

Chapter 6 Summary and Suggestions for Further Work

6.1 Summary

The objective of the present study is six-fold:

1. Mineralogical studies of low-grade iron ore
2. Beneficiation studies of low-grade iron ore by using several techniques and developing an appropriate route for beneficiation with good recovery of iron and upgrading the iron content
3. Different sizes of composite briquettes making and testing of composite briquettes
4. Reduction studies (isothermal and non-isothermal) of composite briquettes and characterization of isothermal composite briquettes
5. Utilization of composite briquettes in liquid metallic bath for steel making. As well as auxiliary studies as backup investigations with an emphasis on isothermal reduction kinetics.
6. Testing of produced steel samples

The following raw materials were selected and procured for the present study:

Iron ore	:	Bonai ranges of Badjamada Mines, Jharkhand-Odisha sector (Monet Ispat Ltd.) [<i>Sample – O</i>] Bhilwara – Rajasthan state (Red and Yellow ochre – weathered) [<i>Sample – R-1 and R-2</i>]
Coke	:	procured from local market of Rajkot
Charcoal	:	procured from local market of Vadodara
Binder	:	Polyvinyl alcohol (PVA) - procured from local market of Vadodara
Flux	:	Lime - procured from local market of Vadodara
Charge material for smelting reduction	:	TMT steel bar – available at Metallurgical and Materials Engineering Department, M. S. University of Baroda

Mineralogical studies have been initiated from megascopic studies, hardness and density of ore. Ores were thoroughly observed with the help of: a polarized and reflected microscope. An XRD analysis is carried out for the identification of phases present in samples. Sample O has hematite and quartz as major phases while samples R-1 and 2 have Goethite and quartz as major phases. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) are used for surface topography, texture, size analysis and chemical analysis of spot or identified surface area.

Based on the mineralogical studies, beneficiation studies were carried out. For sample O, the conventional beneficiation route is suitable. Odisha ore is beneficiated by two stage beneficiation of jigging and tabling operation. Ore is upgraded from 53.1 pct to 60.26 pct with iron recovery of 59.75 pct. Rajasthan ore was initially beneficiated by conventional beneficiation route but it was ineffective on ore. Magnetic roasting is employed to beneficiate iron ore which is followed by wet magnetic separation. XRD analysis is confirmed phase transformation of goethite into maghemite. Ore is upgraded by coke (high in ash) and charcoal (high in volatile matter). Ore is upgraded with recovery of 90 pct by both carbonaceous materials.

Rajasthan iron ore was upgraded by coke and charcoal. Four different types of composite briquettes were prepared for smelting reduction for isothermal and non-isothermal reduction (TG-DTA) and smelting reduction studies. These are as follows:

1. **AA** - Upgraded iron ore (Rajasthan) by coke + Coke
2. **AB** - Upgraded iron ore (Rajasthan) by coke + Charcoal
3. **BA** - Upgraded iron ore (Rajasthan) by charcoal + Coke
4. **BB** - Upgraded iron ore (Rajasthan) by charcoal + Charcoal

Cylindrical shaped iron ore – coke / charcoal composite briquettes were prepared. Two different sizes of iron ore-carbonaceous materials were prepared as per stoichiometric calculation: i) for Isothermal reduction studies - diameter 10 mm, height 12-13 mm and weight between 1.6 to 1.9 gm and (ii) for smelting reduction - diameter 25 mm, height 24-25 mm and weight in between of 31 to 33 gm. Based on a detailed literature survey, a

10 pct Polyvinyl Alcohol (PVA) solution was used as a binder. Further, briquettes were tested for evaluation of properties.

Isothermal reduction studies are carried out of four types of composite briquettes for 1223, 1273, 1323 K and 150, 300, 450, 600 and 1200 s. Reduced composite briquettes were characterized by XRD and SEM analysis. The degree of reduction and Activation energies are calculated. Non-isothermal reduction is also studied up to 1473 K with an aim to compare the data with isothermal studies. In non isothermal studies, the activation energy of the initial stage has lower values than a later stage.

Smelting reduction of composite briquettes was carried out in a laboratory induction furnace. The experiments were designed to investigate: dissolution behavior and bulk dissolution of composite briquettes in molten bath, to make steel and to evaluate the recovery of iron. Composite briquettes were charged 5, 10, 15, 20 pct. Iron yield is calculated for smelting reduction studies.

Steel produced from the smelting reduction process is normalized and microstructure is observed at different magnifications. The hardness of normalized steel is measured.

From the above studies, summarised the following:

1. Mineralogical studies provide key information about texture, morphology, and phases present in ore which help to decide a suitable beneficiation process.
2. Odisha ore is BHQ type. The size of gangue and ore minerals is in microns. So, ore can be processed by conventional beneficiation route but at fine size only. $Fe_{(T)}$ is achieved from 53.1 pct to 60.26 pct with a recovery value of 59.75 pct by jigging and tabling operations. By this beneficiation route, Odisha ore is upgraded and it can be used in the agglomeration process.
3. Rajasthan ore has a limonite type of ore; from which goethite is major ore mineral and quartz is major gangue mineral. Goethite is always challenging to beneficiate by any beneficiation process. Ore texture and particle size were not preferred for the conventional beneficiation route.
4. For Rajasthan ore, the magnetic roasting process achieved recovery of iron in the range of 85 to 90 pct by a transformation of goethite into maghemite at 1173 K

and 120 min. $Fe_{(T)}$ is attained from 33.02 pct to 49.12 pct and 49.60 pct by coke and charcoal respectively. Coke and charcoal did not affect on recovery of iron significantly. Due to the presence of less amount of ash content in charcoal, it can be advantageous over coke. Upgraded ores by coke and charcoal are taken for further studies.

5. The highest compressive strength is achieved by BA for 10 mm (1170 N/briquette) and BB for 25 mm (630 N/briquette) composite briquette.
6. The lowest shatter index is obtained by BA for 10 mm (0.1 pct) and BB for 25 mm (4.89 pct) composite briquette.
7. Isothermal reduction studies carried out at different temperatures - 1223, 1273, 1323 K and time – 150, 300, 450, 600, 1200 s.
8. It was observed that the degree of reduction increases with an increase in temperature.
9. In reduction studies, the presence of volatile matter and ash content affect critically on the degree of reduction and activation energy.
10. An upgraded ore by charcoal type of composite briquettes (BA and BB) have shown better reduction behavior. Out of which composite briquette BA (iron ore roasted by charcoal + coke) have a better degree of reduction at 1323 K, activation energies of isothermal and non-isothermal reduction in general.
11. Based on activation energy values of the initial and later stages of non isothermal reduction studies, two stage reduction processes are observed in the present study.
12. Highest activation energy is obtained in BA composite briquette for isothermal reduction and BB composite briquette for non isothermal reduction.
13. The presence of high ash content in Coke adversely affects the reduction process.
14. Low amount of activation energies indicates reduction is controlled by gasification reactions.
15. From XRD, iron is observed as the major phase and silica as a second major phase.
16. SEM images revealed metalized iron in a reduced briquette.
17. In smelting reduction studies, iron yield is achieved at 90 to 95 pct which is quite significant at the laboratory level.

18. In smelting reduction, the highest recovery (93-95 pct) is achieved by BA (iron ore roasted by charcoal + coke) composite briquette among all types.
19. Although all the four type of 20 pct charged composite briquettes have ~94 pct iron yield which signifies less impact of impurities at higher temperatures in smelting reduction.
20. 25 mm diameter cold bonded composite briquettes are dissolved and reduced with 45 sec in a molten bath which is significant for direct use of ore as composite briquette in ironmaking / steel making.
21. Composite briquette can act as feed material in ironmaking / steelmaking.
22. Bulk quantity of composite briquette lowered down molten bath temperature which can be used as a coolant and another source of iron and oxygen for steelmaking.
23. Slag volume is higher in the higher proportion of composite briquette in steelmaking which is due to higher ash and gangue content in briquette.
24. 1.5 to 1.87 pct carbon in steel has cementite and pearlite phase while medium carbon steel has ferrite and pearlite in microstructure.
25. Hardness of normalized cast structure is measured between 85 to 95 HRB except few readings.

In the present work, two types – BHQ (*Odisha*) and Limonite (*Rajasthan*) of low-grade iron ore are taken for upgradation studies. Odisha ore has achieved 60.26 pct Fe with a recovery of 59.75 pct in a convention type of beneficiation route while Rajasthan ore has achieved about 49 pct with a recovery of 90 pct by magnetic roasting and wet magnetic separation route. Mineralogical studies play a crucial role in designing of beneficiation flow sheet of any type of iron ore. Odisha ore is upgraded into high grade ore. So it will be utilized in the agglomeration process and further ironmaking process. Rajasthan ore is beneficiated, agglomerated, studied reduction kinetics and smelted it in steel making to generate steel (i.e. final product). Isothermal, non-isothermal and smelting reduction (*90-95 pct iron yield*) are obtained at par for iron and steel making comprehensively. So, this ore is used for *Mine-to-market* which can consume as raw material for iron and steel making. Composite

briquette of Rajasthan ore can also be used as a coolant in steel making which can be an alternative to steel scrap and an additional source of iron.

6.2 Suggestions for Further Work

1. The iron ore-coal composite briquettes produced in the present study have good dry strength but swelling behavior and strength, after reduction, were not studied. Such specific investigations are essential for a better understanding of the briquette properties and their behavior in reduction/smelting furnaces.
2. Economic estimation of the smelting reduction of composite briquettes by conducting trials at the pilot plant level is required for commercialization in future.
3. By adding composite briquettes in melt, it is possible to get steel directly by controlling the $Fe_{(T)}/C_{fix}$ ratio in composite briquettes. Although the dissolution rate of composite briquette is very fast. After complete dissolution of composite briquettes, oxygen lancing can be used in the liquid bath to control carbon and phosphorous in the bath and desulphurization can be carried out in the ladle.
4. By heat balance calculation, it is possible to design the reactor to produce steel directly by continuous charging of composite briquettes.