CHAPTER 6

Summary and Conclusions

6.1 Summary

Steel is the main driving force of economic progress of a country. The industrial development programmed of any country, by and large, is based on its natural resources. There are planning for about 300 Mt steel production by India in 2030, that will be required 513 Mt of processed iron ore and 639 Mt run of mine ore. India is fortunate to have reserves of high-grade iron ores. But with time these reserves of high-grade iron ores are bound to be diluted.

However, in a steel industry where several processes are employed using of various raw materials. It is natural that many valueless substances are generated which can be termed as waste materials. The waste can be categorized in terms of solid, liquid and gases. The solid wastes are from process units and also from pollution control units. The process wastes, dust and sludge from pollution control unit, are the area of attention. Solid wastes generated from process units are generally characterized by their uniform size and composition. Low moisture content, high levels of metallic (i.e. Fe) and non-metallic values (e.g. CaO, C etc.) content in wastes, which makes these suitable for recycling within the plant or to be sold out to consuming industries.

Efforts are being made to utilize the waste materials by proper characterization, beneficiation and agglomeration techniques. The treatment/utilization of steel plant sludge/dusts is still a problem in many countries of the world. Effective utilization of dust and sludge for iron and steel making can be possible after upgradation of Fe percent and discard the valueless materials. There is also shortage of coking coal all over the world in general and in particular at India. Enormous amount of coal fines and coke breezes are generated during coal mining and coking of coal respectively. By incorporating non-coking coal fines or coke breezes with up-gradated dust and sludge utilized in producing cold bonded iron oxide-coal composite pellets, the metallurgical coke requirement in the blast furnaces can be reduced.

The term composite pellet is employed here to mean pellet containing mixture of fines of iron bearing oxide and carbonaceous material (i.e. coal) which has been imparted sufficient green strength for subsequent handling by cold bonding technique. The prepared cold bonded composite pellet should have sufficient mechanical strength to withstand high temperature and stresses in reduction furnaces. Interest in composite pellets have grown from the decade of 1980s because of the following advantages:

1. Utilization of cheaper resource and pollution control,
2. Very fast reduction rate due to intimate contact between reductant and oxide particles,
3. Reduction in energy consumption for production because cold bonded composite pellets do not require induration,
4. Promising prospect for iron making at small scale with higher production rate,
5. Because of their uniform size and convenient form, composite pellets can be continuously charged in to the furnace leading to higher productivity, and
6. Consistent production quality as the chemical composition of composite pellets does not change.

The concept of Smelting Reduction (SR) process of iron ore, an alternative to blast furnace technology was initiated around 1970. The SR processes involving both reduction and smelting are very similar to blast furnace in which all the reactions takes place in a single reactor. Most of the smelting reduction processes involve by removal of oxygen from the iron ore in the solid state (initially) followed by further removal of remaining oxygen in the liquid phase reduction reaction. Ideally, a smelting reduction process should have 100 pct reduction of iron oxides in the liquid state in a single stage in a single reactor.

There is a shortage of coking coal in India. On the other hand, India has vast reserves of non-coking coal, which is widely available and cheapest reducing agent for iron oxide. Hence, non-coking coal based iron making technology has special relevance for country like India. In fact, the need to make non-coking coal based iron making units economically viable has resulted in the development of SR processes, which do not face sticking problem at high temperature.

The composite pellets, produced from steel plant dust or sludge (after beneficiation), can be utilized as the feed material for smelting reduction. Rate of production is expected to be higher with composite pellets due to high degree of pre-reduction to the smelting reactor. There have been very few studies for the utilization of various steel plant wastes in the steel making process. However, the dust and sludge are used in steel making at some places, but the productivity is not good by using directly. There are a few published literatures on utilization of steel plant dust and sludge. Looking into the above aspect, the objective of present study was three-fold:

1. Characterization and beneficiation of dust and sludge by using various methods and establishing proper route for beneficiation with good recovery of iron bearing oxide.
2. To prepare composite pellets using various binders by cold bonding techniques in the laboratory and evaluate their properties; this would be a contribution towards development of suitable binder for cold bonding composite pellets.
3. Utilization of composite pellets in liquid metal bath for steel/iron making. As well as auxiliary studies as backup investigation with emphasis on isothermal reduction kinetics.

To achieve the set objectives, the overall study consisted of four parts:

i) Characterization of raw materials,

ii) Beneficiation of waste materials to upgrade iron content,

iii) Selection of binder for waste-coal composite pellet making,

iv) Fundamental studies on isothermal reduction of waste-coal composite pellets, and

Bulk dissolution of composite pellets in molten bath to produce steel/cast iron.

Therefore, it was decided to carry out the beneficiation of the waste to enrich iron content. Preparation and testing of waste-coal composite briquettes / pellets were done. Isothermal reduction of waste-coal composite pellets and investigation on reduction smelting of composite pellets in liquid metal bath were done. Some auxiliary studies as back-up investigations with emphasis on kinetics, for better understanding of reduction behaviour of composite pellets were also done.

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

Sources of Iron Oxide (Steel Plant's wastes)	
Steel melting shop dust	Jindal Steel Works, Bellari, Karnataka, India
Steel melting shop sludge	Jindal Steel Works, Bellari, Karnataka, India
Steel melting shop sludge	Vizag Steel Plant, Vishakhapatnam, Andhra Pradesh, India
Coal	
Coal	Procured from local market
Binder	
Lime	Procured from local market (laboratory reagent grade)
Fly ash	Thermal Power Plant, Vanakbori, Gujarat.
Molasses	Procured from local Foundry
Starch	Procured from local market
Charge material for induction furnace	Steel scrap (procured from local market)

Chemical analysis of waste samples were done using Energy Dispersive X-ray Fluorescence (XRF) Spectrometer. The proximate analyses of coal was done according to the standard method. The Scanning Electron Microscopic (SEM) examination of waste sample were carried out using JEOL SEM (Model: JSM-5610 LV) coupled with Oxford Energy Dispersive Analytical X-ray (EDAX) system. The waste powder sample showed the presence of mostly spheroidal shaped particles. XRD of the waste samples showed the waste were amorphous in nature. A wide variation in particle size was observed in sieve analysis of the samples.

The ground dust and sludge were beneficiated using various methods like Air Classifier, Welfley Table and Hydraulic Classifier. Finally, after beneficiation trials, two stage beneficiation route was selected. After the two stage beneficiation route, it was observed that in case of JSW dust, JSW Sludge and VIZAG Sludge there was increase in percentage of Fe_2O_3 up to 87.33 pct, 90.69 pct and 85.77 pct from initial 55.39 pct, 73.77 pct and 70.70 pct of Fe_2O_3 respectively.

To select the proper binder, cylindrical shaped briquettes (diameter 9.70 - 9.75 mm and height 13-14 mm) were prepared and tested. It was observed that the highest compressive strength of 1436 N/briquette was obtained for briquettes prepared using 5 pct starch and 2.5 pct molasses as binder in JSW sludge, 1167 N/briquette strength was for JSW dust using 7.5 pct starch and 5 pct molasses as binder and 1063 N/briquette was obtained for briquettes prepared using 7.5 pct starch and 2.5 pct molasses as binder for VIZAG sludge. From these results of briquettes, composite pellets were prepared. Variation in compressive strengths were observed mostly by ±15 pct of the average value. Similarly, the highest drop strength (more than 200 drops) and lowest shatter index value (0.064 pct) were also obtained.

The iron ore-coal composite pellets were produced using starch and molasses as binder with Fe_{tot}/C_{fix} ratios as per stoichiometry. The degree of reduction of composite pellets were obtained by reducibility studies. For measurement of degree of reduction for composite pellets, the weight loss method was used. The loss in weight due to loss of oxygen, carbon and volatile matters were taken into consideration. The isothermal reduction of composite pellets was carried out in nitrogen atmosphere. The reduction studies of composite pellets were analysed, and rate of reduction and activation energy was calculated. The activation energies were found to be low (49.8–59.28 kJ mol^{-1}) which means, volatile gases (in particular H_2) diffused through porous solid iron-oxide particles boundary. Overall reduction was controlled by gasification reactions. Reduced composite pellets were examined by SEM to observe the microstructure of the reduced composite pellets. XRD was carried out to identify the phases present in reduced composite pellets.

The experiments for smelting reduction of composite pellets were done in an induction furnace of 5 kg capacity at temperature 1723 ± 10 K. The process deals with the bulk dissolution of composite pellets into the molten bath and iron recovery was calculated in terms of yield. During smelting reduction, it was observed that the 16-17 mm diameter composite pellets completely dissolved in 24 to 30 seconds. The maximum yield 98.2 pct for JSW Dust composite and 98.3 pct for Vizag Sludge composite were obtained.

In summary, the present investigation has demonstrated effective recycling and utilization of steel plant waste like BOF Dust and sludge. Beneficiation of dust and sludge was done to increase the Fe pct of raw materials. Beneficiation methods were selected such that there was no chemical used. This investigation also demonstrated smelting reduction of composite pellets in an induction furnace a feasible alternative route to produce hot metal using dust and sludge. The investigation on kinetics and dissolution behavior of composite pellets in liquid metal bath gave insight for fundamental and fair understanding of the reduction behaviour of waste-coal composite pellets. The metal, produced in smelting reduction, has reasonable iron yield up to 98.3 pct. The present studies also demonstrate an effective way of utilization of BOF dust and sludge for extracting metal which is of vital concern for resource conservation and pollution control. Using cold bonding technique, composite pellets of sufficient green strength were produced. This is a contribution towards development of suitable binder for cold bonding technology.

6.2 Conclusions

1. The steel plant wastes (like JSW dust, JSW sludge and VIZAG sludge) can be easily beneficiated for the upgradation of the iron (Fe) values.
2. For single stage beneficiation method: i) JSW dust improved the iron (Fe) values from 38.77 pct to 46.24 pct by Air Classifier with 94.97 pct recovery; ii) JSW sludge improved the iron (Fe) values from 51.64 pct to 60.45 pct by Tabling with 56.83 pct recovery ; and iii) VIZAG sludge improved the iron (Fe) values from 49.49 pct to 60.08 pct by Tabling with 51.2 pct recovery.
3. It was observed that Air Classifier was the most suitable beneficiation method for all the samples and the next common beneficiation technique was Wilflay Table, so the first stage in two stage beneficiation was Air Classifier and then Wilfley Table (if it is needed) in the second stage. For better recovery concentrate and middling were mixed together.

4. For two stage beneficiation method (i.e. Air Classifier was used in the first stage and the underflow of Air Classifier was treated again in Wilfley Table): i) JSW dust improved the iron (Fe) values up to 61.13 pct (concentrate + middling) with 93.8 pct recovery; ii) JSW sludge improved the iron (Fe) values up to 63.48 pct (concentrate) with 78.39 pct recovery; and iii) VIZAG sludge improved the iron (Fe) values up to 60.04 pct (concentrate) with 57.72 pct recovery.
5. After two stage beneficiation method, it was observed that in case of JSW dust, JSW Sludge and VIZAG Sludge there was increase in percentage of Fe_2O_3 up to 87.33 pct, 90.69 pct and 85.77 pct from initial 55.39 pct, 73.77 pct and 70.7 pct of Fe_2O_3 respectively.
6. During trails for binder selection, it was found that TB3 (with 7.5 pct fly ash, 5 pct lime and 5 pct molasses) gave good green drop strength (8) and dry drop strength (24), but TB6 (with 7.5 pct fly ash, 5 pct slake lime and 5 pct molasses) gave higher compressive strength (107.8 N/briquette) and as well as good shatter strength (7.17); that means slake lime was more effective to form calcite due to CO_2 passing.
7. Further trails with starch and molasses as binder were done with JSW dust. Taguchi technique was used for selection of binder proportion for pellets making. It was found

that E2 (with 2.5 pct starch and 5 pct molasses) gave highest strength (1196.82 N/briquette) and lower shatter index (0.18).

8. During reducibility study of pellet, it was found that fraction of reduction increases with increasing in temperature and time for all three materials. The fraction of reduction for pellet was increased with time of heating and rise in temperature. Initially the fraction of reduction was very low which may be due to the release of volatiles, which was slow process. But later on-the fraction of reduction increased with time, which might be attributed to the faster gas-solid reactions at high temperature.
9. The activation energies for reduction were found - 52.59, - 49.80 and - 59.28 KJ/mol for JSW Dust, JSW Sludge and VIZAG Sludge composites respectively.
10. The activation energies for composite pellets reduction were found to be low (49.8–59.28 kJ mol^{-1}) which means, volatile gases (in particular H_2) diffused through porous solid iron- oxide particles boundary. Overall reduction was controlled by gasification reactions.
11. From XRD, it was confirmed that the reduction took place in topochemical manner, i.e. stagewise reduction (i.e. $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$).
12. It was also confirmed that the presence of metallic iron in reduced composite by SEM.
13. It was observed during smelting reduction that the composite pellets were completely dissolved easily at the molten bath.
14. It was also observed that the 16-17 mm diameter composite pellets completely dissolved in the molten bath at an average 27 seconds. That means dissolution rate of composite pellet is very fast. Hence, production rate would be faster.
15. As addition of composite pellets increased during smelting reduction, carbon content in product also increased in general.
16. It was observed that above 20 pct addition of composite pellets to the molten metal formed cast iron, due to higher carbon input along with composite pellets. There was also some carbon dissolved from graphite crucible, due to more time were spend for dissolving the total composite pellets.
17. The maximum yields were obtained 98.2 pct, 96.1 pct and 98.3 pct for JSW Dust composite, JSW Sludge composite and Vizag Sludge composite respectively.
18. Above 20 pct addition of composite pellets to the molten metal, in general, iron yield decreased due to loss of iron in slag.

19. It is possible to charge composite pellets as feed material in Smelting Reduction Process to get faster steel/cast iron production.
20. An alternate method of iron/steel making is possible by charging composite pellets as feed material.

6.3 Suggestions for Further Work

1. TG-DTA of composite pellet should be carried out at a single heating rate and at different heating rates.
2. The waste-coal composite pellets produced in present study have good dry strength but swelling behaviour and strength after reduction were not studied. Such specific investigations are essential for better understanding of the pellet properties and their behaviour in reduction/smelting furnaces.
3. Economic evaluation of the smelting reduction of composite pellets by conducting trials at pilot plant level is required for commercialization in future.
4. By adding composite pellets in melt, it is possible to get steel directly by controlling the Fe_{tot}/C_{fix} ratio in composite pellet. Since dissolution rate of composite pellet is very fast, after complete dissolution of composites, oxygen lancing can be done to the liquid bath to control carbon and phosphorous in the bath and desulphurization can be carried out in the ladle.
5. By proper heat balance calculation, it is possible to design the reactor to produce steel directly by continuous charging of composite pellets.