Chapter 7:
Summary

7.1. Introduction

This chapter summarizes the important observations presented in this thesis and gives a brief incitement of the scope of future research work to be carried out.

7.2. Summary

7.2.1. Preparation of Hardened Pellets

Pelletization behavior of MMO fines using four different binders: colemanite, dextrin, cornstarch, and carboxymethyl cellulose was investigated. Each binder was tested at varying dosages of 0.5 wt.%, 1 wt.%, 1.5 wt.%, and 2 wt.%. Various physical properties of the pellets were evaluated, like green strength, dry strength, Cold Crushing Strength (CCS), porosity, tumbler index (TI), shatter index (SI), and abrasion index (AI). The results revealed that all binders provided sufficient green and dry strength. However, only pellets containing at least 1.5 wt.% colemanite met the required CCS according to industrial standards. Pellets with 2 wt.% colemanite, hardened at 1250 °C, showed the highest CCS of 379 kg/pellet, albeit with low porosity at 19 vol.%. Consequently, the optimal binder dosage and induration temperature were determined to be 1.5 wt.% colemanite and 1250 °C, respectively. This combination yielded pellets with a CCS of 297 kg/pellet and a porosity of 25 vol.%. Additionally, pellets bonded with 1.5 wt.% colemanite exhibited favorable values for other physical properties: a TI of 95.35%, SI of 99.2%, and AI of 4.23%. These results suggest minimal dust generation during handling and transportation of the hardened pellets, indicating ease of handling. Sintering and the transformation of magnetite to hematite are the primary reasons for achieving high CCS values (>200 kg/pellet) in pellets bonded with 1.5 wt.% colemanite.

7.2.2. Carbothermic Reduction of Hardened Pellets

The reduction and kinetic behavior of pellets made from MMO fines were studied within the temperature range of 950-1150 °C using two solid reductants: non-coking coal and coke. At a reduction temperature of 1100 °C and a reduction time of 90 mins, pellets reduced with non-coking coal achieved a desired % Fe_M of greater than 85%. However, pellets reduced with coke reached a maximum % R of 76% and a maximum % Fe_M of 83% at 1100°C with a reduction time of 120 mins, which fell short of industrial standards. Interestingly, at 1100°C, the % R after 60 mins was higher than that at 1150 °C for both non-coking coal-reduced and coke-reduced pellets. XRD analysis of MMO pellets reduced at both temperatures showed no major phase change. However, SEM analysis revealed a higher degree of sintering in pellets reduced at 1150°C, resulting in decreased porosity. This reduced porosity led to increased resistance to gas flow to the pellets' inner core, thereby affecting the subsequent %R. The kinetic model $[(1-\alpha)^{-1/3}-1]^2 = kt$ was found to be the best fit for the reduction of MMO pellets regardless of the reductant used. The calculated activation energy was approximately 165.38 KJ/mole for non-coking coal-reduced pellets and 220.19 KJ/mole for coke-reduced pellets. These values fall within the range observed in studies conducted on similar types of multimetallic ores.

7.2.3. Hydrogen Reduction of Hardened Pellets

The effect of reduction time, temperature, and H_2 gas flow rate on reduction of pellets made from MMO fines were investigated. A % R of more than 90 % and % Fe_M of more than 85% after about 20 mins of reduction time at a reduction temperature of 900°C and gas flow rate of 1 L/min was achieved. This demonstrated the viability of hydrogen reduction for processing MMO pellets, notably reducing the required reduction times compared to carbothermic reduction methods. However, due to the low % H_2 utilization and the high cost associated with H_2 gas, optimal process parameters were selected, including a reduction time of 45 mins, a reduction temperature of 900°C, and a gas flow rate of 0.25 L/min. Under these optimized conditions, the % R reached approximately 90%, the % Fe_M was measured to be 89%, and the % H_2 utilization exceeded 40%. At the optimized reduction parameters, pellet cracking was observed, and there was a drastic decrease in CCS from 285 kg/pellet (hardened pellet) to 60 kg/pellet after reduction, slightly above the minimum limit specified in standards. SEM studies indicated that the cracking of pellets and the decline in CCS were caused by the large-scale nucleation of reduced phases, appearing as needles and spherical particles within a brittle slag phase

The impact of gangue oxides (MgO, Al_2O_3, SiO_2) on the CCS and H_2 reducibility of pellets was investigated by reducing synthetic pellets. It was found that the porosity and drop in CCS of pellets after reduction increased with the addition of Al_2O_3 and MgO, while it decreased with higher SiO_2 content. Complete removal of SiO_2 resulted in a significant deterioration in CCS after reduction, dropping from 186.48 kg/pellet to 22 kg/pellet. Conversely, complete removal of Al_2O_3 led to a low porosity of just 3.6 vol.% and a % R (reduction extent) of 20%.

These observations suggest that despite the negative impact of gangue oxides on furnace productivity, it should not be entirely eliminated when low-grade iron ore pellets are reduced by hydrogen.

B_2O_3 present in the colemanite binder formed a melt phase with SiO_2. An increase in SiO_2 content increased the amount of melt phase, reducing pellet porosity from 36.5 vol.% to 25.8 vol.%. SEM studies confirmed that porosity decreased with increase of SiO_2 content and improved with increased Al_2O_3 content. The increment in Al_2O_3 content increased viscosity and reduced the flowability of the borosilicate melt phase, resulting in improved pellet porosity from 3.6 vol.% to 25.8 vol.%. Thus, proper control of gangue oxide content in low-grade ores could maintain porosity and CCS after reduction of H_2-reduced pellets without compromising on reducibility.

7.2.4. Exploratory melting studies

Exploratory melting studies were conducted on MMO pellets reduced using both carbon and hydrogen. It was found that the metallic yield increased from 34.8% to 40.2% when H_2-DRI was used instead of C-DRI. With H_2-DRI, the Fe (Iron) and Cr (Chromium) content in the metal increased to a maximum of 97 wt.% and 1.2 wt.%, respectively, with longer melting times. Concurrently, the C, S, and Si content decreased to 0.069 wt.%, 0.0108 wt.%, and 0.0166 wt.%, respectively. The initial $\%Fe_M$ of H_2-DRI (90%) were higher than C-DRI (85%), indicating a more pronounced effect on the recovery of iron and chromium with hydrogen. The metal produced from C-DRI had higher S and C contents compared to H_2-DRI, as the coal used during reduction contributes to the S and C in the melt. Furthermore, the metal produced from C-DRI had higher Si content than H_2-DRI. This is because carbon reduces SiO_2 to Si, bringing it into the metallic phase. The low initial carbon content could explain the lower Si content of H_2-DRI.

7.3. Suggestions for Future Work

- Use of other cold-setting binders like cement for pelletization of low-grade ores
- Use of composite binders (organic + inorganic) for pelletization of low-grade ores.
- Hydrogen reduction of pellets at higher temperatures (>1000°C) for longer periods.
- Pilot-scale hydrogen reduction of pellets.
- Optimization of oxyacetylene flame melting for iron ores and pellets.