for further reaction and is supposedly responsible for enhanced slag-metal reaction rates, influencing the blast furnace operations and the quality of the metal. The flow-characteristic of blast furnace slags is strongly influenced by the extent of reduction of iron oxide at low temperature (in the granular zone) besides being influenced by the composition, and the quality and the quantity of the gangue in the iron bearing materials.

II. LITERATURE REVIEW

Y.S. Lee et al [1] studied and observed the viscous behavior of CaO-SiO2-Al2O3-MgO-FeO slag under controlled conditions of C/S = 1.15-1.6, 10-13mass% Al2O3, 5-10mass% MgO and 0-20% FeO. The study of such a slag by the scientists leads them to infer that there is de-polymerization of silicate network above the C/S ratio of 1.3 and less than the ratio of 1.5 this causes the viscosity of the slag to increase. The slag viscosity otherwise up till the ratio of 1.3 decreases due to the increasing chemical potential of the dicalcium silicate which is a primary solid phase. This good correlation between the viscosity and the slag components was basically due to the thermodynamic approach taken up for the activity of primary solid components. So it was confirmed that slag viscosity in highly basic slags (C/S>1.3) can be estimated by the chemical potential of dicalcium silicate. They proposed trough their studies that for a low value of FeO content of about less than 7.5% the slag viscosity showed minimum value with increasing MnO content.

While, with the FeO content being more than that of 7.5% there is no particular effect on the slag viscosity with increasing MnO content. They also concluded that the BF slag viscosity decreases with increasing FeO content for a fixed CaO/ SiO2 ratio. The variation in the slag basicity as well as the Si content in the metal can be minimized by less reduction of SiO2 into Si. This can be achieved by injection of flux in the blast furnace according to some tests conducted by some Japanese companies.

Kai DONG, Long WU [2] The Best Combination Of The Experimental Condition By Orthogonal Analysis Is $A_3B_2C_3$. This Condition Means The Binary Basicity of The Optimal Slag is 7, The Content of Al_2O_3 In The Slag Is 30%, And The Content of TiO_2 Is 3%.Experimental Results Showed That The Sulfur Distribution Coefficient Of The Optimal Refining Slag Was 58.14, Which Is Higher Than The Commonly Used Refining Slag. Higher Binary Basicity of The Slag Will Greatly Improve The Desulfurization Ability of The Cao–Al_2O_3–SiO_2–TiO_2 Slag System. Compared With The Content of The Al_2O_3 and TiO_2, The Change Of The Binary Basicity Is The Main Influencing Factor On The Sulfur Distribution Coefficient. The Addition Of TiO_2 Will Retard The Desulfurization Reaction, The Results From The Experiments And The Calculations Above All Show That, When The Content Of TiO_2 Is In A Lower Range (Lower Than 3–4%), The Desulfurization Ability Of The CaO–Al_2O_3–SiO_2–TiO_2 Slag System Is Quite Approach To That of The Cao–Al_2O_3–SiO_2 System. The Lower TiO_2 Containing Slag System Can Be Applied To Steelmaking Desulfurization, Which Will Promote The Recycling Of The Waste, Containing Titanium

Masashi Nakamoto et al [4] they used the rotating cylinder method to measure the viscous behavior of molten CaO- SiO_2-MgO-Al_2O_3 and compared the result with its model that was created. They actually wanted to study the viscosity of slags that melt at low temperatures to improve the blast furnace operations at lower temperatures i.e. at around 1673K. They showed that slag of the following composition 35% Al_2O_3-43.1% CaO-7.5% MgO-14.4% SiO_2 has a viscosity less than 0.6 Pa.s below 1673 K and it melts at around 1673K and below.

J.-Y. Jia, C.-G. Bai, G.-B. Qiu, D.-F. Chen And Y. Xu [3] a calculation model was established based on the studies of the ternary slag system of CaO-SiO2-TiO2. Thus, they were able to form a mass action concentration calculation model and viscosity calculation model based upon the existing theories and documented data at different temperatures of the ternary slag system at different compositions. The results obtained from the calculation are consistent with the literature values. With increasing TiO2 content the mass action concentration also increases. This is also applicable practically. Temperature is a key to viscosity. If the temperature rises, viscosity decreases, and running quality is good.

Seong-Ho Seok et al [5] the viscous behavior of CaO-SiO_2-FeO-MgO and CaO-SiO_2-FeO- Al_2O_3-MgO melts were studied which were saturated with dicalcium silicate with a MgO content of 8% under conditions of high basicity and temperature of around 1873K. Through their studies they inferred that the viscosities of slag depend relatively more on the alumina content as the solid phases present is more in case of alteration in alumina content than that of MgO.

Hazem Labib Geo [6] High temperature experiments were carried out to simulate the passage of slag through the pore necks between coke particles in the lower zone of an iron making blast furnace. Slag pellets were melted at 1500°C in coke or coke analogue funnels feeding into channels of known diameter. It was determined that there is a minimum channel diameter needed to allow free flow of slag. For the slag/coke systems tested, the minimum channel diameter ranged between 4.4 and 5.0 mm. The results were in good agreement with previously reported figures of pore neck diameter that led to blockage of similar liquid slags in coke beds. A simple force analysis based on gravity and interfacial forces, where the slag surface tension and wettability play a dominant role in the resistance to slag flow through the channel, was found to adequately describe the system. Separately, the flow pattern showed time dependency that was explained in light of the time-dependent inter facial properties between the slag and coke tested. A description of the slag slug-flow pattern though the coke was given in view of the analysis of the forces acting on the liquid phase and the time dependent interfacial properties. This approach could form the basis of a predictive model for establishing flow conditions through a coke packed bed subject to further characterization of the influence of coke and slag properties.

Lei Shao and Henrik Saxén [7] The iron and slag flows in the BF taphole have been investigated using the ZRC model, which is based on the stability analysis of two immiscible liquids flowing through an upwards inclined tube. The model, which is here applied to predict the two-liquid flow pattern (i.e., separated or dispersed flow) in the taphole of an industrial BF, was first validated on a set of physical modeling results taken from the open literature. The experimental system for which the experiments were available was believed to represent the BF taphole conditions according to similarity laws. The ZRC model was next evaluated on short-term tapping data and the calculated results showed that separated flow of iron and slag more likely occurs in the taphole of the BF studied. The proposed method has thus been demonstrated to be able to shed some light on and deepen the understanding of the BF taphole flow. Still, a number of issues need further consideration. The inaccuracies in the measurements of iron and slag outflow rates, and the “real” taphole shape would be important factors with an impact on the taphole flow patterns.

III. EXPERIMENTAL PROCEDURE

The experimental work is planned in THREE phases, the aim being to determine the characteristics temperatures of the B.F. slag for proposing a composition that would indicate narrowed down. The three phases of experimentation include the following:

- Collecting B.F. slag from different industrial Blast furnaces; study of the flow characteristics and chemical analysis to determine the most desired composition (to ensure a narrow cohesive zone lower down the furnace).
- To Prepare synthetic slag in the laboratory with pure oxides as obtained from the market, resembling the chemical composition of the slag with best results (narrow cohesive zone lower down the furnace) as per the first set of experiments determination of the flow characteristics of these synthetic slags and
- (a) Preparation of pellets of Hematite varying the composition around the same as obtained from the first set of experiments.

  (b) Determination of Tumbler Index and Abrasion Index of cold-set pellets.

  (c) Subjecting the pellets to different experts of reduction and

  (d) Determination of the flow characteristics of the reduced pellets.

IV. EXPERIMENTAL DATA

PHASE I

Below table gives the compositional details of the slags obtained from blast furnaces.

Table 1. Chemical Composition of Industrial Blast Furnace Slags

Serial No	CaO %	SiO_2 %	MgO%	Al_2O_3%	C/S	IDT ˚C	ST ˚C	HT ˚C	FT ˚C	FT-ST ˚C
1	34.04	32.05	10.09	19	1.062	1203	1271	1318	1383	112
2	33.25	30.84	11.01	20.89	1.078	1220	1240	1274	1330	90
3	35.1	32.24	10.4	18.77	1.089	1210	1324	1345	1400	76
4	33.4	31.3	10.4	19	1.067	1204	1245	1266	1368	123
5	32.55	31.58	10.4	20.28	1.031	1225	1315	1335	1423	108
6	33.61	32.05	10.09	20.05	1.049	1217	1330	1363	1410	80
7	30.85	30.85	9.79	18.54	1.000	1200	1251	1307	1388	137
8	36.2	34.6	7.05	17.9	1.046	920	1220	1362	1376	156
9	34.57	36.72	6.51	19.04	0.941	827	1148	1310	1420	272
10	34.15	34.06	6.5	18.07	1.003	810	1224	1324	1370	146
11	31.9	33.5	10.4	20.8	0.952	817	1217	1331	1373	156
12	31.9	33.7	10.5	20.6	0.947	820	1195	1323	1392	196
13	31.6	33.9	10.6	20.6	0.932	813	1216	1326	1390	174
14	31.8	33.8	10.5	20.6	0.941	818	1224	1324	1393	169

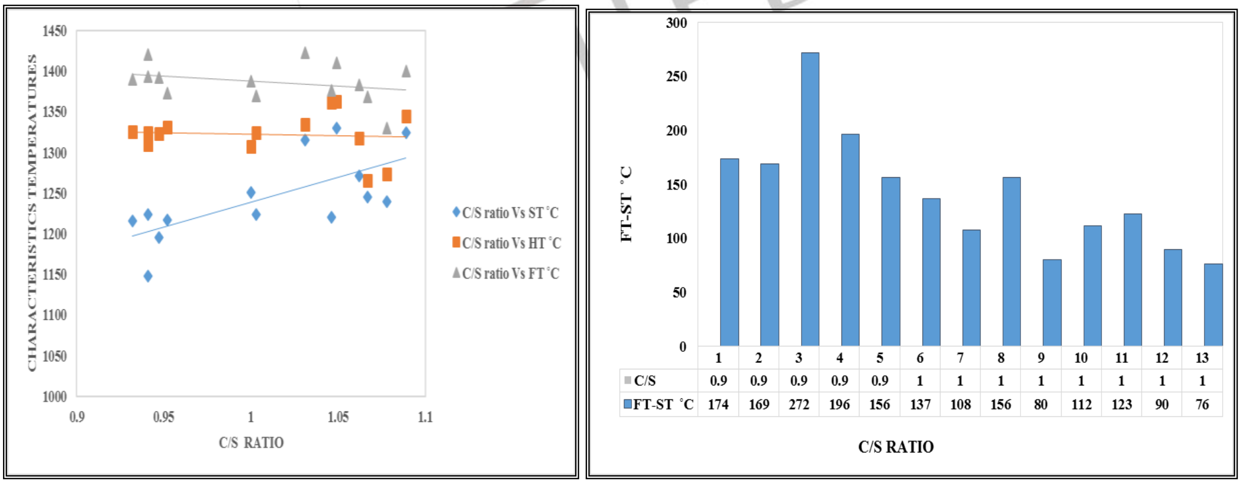


Fig.1 Variation of different characteristic temperatures with C/S ratio

The experimental data is plotted in Fig.1 as evident from the figure it is seen that the softening temperature of the industrial slags increase with the c/s (CaO/SiO_2) ratio. It can also be seen that the flow temperature at which the slag acquires liquid mobility, decreases with the c/s ratio and in general the rate of decrease of the flow temperature is low and low as the c/s ratio goes up.
The net effect of increase in ST and relative decrease in FT establishes that the 0 gap 6 between ST and FT (FT-ST) decreases with increase of c/s ratio, in general, for the blast furnace slags. Thus, for the industrial slag, in general under the range of compositions

studied, as increases of c/s ratio result in lowering of the cohesive zone (high ST) and developing a narrow (small FT-ST) cohesive zone. This is evident from Fig.1 which plots the gap between the FT and the ST (FT-ST) as a function of the c/s ratio.

PHASE-II Synthetic Slags

As discussed earlier the 1st set of experiments provided the basis for preparing the synthetic slags in the laboratory. These slags prepared from pure oxides as obtained from market are categorized under three headings. Table 4.3, table 4.4 and table no 4.5 show the comparison of the slags varied systematically. In these slags Al_2O_3 is kept constant at 19.71%.

Table .2 Variation of c/s ratio at fixed MgO percentage

Sample. no.	C/S ratio	MgO%	CaO %	SiO_2%	Al_2O_3%	IDT ˚C	ST ˚C	HT ˚C	FT ˚C	FT-ST ˚C
1	0.906	9.25	32.03	35.65	19.72	814	1233	1249	1425	192
2	0.965	9.25	33.15	34.36	19.72	837	1233	1250	1429	196
3	1.01	9.25	33.85	33.52	19.72	836	1243	1251	1432	189
4	1.06	9.25	34.8	32.83	19.72	831	1231	1259	1436	205
5	1.12	9.25	35.5	31.62	19.72	827	1229	1276	1421	192

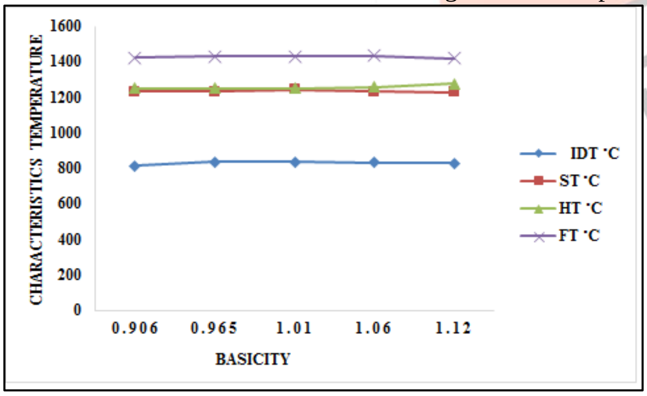
Table .3 Variation of MgO percentage at fixed c/s ratio

Sample. no.	C/S ratio	MgO%	CaO %	SiO_2%	Al_2O_3%	IDT ˚C	ST ˚C	HT ˚C	FT ˚C	FT-ST ˚C
6	1.02	7.42	34.785	34.103	19.72	820	1224	1254	1329	105
7	1.02	8.31	34.324	33.651	19.72	825	1236	1264	1333	97
8	1.02	9.25	33.85	33.186	19.72	830	1235	1254	1346	111
9	1.02	10.21	33.381	32.726	19.72	823	1231	1253	1340	109
10	1.02	11.92	32.525	31.887	19.72	819	1226	1284	1354	128

Table 4 Variation of MgO (theoretical) at fixed c/s ratio

Sample. no.	C/S ratio	MgO%	CaO %	SiO_2%	Al_2O_3%	IDT ˚C	ST ˚C	HT ˚C	FT ˚C	FT-ST ˚C
11	1.12	4.6	38.051	33.974	19.72	831	1232	1284	1329	97
12	1.12	7.8	36.401	32.501	19.72	839	1271	1284	1364	93
13	1.12	8.6	35.942	32.091	19.72	837	1219	1261	1317	98
14	1.12	10.5	34.921	31.179	19.72	818	1228	1334	1441	213
15	1.12	11.95	34.304	30.629	19.72	816	1209	1301	1329	120

The data obtained is plotted in Fig.3 through fig. no. 4.8 which shows the characteristic temperatures and the difference of FT and ST as a function of the c/s ratio and the MgO content respectively. One of the c/s ratio and the MgO content respectively.



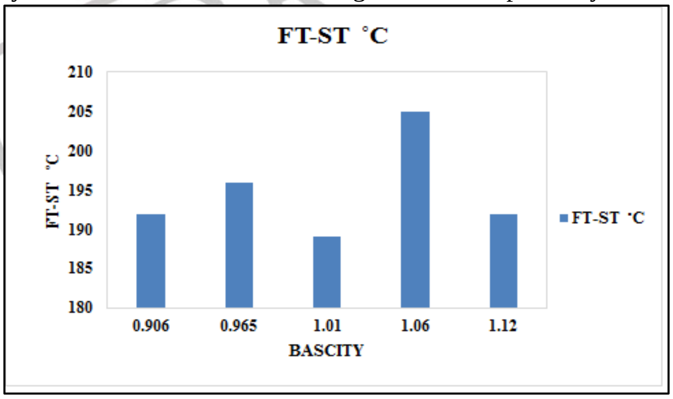


Fig.3 Variation of characteristic & ST-FT temperatures with C/S ratio for slag nos. 1-5

Table no.4 and fig.3 revel that MgO content at 9.26% with c/s ratio varying from 0.907 to 1.13 has no significant effect on the characteristic temperatures. In this category of slags studied, the difference between FT and ST is much above 100°C, meaning none of these slags are short-slags. An increasing C/S ratio in these groups of slags exhibits an increase in difference between the FT and the HT through the difference is very nominal.

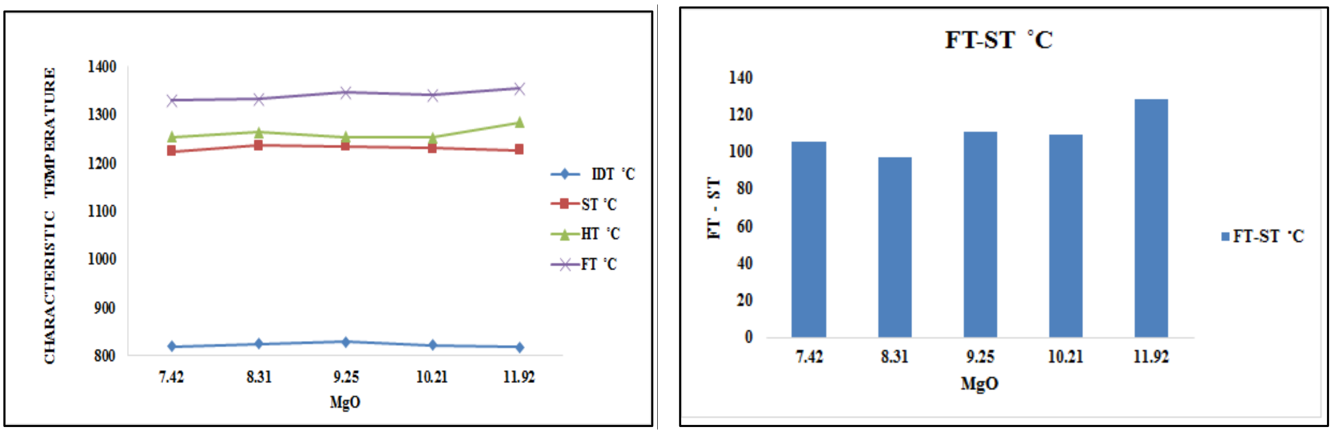


Fig.4 Variation of characteristic & ST-FT temperatures with MgO content for slag nos. 6-10

Slag no. 7 in the 2nd group of slags seems to be a short slag. But its comparison is identical to slag no. 3, which is not a short slag. This variation of results between two identical slags may be a result of experimental error. A report of the experiment reveals that an accurate measurement of characteristic temperature in the case of slag no. 7 could not be had due to excessive bubble formation. It is reported that bubble formation conformed till 1370°C and a correct deformation of FT could not be done. Thus in all probability this step also has a difference between FT and ST in excess of 100°C. However, it is also revealed slag no. 10 in this category, all steps are very close to being short slags. It can thus be concluded that variation at MgO from 7.4% to 10.2% at C/S ratio of 1.01 may be reported to the Blast Furnace process of iron making.

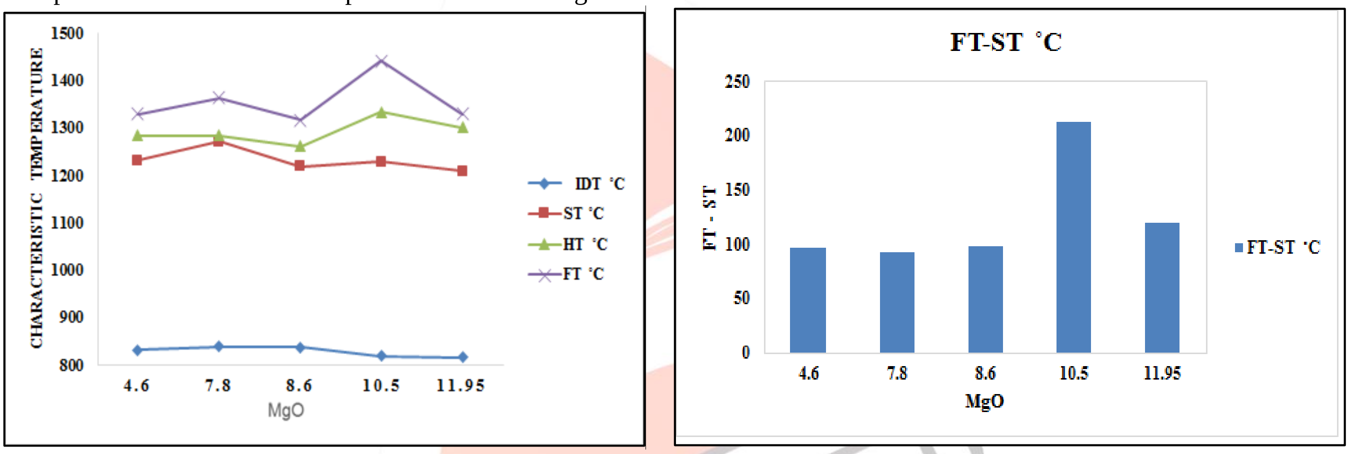


Fig.5 Variation of characteristic & ST-FT temperatures with MgO content for slag nos. 11-15

Most of the slags in the next category with variation of MgO corresponding to theoretical values for save of the academic interest are short slags. The experimental data revels that at C/S ratio of 1.1 variation of MgO between 4 to 8 percent may be considered beneficial. On the light of the above, it can be concluded that through the synthetic slags show same trend of variation, especially for the slags with c/s ratio of 1.01 with variation of MgO from 7.4% to 10.2% and for slags with c/s ratio 1.1 and MgO variations from 4 to 8 percent, these slags don't exhibit any definite trend with variation of composition. However, in the phase 3 set of experiments pellets may be provided with c/s ratio and MgO variations as noted above.

PHASE-III experiments

The chemical analysis of iron ore and other raw materials used for producing the pellets. The chemical analysis of the pellets cured at 950°C for 2 hours is given in Table 5. The tumbler index of the pellets is found to be 94 and the abrasion index is found to be 0.6.

Table 5. Chemical composition of pellets after curing at 950°C for two Hrs.

Chemical composition	wt %
Fe_2O_3	64
SiO_2	5.39
CaO	5.31
MgO	11.4
TiO_2	0.41
Al_2O_3	13.49

As discussed in the "experimental" section the pellets with reduction % of 10, 50 and 65 are considered for flow characteristics measurements.

Table 6. %Reduction Vs. characteristics temperature

% Reduction	Characteristic temperature			
	IDT	ST	HT	FT
10%	1180	1360	1524	1566
50%	1195	1424	1470	1583
65%	1284	1452	1494	1540

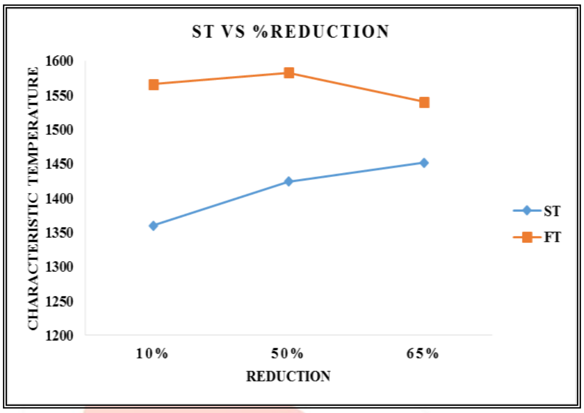


Fig.7 % of reduction vs. characteristics temperature

V. CONCLUSION

- The flow characteristics of blast furnace slags depends on the chemical composition of the slag high c/s ratio coupled with high MgO content (C/S ratio 1.049 to 1.078 and MgO 10.09 to 11.01%) resulting in a short slag.
- Synthetic slags do not show a definite trend of variation with the variation of composition may be due to the absence of minor constituents in the slag which are not considered while preparing the synthetic slags this may also be due to the temperature and pressure conditions prevailing in the blast furnace however slags with 1.1 C/S ratio and MgO content varying from the 4-8% may be of interest.
- Higher degrees of pre reduction established a favourable situation in the blast furnace, lowering the FT and increasing the ST for the range of compositions studied. However, a definite conclusion needs more experiments.

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