UDK 539.4; 622.781

The Study of Pelletizing of Mixed Hematite and Magnetite Ores

P. S. Kumar\textsuperscript{1}, B. P. Ravi\textsuperscript{2}, O. Sivrikaya\textsuperscript{3)}, R. K. Nanda\textsuperscript{4}
\textsuperscript{1,2,4Department of Mineral Processing, VSKUPG Centre, Nandihalli, Karnataka, India
\textsuperscript{3}Dept. of Mining and Mineral Process. Eng., Adana Science and Technology University, Adana, Turkey

Abstract:

The present study aims to investigate the use of mixed hematite and magnetite ores in iron ore pellet production. Pelletizing tests were carried out on the hematite and magnetite premixed pellet feed. Drop number and compressive strength tests for green and dry pellets; porosity, compressive strength and reducibility tests for fired pellets were carried out to determine the influence of mixing ratios of both iron oxides on those pellet properties. Experimental results showed that as the hematite content in the mix pellets is increased, the green drop number decreased from 6.5 to 5.2, the green compressive strength decreased from 1.51 to 1.28 kg/pellet and the dry compressive strength decreased from 2.50 to 1.60 kg/pellet. It was determined that fired compressive strength of mix pellets decreased from 380 to 230 kg/pellet when the hematite content in the mixed pellet is increased. The reducibility of mix pellets had almost the same trend and it was faster up to 40 min reduction time. The results showed that the use of hematite together with magnetite is possible to produce pellets with sufficiently good quality in terms of wet, dry and fired mechanical strengths. The porosity and reducibility values of mix pellets were also found to be adequate to use as feed for the blast furnace.

Keywords: Iron ores; Magnetite; Hematite, Pellets; Compressive strength.

1. Introduction

The main natural raw material for iron and steel industry is iron ores. Iron ores can be classified as high grade and low grade in terms of their iron contents. High-grade iron ores which can be used directly in the blast furnace to produce metallic iron are not abundant in the earth’s crust to supply the need of iron and steel industry \cite{1}. Therefore, the utilization of finely distributed iron oxides in low-grade hematite and magnetite ores through agglomeration has gained much importance in the present situation due to depletion of high-grade iron ores. Among all agglomeration techniques, pelletizing utilizes very finely ground ores or concentrates with sufficient iron content greater than 63\% \cite{2}. Both magnetite and hematite ore concentrates can be used in agglomeration processes. However, magnetite ore concentrates obtained from magnetite sources through enrichment processes are more suitable for iron ore pellet making. Because of the heat supplied during thermal treatment and oxidation of the magnetite fines causing the development of chemical bond through recrystallization of magnetite grains to hematite in pellets and in consequences, more strong pellets can be produced after sintering/firing. Hence, pellets are desired to withstand against degradation during pellet production, handling, and charging in both stockpiles and in reduction facilities such as blast furnaces. The oxidation of magnetite to hematite may start at

\textsuperscript{3)} Corresponding author: osmansivrikaya@gmail.com
relatively low temperatures. With the increase of temperature, hematite grains grow as soon as they are formed and bond themselves one another so as to give consistency in solidity and at the end provide strength to pellets. Therefore, high-grade magnetite ore fines or fine concentrates can be easily utilized to produce pellets with sufficient strength and quality. Whereas, hematite ores or concentrates require much more heat supply during firing stages in pelletizing since the absence of exothermic oxidation reaction as happened in the oxidation of magnetite ores. So the energy consumption of hematite ore pellet firing is greater than that of magnetite pellets [3-5]. This topic was investigated by many researchers and they concluded that during thermal treatment of magnetite pellets, very resistant chemical bonds are developed and they provide strengths to the pellets. They determined that hematite ores can be fired at only very greater temperatures when compared to the magnetite to obtain satisfactory mechanical pellet properties. Thus, the use of hematite ores or concentrates in pelletizing is not so easy or requires high energy during firing. The mixing of both iron oxide sources (magnetite and hematite) in pelletizing operations is one of the studied topics in literature and in industrial applications to benefit advantages of each material. Pelletizing of magnetite and hematite ores with different mixing ratios have been studied [4, 6-9]. Some problematic ore sources can be used by this method and the firing operation can be done at standard or expected temperatures.

In this study two iron oxide sources, magnetite and hematite ore concentrates were used in pelletizing tests. The aim of the present study is to produce the iron ore pellets with hematite and magnetite concentrate mix and determine the mix pellet properties. The tests were conducted to investigate the influence of mixing ratios on the below-listed pellet properties.
- Drop number, compressive strength tests for green pellets,
- Drop number, compressive strength tests for dry pellets,
- Compressive strength, porosity, reducibility for fired pellets.

2. Materials and Experimental Procedures

2.1. Materials

Magnetite and hematite ore concentrates were used as iron oxide sources. Both magnetite and hematite samples used to produce mix pellets in this study were taken from Belagal Range, Bellari District, Karnataka State, India. Bentonite was used as a binder for pelletizing studies. A non-coking coal from Jharkhand, India was used as a carbon source during reducibility tests of fired mix pellets. Representative samples were taken from each ore samples with standard coning and quartering, riffing methods. The elemental analyses of both magnetite and hematite representative samples were carried out and the results are shown in Table I. The proximate analysis of non-coking coal used as a reductant was carried out according to standard methods [10-12] and the results are shown in Table II.

<table>
<thead>
<tr>
<th>Component, wt%</th>
<th>Magnetite</th>
<th>Hematite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>68.03</td>
<td>65.54</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1.87</td>
<td>1.53</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.31</td>
<td>1.23</td>
</tr>
<tr>
<td>MgO</td>
<td>0.21</td>
<td>0.20</td>
</tr>
<tr>
<td>CaO</td>
<td>0.21</td>
<td>0.10</td>
</tr>
<tr>
<td>MnO</td>
<td>0.07</td>
<td>0.11</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.09</td>
<td>0.05</td>
</tr>
<tr>
<td>LOI</td>
<td>2.48</td>
<td>2.30</td>
</tr>
</tbody>
</table>
Representative magnetite and hematite concentrate samples were separately ground in a laboratory scale ball mill to get a suitable fineness. The ground magnetite sample was 100 % passing 106 μm size with $D_{80}$ 54 μm and the ground hematite sample was 100 % passing 106 μm with $D_{80}$ 38 μm. The non-cooking coal sample was ground to 100 % passing 74 μm.

2.2. Pelletizing procedure and tests

Green pellets were produced with the laboratory-scale study. Wet, dry, and fired pellet properties were determined; porosity and reducibility tests were carried out on the produced mix pellets.

2.2.1. Preparation of magnetite and hematite mix

A set of trials has been designed with four types of mixtures in order to know the properties of pellets produced with hematite and magnetite concentrates. The mixing ratios of magnetite and hematite used in the pellet feed to produce mix pellets are shown in Table III.

Table III The mixing ratios of magnetite and hematite used to produce mix pellets

<table>
<thead>
<tr>
<th>Mixing Ratio Codes</th>
<th>Magnetite Concentrate (%)</th>
<th>Hematite Concentrate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10M</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>7M3H</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>6M4H</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>5M5H</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

2.2.2. Flow sheet of pelletizing experiments

Laboratory pelletizing procedure and pellet properties testing methods explained in the previous studies were followed [13-16]. The flow sheet of the laboratory pelletizing procedure and the tests carried out are shown in Fig. 1.

A laboratory mixer was used to mix the magnetite, hematite, bentonite, and water. The bentonite binder dosages and moisture content were calculated as a percentage by weight of dry iron ore concentrates. The feed materials were mixed in the mixer for 5min. Mixed material was screened through 850 μm screen before balling. A laboratory scale 45° inclined balling disc with 600mm diameter, 120mm height, rotating at 30 rpm was used to produce green pellets (Fig. 2).

Premixed samples as shown in Table III were fed into the balling disc to form the green pellet seeds. Water sprayed on the rolling bed of the fed material. Fresh feed was added over the pellet seeds to enlarge them into sufficient diameter size. Pellets were periodically removed from the balling disc and were slightly screened to collect the -16+9 mm diameter size. The balling disc conditions were kept constant throughout all the pelletizing experiments.
2.2.3. Mechanical tests of pellets

The mechanical testing methods of pellets explained in the literature were applied [1, 5, 17-20]. After completion of the green pellet production, a portion of produced green pellets was subjected to green pellet drop test and compressive strength test. Green pellet drop test was carried out by repeatedly dropping a single green pellet from a height of 46 cm till the first crack was observed on the green pellet. The average number of drops for a certain number of green pellets gives the drop number. The remaining pellets were dried in a laboratory oven at 105° for overnight to obtain dry pellets for further tests. A portion of the dry pellets was subjected to a dry pellet drop test and compressive strength test. The remaining dry pellets were used in the firing. After firing of pellets the fired pellet
compressive strength tests were carried out. About 12 mm diameter pellets are selected for tests and at least 15 pcs pellets were used to determine the average value for each test.

2.2.4. Firing, porosity and reducibility tests

After the mechanical testing of green and dry pellets, the remaining dry pellets were fired at 1200 °C for 30 minutes in a laboratory muffle furnace with a heating chamber of 150*150*200 mm to produce fired pellets. Fired pellet compressive strengths were determined on those pellets according to related ASTM standard [21]. The porosity of the fired pellets was calculated using the following equation:

\[
\text{Porosity} \, \% = \left( \frac{\text{True density} - \text{Apparent density}}{\text{True density}} \right) \times 100
\]

(1)

The true density of the powder of fired pellets was measured by liquid pycnometer method and the apparent density was determined by the Archimedes method [22]. A portion of the fired pellets was used in reducibility tests. Reducibility tests were carried out in a laboratory muffle furnace as explained in [23] to study the effect of reduction behavior of mix pellets. The details of the laboratory reducibility test are shown in Fig. 3 and Fig. 4. Reducibility tests were conducted using a cylindrical steel reactor of 25 mm diameter and 65 mm length Fig. 5. Steel reactor including non-cooking coal and fired pellets were put in muffle furnace which is preset to 1000 °C.

Fig. 3. The flowsheet of fired pellet reducibility test.
Fig. 4. Reducibility test furnace setup. 1. Heating elements, 2. Steel reactor, 3. Reductant powder (non-coking coal), 4. Thermocouple, 5. Pellets located at the center, 6. Fire brick powder.

Fig. 5. Cylindrical steel reactor used for reducibility test.

The fired pellets were kept in the muffle furnace for different residence time (10, 20, 30, 40, 50 and 60 min) in order to determine reducibility percentages. Before and after reducibility test the weights of the pellet samples were determined. The percent of reducibility was calculated with the following equation. A similar reduction calculation was carried out by researchers for ilmenite ore [17, 24].

\[
R\% = \left( \frac{W_{Pf} - W_{Pr}}{WO_{l}} \right) \cdot 100
\]

(2)

where:
- \( R\% \) : Reducibility value of fired pellets.
- \( W_{Pf} \) : Weight of pellets before reducibility test.
- \( W_{Pr} \) : Weight of pellets after reducibility test.
- \( WO_{l} \) : Weight of oxygen associated with iron in the pellet sample before reducibility test.
3. Results and Discussion

3.1. Mechanical strengths of green pellets

Drop number and compressive strengths are two mechanical strength indicators for green pellets. The acceptable minimum drop number of green pellets is 4 from a height of 46 cm according to [3]. The compressive strength of industrial green pellets lies generally between 1.0 and 2.0 kg/pellet [16, 25]. Fig. 6 shows the drop numbers and compressive strengths of green pellets as their green mechanical strengths.

![Graph showing mechanical strengths of green pellets](image)

**Fig. 6.** Mechanical strengths of green pellet.

It is clear from Fig. 6 that, drop numbers and compressive strengths of green pellets decreased with the addition of hematite in the pellet mixes. This may arise from the particle size distribution differences of both iron oxides and interactions of the particles with water and binder. The strength of green pellets mainly depends on the capillary negative pressure of the liquid saturated pores and surfaces, which lays between iron ore particles [3, 26]. The linear relationship between the green pellet mechanical strength and the saturation degree of the particles with water is explained by researchers [27-29]. Results showed that, as the hematite content in the mix pellets increased, the green pellet drop number decreased from 6.5 to 5.2 and the compressive strength of green pellets decreased from 1.51 to 1.28 kg/pellet. These values of green mix pellets are acceptable when the above-mentioned limits are considered.

3.2. Mechanical strengths of dry pellets

Dry pellets in the travelling grate are subjected to pressure from hot gases airflow and the load from pellet bed itself. Therefore, dry pellets should have a minimum strength and this strength should be greater than 1.8 kg/pellet [16, 25, 30, 31]. For the mechanical strengths of dry pellets, drop number and compressive strengths of dry pellets were determined. Green pellets were dried for overnight. Fig. 7 shows the drop numbers and compressive strengths of dry pellets as their dry mechanical strengths. From Fig. 7 it is clear that drop numbers and compressive strengths of dry pellets decreased with the addition of hematite in the pellet mixes. The pellets produced with the only magnetite had 8.4 drop number and this decreased to 7 for the pellets produced with 40% addition of hematite. On the other hand, dry compressive strengths were found to decrease from 2.50 to 1.60 kg/pellet when the hematite
content in the mix pellets increased. These compressive strengths were evaluated sufficient when the above-mentioned acceptable limits are considered.

![Graph showing compressive strengths of dry pellets.](image)

**Fig. 7.** Mechanical strengths of dry pellets.

### 3.3. Properties of fired pellets

#### 3.3.1. Mechanical strengths of fired pellets

Compressive strength is the most important mechanical strength indicator for fired pellets against the load during handling and use in the blast furnace. The acceptable minimum fired pellet compressive strength should be at least 204 kg/pellet and 250 kg/pellet according to [3, 25], respectively. Pellet firing was carried out in a laboratory muffle furnace with a constant temperature of 1200 °C for 30 minutes. Fig. 8 shows the compressive strengths of fired pellets.

![Graph showing compressive strengths of fired pellets.](image)

**Fig. 8.** Compressive strengths of fired pellets.

Fig. 8 shows that with the increase in hematite content in pellet mixes, the compressive strength of fired pellets decreased from 380 to 230 kg/pellet. This is due to a well-known fact that particles of magnetite are rapidly oxidized into hematite grains during the firing stage. The new-formed hematite grain surfaces have greater migrating capability
than those on the original hematite grains, and consequently, the hematite crystallites are easily formed between particles providing strength to the pellets. The strengthening mechanism of pellets at sufficiently high temperature is explained by [5] and most probably due to two reasons: the first is the oxidation of magnetite to hematite, and the second is the crystal growth and recrystallization of magnetite grains. The compressive strength values found here for the fired pellets are in the acceptable industrial limits.

3.3.2. The porosity of fired pellets

Porosity is a significant property of pellets and plays an important role during balling, induration and reducibility stages [18]. Certain porosity is necessary for problem-free reduction in the industry and should be 22-30 % for fired pellets [25]. The porosity of fired pellets was determined according to Equation 1. The porosities of the fired pellets were given in Fig. 9. The maximum porosity, 27.2 %, was found for the pellets produced with only magnetite. The porosity decreased when the percentage of hematite in the pellet mixes increased and it was determined as 26 % for pellets produced with 40 % of hematite in the mix pellets. The reason for the decrease of porosity may be attributed to the presence of relatively finer particles of hematite i.e $D_{50}$ was 38 microns which occupy the porous sites and make the pellet more compact which is also observed by researchers [31]. Those porosity values found here are acceptable when compared to the porosity values of industrially produced pellets.

![Fig. 9. The porosity of fired pellets.](image)

3.3.3. Reducibility of mixed pellets

Reducibility property of fired pellets is important during metal iron production in the blast furnace. The laboratory reducibility percentage of pellets is expected to be greater than 60 % according to many reducibility tests such as Linder, Gakushin, Chiba, VDE. The reducibility tests were carried out in laboratory muffle furnace at 1000º for varying time from 10 to 60 min. The test procedure explained by Gupta 2010 [20] was followed as shown in Fig. 3. The reducibility percentages of mix pellets with respect to reduction time are shown in Fig. 10. It was observed that the reducibility of mix pellets had almost the same trend and was faster up to 40 min reduction time. The pellets produced with only magnetite reached the 60 % reducibility after 30 min; the other mix pellets reached this reducibility level after 40 min. Those reducibility behaviors are evaluated sufficient when compared to the reducibility limit given by different reducibility tests.
4. Conclusion

The followings are the results when magnetite and hematite are used together to produce iron ore pellets:

- As the hematite content in the mix pellets increases, the drop number of green pellets decreases from 6.5 to 5.2, the compressive strength of green pellets decreases from 1.51 to 1.28 kg/pellet and the compressive strength of dry pellets decreases from 2.50 to 1.60 kg/pellet.
- The compressive strength of fired pellets decreased from 380 to 230 kg/pellet with the increase in hematite content in the pellet mixes.
- The porosity of fired pellets decreased from 27.2 % to 25 % when the percentage of hematite in the mix pellets increased.
- The pellets produced only with magnetite reached to the 60 % reducibility after 30 min; the other mix pellets reached this reducibility level after 40 min.

As a result, the pelletizing of hematite and magnetite mix pellets is possible to produce sufficiently good quality pellets in terms of wet, dry and fired mechanical strengths. The porosity and reducibility values of mix pellets are also found to be sufficient to use in the blast furnace.

5. References
Садржај: У овом раду испитивана је употреба руда магнетита и хематита за добијање пелета руде гвожђа. Тестови компактирања су вршени са претходно помешаним рудама хематита и магнетита. Утврђен је пад броја и чврстоћа за почетне и печене узорке; порозност, чврстоћа и тестови редукције су рађени да се одреди утицај мешања руда са различитим односима на својства добијеног материјала. Експериментални резултати су показали да како је повећан уdeo хематита у смеши, тако је за почетне узорке број пао са 6,5 на 5,2, чврстоћа је пала са 1,51 на 1.28 килограма/пелету а тврдоћа са 2,50 на 1,60 килограма/пелету. Утврђено је да је за печене узорке чврстоћа пала са 380 на 230 килограма по пелету када је удо хематита у смеши повећан. Редукција је имала исти тренд. Резултати су показали да је употребом хематита и магнетита могуће добити узорке доброг квалитета у погледу механичке чврстоће мокрог, сувог и печеног материјала. Порозност и вредности редукције су такође адекватни за употребу у високим пећима. Кључне речи: руде фвожђа, магнетит, хематит, пелет, чврстоћа.

© 2018 Authors. Published by the International Institute for the Science of Sintering. This article is an open access article distributed under the terms and conditions of the Creative Commons — Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0/).