1.1 WORLD CRUDE STEEL PRODUCTION SCENARIO

Steel is the largest alloy (1808 million ton in 2018) produced in the world out of which India produced 106.5 million ton [1]. Crude steel production of the top ten countries in the world is shown in **Figure-1.1**. India (106.5MT) has attained the position of 2nd largest crude steel producer in the world, after china (928.3MT) [1].

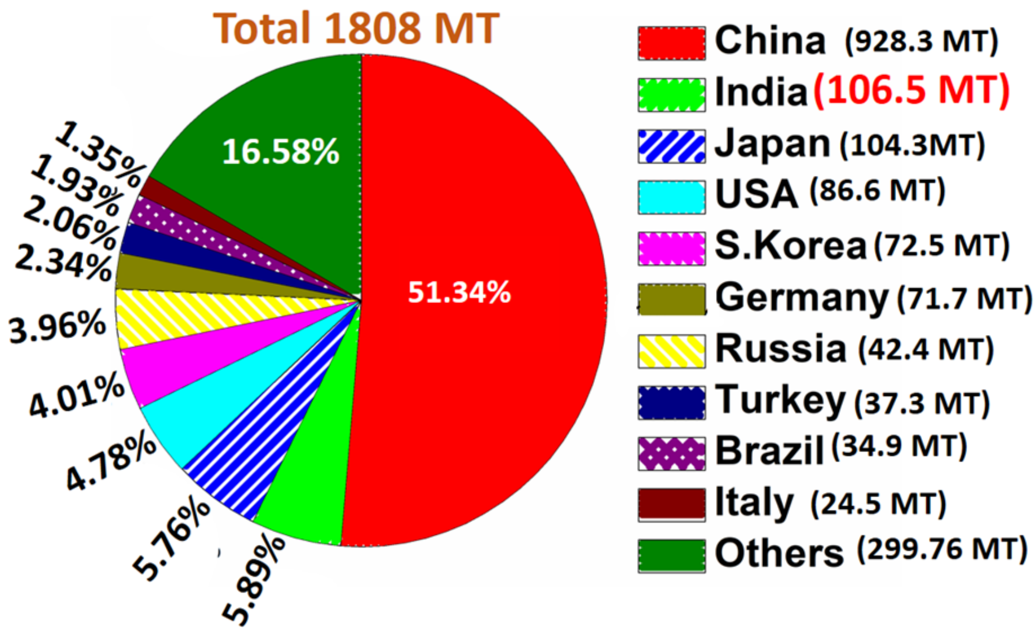

Figure-1.1 World crude steel production scenario of the top ten countries

Indian government targeted 300MT crude steel production by 2030. There is a massive difference between current production and targeted value in the Indian scenario. This plan of the Indian government opened up new ways for the researchers or scientist to work in this area.

1.2 STEELMAKING TECHNOLOGY

There are primarily two routes of steelmaking technology in the vague all around the world. One is the BF/BOF route also called oxygen steelmaking route, and another is electric steel-making comprising of Electric Arc Furnace(EAF) and Air Induction Furnace(AIF)

[2],[3]. Percentage of steelmaking by different technology is shown in **Figure-1.2**. India produced 53% (~27% by Induction furnace and ~26% by Arc furnace) steel by the electric route and 47% by oxygen route while in the world 79% steel produced by the oxygen route and only 21% of steel produced by the electric route [1].

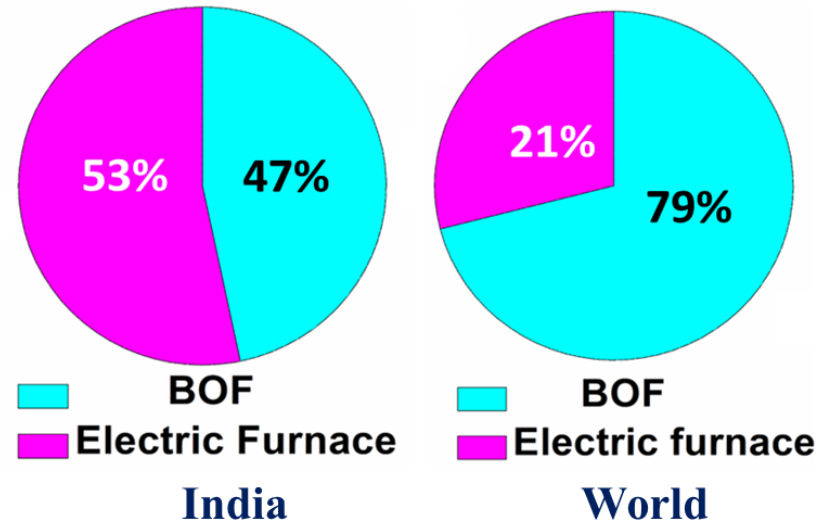

Figure-1.2 Steel making technology in India and world

The use of these technologies depends on the quality of raw materials, source of energy (availability of good quality coke/coal, electricity). Due to the unavailability of good quality coke, India is shifting their technology towards electric route. Installation of electric route steelmaking plants is cheaper than oxygen-based steel making plants therefore a large number of small scale electric industries established in India.

1.3 RAW MATERIALS FOR STEELMAKING

There are primarily two types of raw material used in the steelmaking.

Metallic: These are the primary source of metal, i.e. iron in the steel making process.

Examples: - Hot-Metal from Blast Furnace, Steel scrap, Direct Reduced Iron (DRI)

Additives: These are the primary source of slag forming compounds, Oxidizers, Coolant and deoxidizer which are generally used in the steelmaking process.

Examples: - Lime & Dolomite (fluxing agent) provide basicity and form slag in the steelmaking process. Pure Oxygen, Air, Mill-Scale and Iron ore are used as oxidizers. Steel scrap/DRI used as coolant, Coke breeze and graphite are used as a carburizer. Fluorides are used to maintain the viscosity of the slag. Quartzite is used as flux or to make silicon alloy in the steelmaking.

1.4 INDIAN RAW MATERIALS SCENARIO

The scenario of steelmaking raw materials in India is shown in **Figure-1.3**. Total 201MT iron ore produced in India out of which 136MT (67%) is fine, and only 65MT (33%) is lumps for Blast Furnace. Total produced lime generate 50% fines. These fines cannot be used directly in any steelmaking technology. These iron ore fines converted into agglomerates in the form of sinter, briquettes, pellets or DRI for their effective utilization. Currently, India is the largest producer of DRI with 30MT production out of which (~24MT) produced by coal based process and (~6MT) gas based process [4].

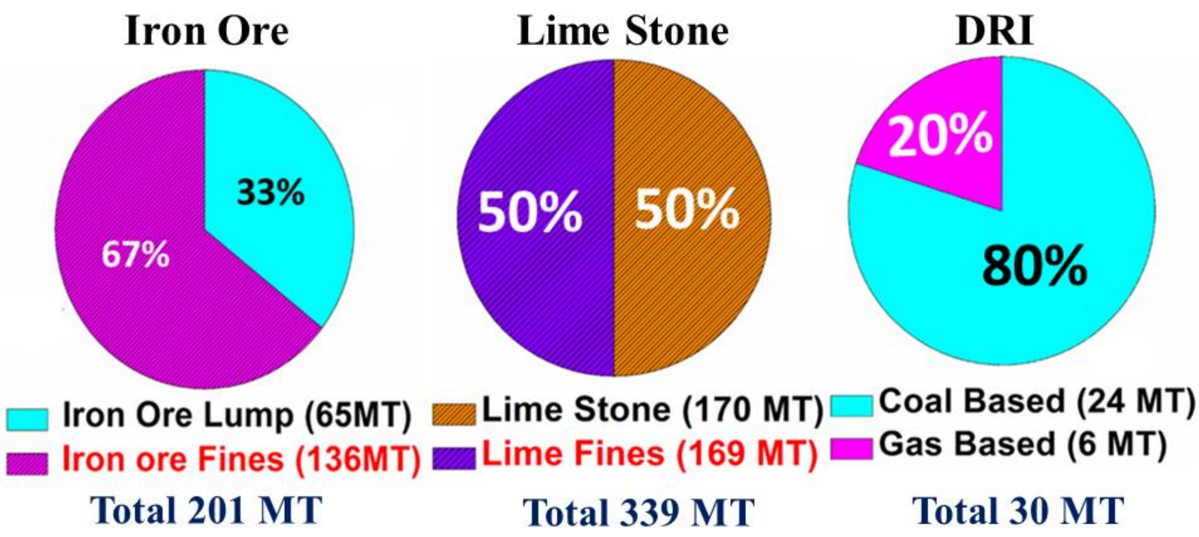

Figure-1.3 Distribution of steelmaking raw materials in India

Low quality coal or Non-coking coal can be used in DRI making industries effectively. New trends are developing in the industries to utilize the waste fines of iron ore and lime. A large amount of lime fines generated open up a new way to form fluxed DRI. Fluxed pellets can be made with the help of lime fines and iron ore fines which further used in blast furnace or steelmaking as charge material. It may increase the yield of the product at a lower cost. Here the lime powder works as a binder for making iron ore pellet and provides basicity as flux in the steelmaking process.

1.5 IMPORTANCE OF LIME IN STEELMAKING

Lime is an essential ingredient of steelmaking. It provides basicity to the bath and forms the slag with combining different impurity oxides available in the bath. Lime is basic; therefore, it combines with the acidic oxides which formed earlier in the steelmaking process due to oxygen blowing or presence of iron oxide.

1.6 FUNCTION OF LIME

In the first step oxygen reacts with iron and form iron oxide after this silicon reacts with iron oxide and form $nFeO.SiO_2$ (fayalite) type slag inside the bath. After this lime dissolves in the fayalite and replace the FeO to form $nCaO.SiO_2$ type slag [5,6]. In such a way FeO and CaO react with Si, Mn, P, S and C parallel and form their respective complex compound. These compound may be $nCaO.SiO_2$, $nCaO.P_2O_5$, nCaO.MnO, $nCaS_2$ etc. During this process viscosity of slag also changes continuously. The viscosity of slag is controlled by the composition of slag and bath temperature. Viscosity is directly proportional to the amount of lime addition in the bath [2],[7],[8]. It can be adjusted by changing the amount of lime inside the bath.

1.7 ISSUES WITH LIME

There are a lot of issues with lime. These are discussed in this section one by one.

1.7.1 STORAGE PROBLEM (HYGROSCOPIC IN NATURE)

Lime is very hygroscopic; therefore, it cannot be stored in the open atmosphere for a longer period. Lime forms its hydroxide during storage in a humid environment (Rainy season) which may be a cause of an accident during steelmaking practice, henceforth need of fresh lime requirement increases due to use in each practice [9]. Integrated steel plants have their lime kilns and produce fresh lime according to their requirements, but small industries depend on others for their lime requirement. During transportation and storage, this fresh lime becomes hydrated by moisture in a humid environment. Therefore, it is a very challenging task to provide safe and fresh lime to small industries for their steelmaking practices.

1.7.2 LIME DISSOLUTION TIME CONSUMING

Dissolution of pure lime is time taking due to its high melting point (2572°C) [9]. Due to long dissolution time, the total time taken by heat increases which increases the consumption of the energy therefore cost of the product will increase automatically. Researchers are trying to minimize the total time taken in the single heat, hence decrease in lime dissolution time is a big breakthrough in this direction [10]. The mixture of iron ore and lime make lower melting constituent phases therefore addition of lime with iron ore in the form of fluxed pellets may be fruitful in the direction to minimize lime dissolution time. The pellet of ~20% lime and ~80% iron ore can be melt at ~1205°C temperature [11].

1.7.3 NECESSITY OF CHARGING LIME IN LUMPY FORM

Charging practice of lime in the form of powder creates many environmental challenges. During melting a huge amount of fumes is generated which is harmful for human and social society. A significant quantity of lime is vanished through exit off-gasses therefore charging of lime in the form of lump is a safe option. Fluxed pellet may be a good option to replace the lime powder/lump in the steelmaking.

1.8 FRESH LIME PREPARATION

To overcome the above issues, the requirement of fresh lime increases day by day in the steel industries. Large scale steel plants (Integrated steel plants) have their lime kiln and produce fresh lime according to their requirements, but small industries depend on others for their lime requirement. During transportation and storage, this fresh lime gets hydrated; therefore it is a very big challenge to provide safe lime to small scale industries [9]. So many researchers are working in this area throughout the world. In the current work, weather resistant fluxed Direct Reduced Iron (Insitu DRI) is prepared to overcome the fresh lime issues for small scale industries.

1.9 CHALLENGES FOR STEELMAKERS

These days there are two main challenges in front of the steelmakers. First one is the preparation of weather-resistant lime which can be stored safely in the steelmaking unit for utilization. The second challenge is to minimize the slag formation time it means reduction in melting time of overall heat.

1.10 LITERATURE SURVEY

An intense literature survey (form 1975 to 2020) has done on the related research topics and summarized in the tabular form and given below. **Table-1.1** shows the work done previously by the researchers as award for PhD degree in the Department of Metallurgical Engineering, IIT (BHU) Varanasi, India. It contains the Name of the researchers, Year of submission, topic of their thesis etc. From the topic of thesis, it is cleared that **RC Gupta** did his work on the making of sponge iron from iron ore lumps using reducing gas in which he optimized the processing parameters for obtaining high metallized product. Similarly, T Sharma worked on acid iron ore pellets for characterizing their swelling behavior which is an important property. SN Mishra did his work to optimize the processing parameters to obtain Composite Pre- Reduced (CPR) pellets which are a good weather resistant product. D Paswan did his work to optimize the processing parameters for obtaining optimum strength in reduced fluxed pellets. In same way, data collected on topics from published articles of different journals and tabulated as following **Tables 1.2 &1.3**.

Table-1.1 Work carried out for the award of PhD degree previously in the Department

SN	Author	Year	Topic of thesis
1	D. Paswan	2012	Reduction and strengthening behavior of fluxed iron ore pellets [12]
2	S.N. Mishra	1992	Studies on composite pre-reduced iron ore pellets [13]
3	T. Sharma	1987	Swelling Characteristics of iron ore pellets [14]
4	R.C. Gupta	1975	Studies on production of sponge iron (Lump-gas based) [15]

Table-1.2 Information on the subjects (melting area) collected from published articles of the different Journals.

SN	Author (Year) Country	Experimental Variables: Raw Materials: Lime/ B	DRI/HBI/FCPR/CPR/FLIP/URP/URCP /PSF/BREX	Degree of Red. / Mett. (%)	Set Up: EAF/IF/BOF/BF/PF/RF/ Lddle/BOS (Temp. °C)		Out Comes wrt. Impurities present (ie. Si, Mn, C, S, P etc) in steel: Removals / Dilutions
1	M. Naseri Seftejani et.al (2020) Austria	0-2.9	Iron Ore	-	PF (H_2 & N_2)	-	Higher degree of reduction can be achieve by melting of all material. The amount of FeO in slag is low.[16]
2	A.K. Mandal et.al (2019) India	-	Bottom Ash & Iron Ore Slime	-	PF (H_2 & N_2)	-	Oxidation loss can be minimized by the inert nature of nitrogen plasma and recovery of aluminium can be reduced by hydrogen plasma. High temperature and reducing atmosphere created by hydrogen plasma.[17]
3	M. Naseri Seftejani & J. Schenk (2019) Austria	-	Iron ore	-	PF (H_2)	1550 - 3000	Highest reduction rate can be achieved at plasma arc zone due to highest temperature. At 1600◦C hydrogen utilized up to 43%. C, hydrogen utilization is 43%. [18]
4	M. Naseri Seftejani & J. Schenk (2018) Austria	-	Molten Iron Oxide	-	PF (H_2 & Ar)	-	Order of the reduction abilities of different hydrogen species are as follow H+>H+2 >H+3 >H>H2. Hydrogen plasma can promote one or two orders higher rate of reduction of iron oxide than other reductants. [19]
5	A. Bizhanov et.al (2015) USA	11-13% Lime	BREX	-	BF	-	Use of BREX in blast furnace improve their economic attractiveness and make it exclusive charge material.[20]
6	J. Pal et al. (2015) India	35% Lime	Pure lump Lime, Lump lime with iron ore, PSF	-	BOS	1350 - 1500	Low softening point (starts at 1 180 °C) of PSF dissolve it very fast in hot metal bath (30 s/g). formation of basic oxidizing nature slag in early stage remove C and P from hot metal shows faster removal [9]

Notations: B-Basicity; DRI.-Direct Reduced Iron; HBI-Hot Briquetted Iron; FCPR-Fluxed composite pre reduced pellets; CPR-Composite pre reduced pellets; URP- Un reduced pellets; Temp-Temperature (°C); EAF-Electric Arc furnace; IF- Induction furnace; BOF- Basic oxygen furnace; BF- Blast furnace; Red-reduction; Mett-Metallization; FLIP-fluxed lime iron ore pellets; RF-Resistance furnace; BOS-Basic oxygen steelmaking; Pre-fused synthetic flux; BREX- Extrusion Briquette;

SN	Author (Year) Country	Experimental Variables			Set Up		Out Comes wrt. Impurities present (ie. Si, Mn, C, S, P etc) in steel
		Raw Materials			EAF/IF/BOF/BF/PF/RF/Lddle/BOS (Temp. °C)		Removals / Dilutions
		Lime/ B	DRI/HBI/FCPR/CPR/FLIP/URP/URCP /PSF/BREX	Degree of Red. / Mett. (%)			
7	K.C. Sabat et.al (2014) India	-	Mineral Oxides	-	PF (H_2)		Reduction of minerals in the hydrogen found very good. The occurrence of hydrogen in the form of atoms, ions or in the excited states is far more operative energetically compare to molecular state of hydrogen.[21]
8	J. Pal et al. (2013) India	30%Lime	FLIP	-	BOF	1650	Dissolution study. The use of FLIP at place of only CaO in the form of flux, lower down the heat loss of process.[22]
9	J. Pal et al. (2011) India	20-40 % Lime	FLIP	-	RF	1370 - 1600	Only CaO-FeO type slag formed on the melting of FLIP which is oxidizing nature therefore it will make faster refining process.[23]
10	C. Brodrick (2009) South Africa	-	CaC Powder	-	Ladle	1300 1350	Effective sulphur removal is observed [24]
11	J. Kijac, M. Borgon (2008) Slovakia	Lime	Sintered Lime & Magnesia (7:3)	-	-	-	Sulphur partition coefficient increases with activity of CaO in the slag. [25]
12	S.K. Dutta et. al (2004) India	-	HBI	93 (Mett)	IF	1550	Partial replacement of scrap with DRI can produce steel which contains low amount of sulphur as well tramp elements.[26]
13	M.C. Goswami et.al (1999) India	2.0	FCPR & URCP	70 (Red)	IF	1350 1550	Kinetics increases with Temperature and basicity. activation energy values for pre-reduced is 42.01 kJ/mol while for unreduced is 60.75 kJ/mol in these experiments.[27]
14	K. Sadrnezhaad (1990) Iran	0.15	DRI	92.55 (Mett)	IM	1550	Compare to the other source DRI provides clean bath to the steelmakers. Continuous charging of DRI can minimize the time and energy of the process. [28]

Notations: B-Basicity; DRI.-Direct Reduced Iron; HBI-Hot Briquetted Iron; FCPR-Fluxed composite pre reduced pellets; CPR-Composite pre reduced pellets; URP- Un reduced pellets; Temp-Temperature (°C); EAF-Electric Arc furnace; IF- Induction furnace; BOF- Basic oxygen furnace; BF- Blast furnace; Red-reduction; Mett-Metallization; FLIP-fluxed lime iron ore pellets; RF-Resistance furnace; BOS-Basic oxygen steelmaking; Pre-fused synthetic flux; BREX- Extrusion Briquette;

Table-1.3 Information on the subjects collected from published articles of the different Journals.

SN	Author (Year) Country	Experimental Variables							Set Up	Outcomes of the experiments			
		Pellets Making		Redt	Hardening (H)		Reduction (Red)		SB, RK, RH, FD, TGA, RTF	CCS kg/pellet		%R / %M	A.E. KJ/ Mole
		CaO (B)	Bin	GB CB	T	Ti	T	Ti		Hd	Rd		
1	A Majumdar et.al (2018) India	9.12	-	CB	-	-	1100	5-90	SB	At 1373K in 90 minute reduction time maximum 50.37% metallization was achieved.[29]			
2	FO Boechat (2018) (Brazil)	1	-	GB	-	-	950	5-40	HF	Degree of reduction increases the average pore size of the material.[30]			
3	MK Mohanty et.al (2018) India	0.9-2.4 Basicity	Bentonite	CB	1300	30	1100 1400	60	SB	Increasing amount of lime lowers the activity of SiO_2 and increase the calcium ferrite phase formation which assists greater reduction of iron oxide therefore metallization increases with basicity.[31]			
4	A.B. Kotta et.al (2017) India	.5-1% Dextrin 1% Bentonite		-	900-1200	60-120	-	-	At 1473K and 1hr induration time with 1% bentonite 250 Kg/Pellet CCS was obtained and with 1% dextrin 302 kg/pellet while for 2hr induration time it is 350 Kg/pellet and with 0.5% it is 280kg/ pellet.[32]				
5	J. Yu et.al (2017) China	-	-	GB	-	-	500-600	120	Phase transition from hematite to magnetite explained by Avrami–Erofe'ev model. Activation energy calculated for the reaction is 48.70 kJ/mol.[33]				
6	S. Dwarapudi et.al (2017) India	Limestone-0-2.8% Pyroxenite-1.2-9.7% Coal-1.3-1.4%				-	800-1300	-	RH	Amount of melt phase increases with basicity of the pellets. FeO content also decreased in the slag. [34]			
7	M. Meraj et.al (2016) India	0.6-1.5% MgO 0.5% bentonite			1280 - 1350	-	-	-	MgO fluxed with gangue (WMB) shows better CCS than pure MgO fluxed pellets in green as well as in indurated conditions.[35]				

Notations: B-Basicity; Bin.- Binder; Redt.- Reductants; NCC-Noncoking Coal; GB-Gas based; CB-Coal based; T-Temperature(°C); Ti- Time(minutes); H-Hardening; Red.-Reduction; SB-Static Bed; RK-Rotary Kiln; RTF-Rotary Tube Furnace; RH-Rotary hearth; F D-Fluidized Bed; TGA- Thermo Gravimetric Apparatus; CCS-Cold Crushing Strength; Hd- Hardened; Rd-Reduced; %R- %Reduction: %M- % Metallization; A.E. - Activation Energy;

SN	Author (Year) Country	Experimental Variables							Set Up	Outcomes of the experiments			
		Pellets Making		Redt	Hardening (H)		Reduction (Red)		SB, RK, RH, FD, TGA	CCS kg/pellet		%R / %M	A.E.
		CaO (B)	Bin	GB CB	T	Ti	T	Ti		Hd	Rd		KJ/ Mole
8	N.A.El-Husseiny (2016) (Egypt)	0,4,8 %	2.5 % molasses	GB	900 1200	-	700 950	5-60	TGA	Lime addition increases the drop number and green crushing strength of the pellets. Activation energies for respective basicities are as following 0B-35kJ/mol,4B-42kJ/mol,8B-50 kJ/mol.[36]			
9	A.K. Mandal et.al (2015) India	0-2 B	-	-	1100 - 1300	60	-	Porosity of pellets increases up to 1200C hardening temperature (42.8%) but at 1300 C, due to melt slag formation retard the porosity (9.96 %) drastically and increase the CCS (586.76 kg/pellet). [37]					
10	A. Kemppainen et.al. (2015) (Finland)	.09 & 0.22	Olivine	GB	-	-	1200 1350	10, 40, 70	SB	Acid pellets (40% Contraction) softened rapidly compare to olivine fluxed pellets (30-35% contraction) at 1150°C and shows more contraction. [38]			
11	D. Guo et.al (2015) (China)	2% Bentonite 2%pine sawdust		GB	1250	25	850 1050	0 25	SB	Pellets composed with biomass shows higher reduction compare to non-biomass at same reduction temperature.[39]			
12	F.Chen et.al (2015) (USA)	-	-	GB	-	-	1200 1300	8 Sec	DTR	Reduction of hematite with CO consume 231 kJ/mol activation energy compare to 214 kJ/mol for hydrogen.[40]			
13	J.O.Park & S.M.Jung (2015) (S.Korea)	.3&2.6 Basicity	Composite	CB	-	-	1000 1300	30	SB	$CaO-Al_2O_3$ slag stimulated the reaction rate by catalytic effect while $CaO-SiO_2$ retarded it by inhibiting gasification.[41]			
14	J.P. Santos et.al (2015) (Brazil)	-	-	GB	-	-	850 1050	-	SB	Morphology of iron depends on temperature during reduction. At 950 C, the fibrous iron is present. Finally, at (1050C), long fiber and fresh iron precipitate was observed.[42]			

Notations: B-Basicity; Bin.- Binder; Redt.- Reductants; GB-Gas based; CB-Coal based; T-Temperature(°C); Ti- Time(minutes); H-Hardening; RF-Resistance Furnace; Red.- Reduction; SB-Static Bed; RK-Rotary Kiln; RH-Rotary hearth; F D-Fluidized Bed; TGA-Thermo Gravimetric Apparatus; CCS-Cold Crushing Strength; Hd- Hardened; Rd-Reduced; %R-%Reduction: %M- % Metallization; A.E. – Activation Energy;

SN	Author (Year) Country	Experimental Variables							Set Up	Outcomes of the experiments			
		Pellets Making		Redt	Hardening (H)		Reduction (Red)		SB, RK, RH, FD, TGA	CCS (kg/pellet)		%R / %M	A.E.
		CaO (B)	Bin	GB SB	Ti	T	Hd	Rd		Hd	Rd		KJ/ Mole
15	J.W. Cha et.al (2015) (S.Korea)	1-9%	-	CB	-	-	1050 1250	180	TGA	Carbon Gasification improved with increasing temperature which increase the reduction rate with rate constant of indirect reduction by CO. [43]			
16	N.A.El-Husseiny et.al (2015) (Egypt)	2% molasses		GB	-	-	600 950	60	SB	Reduction and rate of reduction increases on increasing the temperature and flow rate of reducing gas.[44]			
17	N. Saleh and S. Rochani (2015) Indonesia	0.49-1.82B		CB	-	-	1600	60-120	SB	High basicity pellets required lower energy for the melting compared to low basicity pellets. [45]			
18	Q. J. Gao et.al (2014) China	2% MgO	Bentonite	GB	-	-	900-1100	240	SB	Rate of reduction of MgO-fluxed pellets is faster than that of traditional acidic pellets. Therefore, degree of indirect reduction can be increased with use of MgO-fluxed pellets in blast furnaces.[46]			
19	M. Iljana et.al (2015) Finland	0.5 & 3.2 %	-	GB	-	-	800 1100	300	SB	Dissociation of limestone during reduction increases the reducibility of pellets. [47]			
20	A. Gul et al (2014) Turkey		2%	-	1200	30	-	-	SB	250 - 510	Mixture of 3% sodium bicarbonate and calcium bentonite gives the best crushing strength.[48]		
21	A.S Nathan et.al (2014) Australia	13% 14% 18%	-	-	25-1350	100	-	-	SB	Thermal range of SFCA increased by increasing the amount of basicity because total amount of SFCA increased with basicity. [49]			

Notations: **B-Basicity; Bin.- Binder; Redt.- Reductants; GB-Gas based; CB-Coal based; T-Temperature(°C); Ti- Time(minutes); H-Hardening; RF-Resistance Furnace; Red.-Reduction; SB-Static Bed; RK-Rotary Kiln; RH-Rotary hearth; F D-Fluidized Bed; TGA-Thermo Gravimetric Apparatus; CCS-Cold Crushing Strength; Hd- Hardened; Rd-Reduced; %R-%Reduction; %M- % Metallization; A.E. – Activation Energy;**

SN	Author (Year) Country	Experimental Variables							Set Up	Outcomes of the experiments			
		Pellets Making		Redt	Hardening (H)		Reduction (Red)		SB, RK, RH, FD, TGA	CCS kg/pellet		%R / %M	A.E. KJ/ Mole
		CaO (B)	Bin	GB SB	Ti	T	Ti	T		Hd	Rd		
22	J. Pal et al. (2014) India	0.1-0.8B		-	1280	10-25	-	-	SB	Limestone can be replace by lime without addition of bentonite. Addition of Lime gives better green pellets properties as well as wanted strength at high temperature.[50]			
23	J. Pal et.al (2014) India	LD Sludge, Coke, Lime, MgO		-	-	-	-	-	Shatter and tumbler index with CCS can be improved by use of LD Sludge in pellets. [10]				
24	KMK Sinha & T. Sharma (2014) India	0.5% Bentonite		GB	1320	20	950-1050		TGA	Temperature have robust effect on the reduction behaviour followed by time and concentration of CO in CO/CO_2.[51]			
25	KMK Sinha et.al (2014) India	-	-	CB	-	-	900-1050	0-90	SB	203.2 KJ/mol activation energy calculated for the reduction in the range of 1173-1323°K temperature.[52]			
26	F.M. Shen et.al (2014) China	0-2% MgO		GB	1250	30	900	60	SB	On increasing MgO content in the pellet from 0 to 2 wt.% value of CS decreased and RCS increased.[53]			
27	Y. Man et.al (2014) China	Composite Pellets 1% Bentonite		GB	-	-	500-1200	120	TGA	Size of particle effect the activation energy of the reduction. For 38µm it is 53.04kJ/mol while for 163µm it is 131.72kJ/mol.[54]			
28	A. Ghosh (2013) India	-	-	CB	-	-	850-1025	-	SB	Devitalization of the coal follow two stages. First at 625 to 875 °K, and second above 875° K temperature.[55]			
29	A. Sarkar etal. (2013) India	0-4.16	-	Green Pellets						Crushing strength of pellets increases with lime content.[56]			

Notations: **B-Basicity; Bin.- Binder; Redt.- Reductants; GB-Gas based; CB-Coal based; T-Temperature(°C); Ti- Time(minutes); H-Hardening; RF-Resistance Furnace; Red.-Reduction; SB-Static Bed; RK-Rotary Kiln; RH-Rotary hearth; F D-Fluidized Bed; TGA-Thermo Gravimetric Apparatus; CCS-Cold Crushing Strength; Hd- Hardened; Rd-Reduced; %R-%Reduction; %M- % Metallization; A.E. – Activation Energy;**

SN	Author (Year) Country	Experimental Variables							Set Up	Outcomes of the experiments			
		Pellets Making		Re dt	Hardening (H)		Reduction (Red)		SB, RK, RH, FD, TGA	CCS kg/pellet		%R / %M	A.E.
		CaO (B)	Bin	GB SB	Ti	T	Ti	T		Hd	Rd		KJ/ Mole
30	H.Park & V.Sahajwala (2013) Australia	2.3 %3. 8%4 .9%	Car bon		-	-	1350 1500	30	SB	Silica-based pellet had greater activation energy (137 kJ/mol) for reduction compare to alumina-based pellet (107 kJ/mol).[57]			
31	T. Umadevi et.al (2013) India	0.7-1.4% coke breeze		CB	-	-	1220 - 1330	-	SB	Addition of carbon in green pellets decreased the reducibility of iron ore pellet. On increasing induration temperature from 1 220°C to 1 330°C decrease the reducibility due to higher magnetite, slag & lower pore phase.[58]			
32	R.Sah & S.K. Dutta (2011) (India)	10% Lim e	5% De xtro se	CB	-	-	1088	125	TGA	Increasing Fe/C ration decrease the degree of reduction of carbon composite pellets. Calculated activation energy values lie in the range of 0.86–8.82 and 12.37–38.32 KJ mol.[59]			
33	T. Umadevi et.al (2011) India	0.8- 1.15 B	0.7 %	-	1300	-	-	-	SB	On Increasing basicity from 0.08 to 1.15, tumbler index improved from 93.15 to 95.38% and cold crushing strength improved from 176 to 264 kg/pellets.[60]			
34	F.X. Hui et.al (2010) China	Lime, MgO, Lime stone Dolomite Bentonite (2%)		-	1250	12	CCS for roasted pellet increases on addition of lime first then decreases. In the range of basicity 0.4−0.6, maximum value of CCS is obtained. The reaction of CaO with Fe2O3 and SiO2 will make binding phase of calcium-ferrite and silicates respectively and provides strength to pellets.[61]						
35	H.C. Chuang et.al (2009) China	0.55 and 1.83 B	-	GB	-	-	1200	24h	Addition of FeO up to 20 mass% to the CaO-SiO2- MgO-Al2O3 system can decrease Softening and melting temperatures of system, further addition of FeO does not produce constant results.[62]				

Notations: **B-Basicity; Bin.- Binder; Redt.- Reductants; GB-Gas based; CB-Coal based; T-Temperature(°C); Ti- Time(minutes); H-Hardening; RF-Resistance Furnace; Red.- Reduction; SB-Static Bed; RK-Rotary Kiln; RH-Rotary hearth; F D-Fluidized Bed; TGA- Thermo Gravimetric Apparatus; CCS-Cold Crushing Strength; Hd- Hardened; Rd-Reduced; %R-%Reduction: %M- % Metallization; A.E. – Activation Energy;**

SN	Author (Year) Country	Experimental Variables							Set Up	Outcomes of the experiments			
		Pellets Making		Redt	Hardening (H)		Reduction (Red)		SB, RK, RH, FD, TGA	CCS kg/pellet		%R / %M	A.E. KJ/ Mole
		CaO (B)	Bin	GB SB	Ti	T	Ti	T		Hd	Rd		
36	M. Kumar & SK. Patel (2009) India	-	-	CB	1200	60	850 1000	15 120	SB	Reduction time and temperature effect the degree of reduction. Rate is faster in the first 30 minutes because of dissociation of volatile matter. $1-(1-\alpha)1/3 = kt$ is best fit model.[63]			
37	M. Kumar et.al. (2008) India	-	-	CB	1200	60	900	30 120	SB	At temperature of 900°C in 2 hrs. more than 90% reduction achieved. [64]			
38	A.A.El-Geassy et.al (2004) (Egypt)	0.32 & 1.62 Basicity		GB	-	-	750-1000	500	TGA	Ca/Mg based pellets shows more reducibility in the initial stage while in the later stage it slow down due to formation of calcio/magnesio-wüstite phases.[65]			
39	K. Mondal et.al. (2004) USA	-	-	GB	-	-	800 900	0-240	TGA	Fe_2O_3 to FeO - 9.97 KJ/mol FeO to Fe - 14.13 KJ/mol Fe to Fe_3C - 14.65 KJ/mol CO to CO_2 - 10.60 KJ/mol [66]			
40	RC Gupta & A Shaik (2004) India	-	-	-	-	-	1000 1250	0 25	SB/ Mixed	400 / 250	CCS increases with increasing apparent density. [67]		
41	RC. Gupta & JP.Gautam (2003) India	-	1-4%	CB	-	-	900 1250	5-20	SB	0-200	Use of 4% bentonite addition can produce reduced pellets with strength up to 200 kg.[68]		
42	Q.Wang et.al. (1998) (China)	Liquid Glass		CB	-	-	1050 1300	-	TGA	Effect of volatiles on the reduction is negligible throughout fast heating at 1050-1300°C. 69-83KJ/mol activation energy of reduction is Calculated. [69]			

Notations: **B-Basicity; Bin.- Binder; Redt.- Reductants; GB-Gas based; CB-Coal based; T-Temperature(°C); Ti- Time(minutes); H-Hardening; RF-Resistance Furnace; Red.-Reduction; SB-Static Bed; RK-Rotary Kiln; RH-Rotary hearth; F D-Fluidized Bed; TGA-Thermo Gravimetric Apparatus; CCS-Cold Crushing Strength; Hd- Hardened; Rd-Reduced; %R-%Reduction: %M- % Metallization; A.E. – Activation Energy;**

SN	Author (Year) Country	Experimental Variables							Set Up	Outcomes of the experiments			
		Pellets Making		Re dt	Hardening (H)		Reduction (Red)		SB, RK, RH, FD, TGA	CCS kg/pellet		%R / %M	A.E.
		CaO (B)	Bin	GB SB	Ti	T	Ti	T		Hd	Rd		KJ/ Mole
43	N. Narcin et.al (1995) (Turkey)	-	-	CB	-	-	910 1050	0 240	RTF	250	At 1000°C reduction temperature in 90 minute 93% metallization is achieved.[70]		
44	S.N. Mishra & R.C. Gupta (1994) India	Composite Pellets		-	-	-	950 1200	350	SB	CPR pellets provides sufficient strength 120kg.During the reduction core reduced about 100% and coating reduced partially up to 27%.[71]			
45	L.H. Hsieh et.al (1993) Taiwan	1.3-2.1B	-	-	1250	3-4	-	-	SB	Calcium ferrite phase formation increases on increasing basicity (CaO/Si02) which favors the higher strength and densification at lower temperature during sintering.[72]			
46	S K Day et.al. (1993) India	-	-	NC C	-	-	900 1050	0-35	SB	Volatiles are responsible for the reduction of Hematite noncoking coal mixed pellets at temperatures below 1OOO°C. [73]			
47	R. Haque (1993) (Banglade sh & India)	-	-	CB	-	-	800 1200	-	SB & FB	Rate of reduction is faster in fluidized bed compare to packed bed system. First order model is fitted for type of reduction. Sulphur present in higher amount in the case of fluidized bed compare to packed bed. [74]			
48	A.K. Ray et.al (1992),Ind ia	-	-	GB	-	-	850 1000	150	SB	Static bed reduction of iron ore with CO can be modelled by shrinking core phase-boundary reaction model. [75]			
49	S.Chakrav arty (1991),Ind ia	-	-	CB	-	-	900 1200	-	SB	Rate of reduction and amount of reduction increases with the volatile matter of reductant.[76]			

Notations: **B-Basicity; Bin.- Binder; Redt.- Reductants; GB-Gas based; CB-Coal based; T-Temperature(°C); Ti- Time(minutes); H-Hardening; RF-Resistance Furnace; Red.-Reduction; SB-Static Bed; RK-Rotary Kiln; RH-Rotary hearth; F D-Fluidized Bed; TGA-Thermo Gravimetric Apparatus; CCS-Cold Crushing Strength; Hd- Hardened; Rd-Reduced; %R-%Reduction: %M- % Metallization; A.E. – Activation Energy;**

SN	Author (Year) Country	Experimental Variables							Set Up	Outcomes of the experiments			
		Pellets Making		Re dt	Hardening (H)		Reduction (Red)		SB, RK, RH, FD, TGA	CCS kg/pellet		%R / %M	A.E. KJ/ Mole
		CaO (B)	Bin	GB SB	Ti	T	Ti	T		Hd	Rd		
49	S.C. Panigrahy et.al (1990) Canada	0.2-1.6B	1% Bentonite		-	-	1200	15-60	SB	Melt formation during pellet induration increases with basicity of pellets which provides good strength and swelling characteristics. It is optimized for basicity 1.3. [77]			
50	J.K Wright et.al. (1981) (Australia)	-	-	CB	-	-	900 1200	150	SB & RK	Reduction rate of pellets by carbonized coal found similar in static bed and small batch rotary kiln.[78]			
51	CE.Seaton et.al (1983) (USA)	-	2 & 7% Lime		-	-	800 1200	0-60	SB	The Boudouard reaction can be used to control the rate of reduction of iron oxide but it does not mean that all process is controlled by chemical kinetics.[79]			
52	M.C. Abraham & A Ghosh (1979),India	-	-	GB	-	-	700-1150	50	SB	Carbon composite pellets lead to reduction rate considerably due to intimate contact of reducing elements and catalytic effect of metallic Fe.[80]			
53	R.J. Fruehan (1977) (USA)	-	-	CB	-	-	900 1200	100	SB	Overall rate is measured by the oxidation of the carbon by CO_2. The reduction of Fe_2O_3 to FeO is faster than that of FeO to Fe.[81]			
54	N.S. Srinivasan & A.K. Lahiri (1977),India	1.5% Bentonite		CB	-	-	925 1060	55 Sec	TGA	This study approve that reduction of hematite is stepwise. [82]			
55	Y.K. Rao (1971) (USA)	Hematite & carbon powder mixtures					850 1087	-	SB	An enthalpy of activation of 72 kcal/per mole was calculated.[83]			

Notations: **B-Basicity; Bind.- Binder; Redt.- Reductants; GB-Gas based; CB-Coal based; T-Temperature(°C); Ti- Time(minutes); H-Hardening; HF-Horizontal Furnace; Red.-Reduction; SB-Static Bed; RK-Rotary Kiln; RH-Rotary hearth; F D-Fluidized Bed; DTR-Drop-Tube Reactor; TGA- Thermo Gravimetric Apparatus; CCS-Cold Crushing Strength; Hd-Hardened; Rd-Reduced; %R-%Reduction: %M- % Metallization;**

1.11 USES OF DRI IN STEEL INDUSTRIES [12]

1.11.1 DRI USED IN EAF STEEL MAKING

DRI making opens up an alternative route for steel making. This can work out economically viable, under certain circumstances. Use of DRI in steelmaking yielded satisfactory quality and recovery of metal values; therefore, it is becoming a predominant source of raw materials for steel making nowadays. 26% of steel is produced by EAF route at present. The use of hot DRI feed can reduce the power intake and tap to tap time due to presence of additional sensible heat. The energy required to produce molten steel by DRI-EAF route is the same as for the BF-EAF, Estimated by the Bureau of International Recycling (BRI). Energy consumption also decreased by increasing the percentage of metallization of DRI. All the above important possibilities of DRI lead to setting up a large number of mini steel plants based on this technology to meet the social aspirations of people at a large number of places rather than setting a big integrated steel plant, particularly at one place.

1.11.2 DRI USED IN BOF STEEL MAKING

DRI is being used as a Coolant of high purity in Basic oxygen furnace. The use of DRI as a substitute of scrap not only gives the metallurgical benefits arising out of DRI but also be supplemented by lower cost of steel production. DRI increases liquid steel production by 15% when the hot metal temperature is 1500^0C and decreases fossil fuel consumption and CO_2 emissions.

1.11.3 DRI USED IN AIR INDUCTION FURNACE (AIF)

India produces 28% steel using Air Induction Furnace. Increasing demand for quality at the place of quantity allowed the use of DRI in the air induction melting furnace. Quality steel contains lower impurity and tramp elements such as sulphur, phosphorous, oxygen, hydrogen, nitrogen therefore DRI is a suitable feed material to produce such type of steel in air induction melting furnace process. Use of DRI in Induction furnace melting increases the melting rate and decreases the power consumption. Melting rate also increases by increasing the percentage of DRI and metallization.

1.12 **CONCLUSIONS OF THE LITERATURE SURVEY**

Followings are the conclusion drawn from the extensive literature survey made globally during 1975 to 2020 to utilize such solid waste (i.e. iron ore and lime fines):

- Hardening and reduction behavior of iron ore pellets utilizing lime fines with basicity more than 2 were not studied in detail.
- Melting behavior of highly fluxed reduced pellets (fluxed DRI) were not studied in detail under melting in Electric (Arc / Induction/ Plasma) Furnaces.
- Weather resistance properties of highly fluxed hardened/reduced pellets were not yet studied.
- The behavior of plasma exposure and partially reduced iron ore (Fluxed DRI) pellets on the elimination of impurities from the pig iron melt were not studied in detail.

1.13 **AIM OF THE PRESENT STUDY**

From the above literature survey it was found that there is a broad scope to do work in this area. The aim of the present work is to prepare the weather-resistant fluxed DRI pellets for steelmaking and studies their behavior for removal of impurities from the pig iron melt under different melting conditions.

1.14 PLAN OF WORK

- Raw materials collection and their characterization
- Preparation of fluxed DRI pellets and their characterization
- The behavior of fluxed DRI pellets during open atmosphere storage
- The behavior of fluxed DRI pellets during steelmaking