The Influence of Different Iron Ores Mixtures Composition on the Quality of Sinter

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Sinters were produced in the pilot plant using four different ore mixtures with varying proportions of iron ores, fluxes and coke. All the resulting sinters were characterised by chemical and granulometric analysis, degradation testing during reduction in the blast furnace (RDI test), cold resistance testing (Tumbler test), reducibility testing, determination of softening and melting temperatures, and determination of the sinter structure by electron microscopy. The obtained result allow for the establishment of better operation conditions to manufacture sinters.

KEY WORDS: sintering; quality of sinter; ore mixtures; iron ores; blast furnace.

1. Introduction

The sintering process is used to agglomerate a mixture of iron ores, fluxes and coke with a particle size of <8 mm so that the resulting sinter, with a screened size of between 12 and 35 mm, can withstand pressure and temperature conditions when loaded into the blast furnace.

The first step in the sintering process is to granulate the ore mixture, which consists of its homogenisation in a rotating drum for several minutes with the addition of 6–8% water.

The resulting granules are loaded onto the sintering grate where they are heated to between 1 250–1 350°C in order to achieve their partial melting and produce a semimolten material which, in subsequent cooling, crystallises into various mineral phases with different chemical and morphological compositions, mainly hematite, magnetite, ferrites and gangue composed mostly of calcium silicates.1,2) The process energy is supplied by combustion of the coke.

The factors that affect sintering and the quality of the sinter produced include: a) the size and composition of the granules; b) the size, composition and relative properties of the ore mixture components (iron ores, fluxes and coke); c) the mineralogical composition of the ores; and d) the thermal profile of the process.

The aim of the present research work is to optimise sintering conditions in order to produce better quality sinter. For this purpose, ores and fluxes have been extensively characterised. Information has been obtained to sintering performance of the ore mixtures. The information will be useful to the operators of the sinter plants to improve the sintering process.

2. Manufacturing of Sinter in the Pilot Plant

The steelmaking company ARCELOR-MIT TAL has two sintering plants with effective sintering areas of 200 m² and 281 m² in its Gijón works (Spain), producing 5.0–5.5 million tons of sinter each year. This sinter is used as burden material for the two blast furnaces operating at Gijón, each with a hearth diameter of 11.3 m and a working volume of 2 349 m³, which produce 3.8–4.3 million tons of pig iron each year.

In the present joint research project, ARCELOR-MITTAL/CENIM have manufactured a series of sinters in a pilot plant that CENIM has installed in ARCELOR-MITTAL’s Gijón works. The pilot plant has a sintering pot with a cross-section of 40×40 cm and a height of 60 cm and is equipped with a suction circuit capable of creating depressions of more than 1 470 mPa, a propane ignition system, and a system for measuring the inflowing gas volume and outflowing gas temperature.

2.1. Ores Used

Iron ores, fluxes and cokes used at the ARCELOR-MITTAL sintering plants at Gijón, were used in this study.

Table 1 shows the chemical analysis of the iron ores. All present a high iron content, from the ‘Mount Wright’ and ‘MBR’ concentrates, with 66–67% iron, to the Spanish ‘Andaluza’ ore, with 53.7% iron. All the iron ores are of an hematitic nature.

Limestone and dunite are used as fluxes. Table 2 shows the chemical analysis of the fluxes. A very thorough characterisation of these ores and fluxes has been elsewhere.3)

The coke was analysed by the National Coal Institute (INCAR) at Oviedo (Spain) with the following results: 83.50% carbon, 12.00% ashes, 2.20% volatile matter, 0.95% moisture, 0.25% hydrogen, 0.96% nitrogen, 0.10% sulphur, and a CRI reactivity index of 60.46.

2.2. Composition of Ore Mixtures

Table 3 indicates the percentages of each component in the ore mixtures used to manufacture the sinters.

2.2.1. Chemical Analysis

Table 4 shows the results of chemical analysis of the ore mixtures. The iron content is high in mixtures 1 and 2, in
line with the ores present, but is three percentage points lower in mixtures 3 and 4 due to the inclusion of ‘Goa Silicioso’ ore with its lower total iron content. The ferrous content between 3.1 and 4.8% can be considered as low as correspond to the hematitic nature of the iron ores that make up part of the mixtures. The alkalis content is low.

2.2.2. Granulometric Analysis
Granulometric analysis has been performed using a ROT-TAP unit, which combines reciprocating eccentric rotary screening with a percussion system on the screen column. Figure 1 displays the granulometric curve for ore mixture 1, with an average particle size of 1.69 mm. Table 5 indicates the average particle size of the ore mixtures.

2.2.3. Granulation Fitness
The ore mixtures are subjected to granulation treatment prior to sintering in order to increase the average size of the very fine grained ores, with the aim of improving their dynamic behaviour during sintering.

Granulation treatment is of basic importance in iron ore sintering, because good sinter bed permeability to a large extent determines the sintering rate and thus the plant’s productivity.

Granulation fitness testing of each iron ore and each ore mixture has been carried out following the SAFE (Size Analysis on Frozen Elements) standard procedure established by Centro Sviluppo Materiali (CSM) of Italy.4) Figure 2 shows the granulometry curve of ore mixture 1 before and after the SAFE test.

Table 1. Chemical analysis of iron ores (wt%).

<table>
<thead>
<tr>
<th></th>
<th>Andaluzo</th>
<th>CVRD-Carajas</th>
<th>CVRD-Tubarao</th>
<th>San Isidro</th>
<th>Mount Wright</th>
<th>SNIM-Tazadit</th>
<th>SNIM-Brasil</th>
<th>Goa Silicioso</th>
<th>Hamersly</th>
<th>MBR Brasil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe total</td>
<td>53.71</td>
<td>65.54</td>
<td>61.21</td>
<td>65.50</td>
<td>66.25</td>
<td>62.98</td>
<td>61.24</td>
<td>56.32</td>
<td>62.57</td>
<td>62.17</td>
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<tr>
<td>Fe++</td>
<td>0.00</td>
<td>0.27</td>
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<td>0.61</td>
<td>1.61</td>
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<td>0.86</td>
<td>4.83</td>
<td>3.04</td>
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<tr>
<td>CaO</td>
<td>4.12</td>
<td>0.10</td>
<td>0.04</td>
<td>0.04</td>
<td>0.13</td>
<td>0.11</td>
<td>0.12</td>
<td>0.07</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td>MgO</td>
<td>0.64</td>
<td>0.03</td>
<td>0.02</td>
<td>0.03</td>
<td>0.08</td>
<td>0.02</td>
<td>0.08</td>
<td>0.09</td>
<td>0.02</td>
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<td>0.90</td>
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<td>1.35</td>
<td>1.44</td>
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<td>8.82</td>
<td>13.43</td>
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<td>0.10</td>
<td>0.05</td>
<td>0.04</td>
<td>0.02</td>
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<td>1.06</td>
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<tr>
<td>Na₂O</td>
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<td>0.011</td>
<td>0.006</td>
<td>0.011</td>
<td>0.017</td>
<td>0.024</td>
<td>0.026</td>
<td>0.013</td>
<td>0.034</td>
<td>0.024</td>
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<td>0.007</td>
<td>0.012</td>
<td>0.011</td>
<td>0.015</td>
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<td>0.027</td>
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<td>0.015</td>
<td>0.006</td>
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<td>0.007</td>
<td>0.008</td>
<td>0.055</td>
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<td>Zn</td>
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<td>0.007</td>
<td>0.011</td>
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<td>P₂O₅</td>
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<td>0.160</td>
<td>0.087</td>
<td>0.069</td>
<td>0.057</td>
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<td>0.064</td>
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<td>Cl</td>
<td>10.16</td>
<td>6.18</td>
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<td>4.75</td>
<td>1.54</td>
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<td>1.42</td>
<td>3.60</td>
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<td></td>
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Table 2. Chemical analysis of fluxes (wt%).

<table>
<thead>
<tr>
<th></th>
<th>Limestone</th>
<th>Dunite</th>
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<td>Fe total</td>
<td>0.13</td>
<td>5.83</td>
</tr>
<tr>
<td>CaO</td>
<td>55.44</td>
<td>2.32</td>
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<tr>
<td>MgO</td>
<td>0.51</td>
<td>35.51</td>
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<tr>
<td>Al₂O₃</td>
<td>0.19</td>
<td>2.82</td>
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<tr>
<td>SiO₂</td>
<td>0.42</td>
<td>39.92</td>
</tr>
<tr>
<td>MnO</td>
<td>-</td>
<td>0.12</td>
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<tr>
<td>Cl</td>
<td>44.97</td>
<td>8.27</td>
</tr>
<tr>
<td>Cl, calcining losses</td>
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<td></td>
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Table 3. Composition of ore mixtures (wt%).

<table>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tr>
<td>Andaluzo</td>
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<td>10.3</td>
<td>10.3</td>
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<td>CVRD-Carajas</td>
<td>25.0</td>
<td>27.8</td>
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<td>24.1</td>
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<tr>
<td>CVRD-Tubarao</td>
<td>-</td>
<td>7.2</td>
<td></td>
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<td>San Isidro</td>
<td>20.0</td>
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<td>Mount Wright</td>
<td>8.0</td>
<td>-</td>
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<td>SNIM-Tazadit</td>
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<td>10.3</td>
<td>-</td>
<td>-</td>
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<td>SNIM-Brasil</td>
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<td>6.2</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Goa Silicioso</td>
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<td>-</td>
<td>10.3</td>
<td>10.3</td>
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<tr>
<td>Nimco</td>
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<td>-</td>
<td>-</td>
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<td>Hamersly</td>
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<td>12.4</td>
<td>-</td>
<td>10.3</td>
</tr>
<tr>
<td>MBR Brasil</td>
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<td>10.3</td>
<td>20.6</td>
<td>10.3</td>
</tr>
<tr>
<td>Limestone</td>
<td>-</td>
<td>-</td>
<td>7.9</td>
<td>6.1</td>
</tr>
<tr>
<td>LD sludge</td>
<td>2.6</td>
<td>2.6</td>
<td>2.1</td>
<td>2.1</td>
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<tr>
<td>LD slag</td>
<td>3.0</td>
<td>3.0</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Scrap iron</td>
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<td>1.3</td>
<td>2.1</td>
<td>2.1</td>
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<tr>
<td>Throat dust</td>
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<td>0.7</td>
<td>0.6</td>
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<tr>
<td>Sinter return fines</td>
<td>7.9</td>
<td>7.9</td>
<td>8.1</td>
<td>8.1</td>
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</table>

Table 4. Chemical analysis of ore mixtures (wt%).

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<th>2</th>
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<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe total</td>
<td>58.64</td>
<td>62.28</td>
<td>56.01</td>
<td>55.62</td>
</tr>
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<td>Fe++</td>
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<td>3.06</td>
</tr>
<tr>
<td>CaO</td>
<td>3.98</td>
<td>4.57</td>
<td>6.58</td>
<td>6.64</td>
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<tr>
<td>MgO</td>
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<td>0.44</td>
<td>0.43</td>
<td>0.38</td>
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<tr>
<td>Al₂O₃</td>
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<tr>
<td>SiO₂</td>
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<td>4.38</td>
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<tr>
<td>MnO</td>
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<td>Na₂O</td>
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<td>0.015</td>
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<td>0.054</td>
<td>0.038</td>
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<td>Pb</td>
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<td>0.015</td>
<td>0.008</td>
<td>0.005</td>
</tr>
<tr>
<td>Zn</td>
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<td>0.044</td>
<td>0.036</td>
<td>0.036</td>
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<tr>
<td>S</td>
<td>0.026</td>
<td>0.023</td>
<td>0.030</td>
<td>0.028</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.073</td>
<td>0.082</td>
<td>0.071</td>
<td>0.121</td>
</tr>
<tr>
<td>Cl</td>
<td>5.49</td>
<td>4.41</td>
<td>7.63</td>
<td>7.91</td>
</tr>
</tbody>
</table>

2.2.3. Granulation Fitness
The ore mixtures are subjected to granulation treatment prior to sintering in order to increase the average size of the very fine grained ores, with the aim of improving their dynamic behaviour during sintering.

The granulation treatment is of basic importance in iron ore sintering, because good sinter bed permeability to a large extent determines the sintering rate and thus the plant’s productivity.

Granulation fitness testing of each iron ore and each ore mixture has been carried out following the SAFE (Size Analysis on Frozen Elements) standard procedure established by Centro Sviluppo Materiali (CSM) of Italy. Fig. 2 shows the granulometry curve of ore mixture 1 before and after the SAFE test. Table 5 indicates the average particle size of the ore mix-
tures after undergoing the SAFE test. All the mixtures present good granulation fitness.

2.2.4. Reducibility

A reducibility test has been performed at 900°C following the ISO standard for sinters, adapted for ore mixtures of the 3.3–2.0 mm fraction. The results are displayed in Table 5. The $R_{60}$ value ranges between 50–56% and may be considered good.

2.2.5. Softening and Melting Temperatures

The test to determine softening and melting temperatures of the ore mixtures has been carried out using a LECO AF-600 unit, with an oven that reaches a maximum temperature of 1650°C, in which the following parameters have been fixed with the help of a computer: ASTM standard with inert atmosphere (N2), programme start and end temperatures, gas flow and heating rate.

Table 5 lists the representative points for mixtures 1 and 2. The melting temperatures are high and the difference between the softening and melting temperatures is small, which is beneficial for sinter behaviour in the cohesive zone of the blast furnace.

2.2.6. Thermoanalysis

The thermal behaviour of the ore mixtures has been studied with a SETARAM thermobalance, which provides a graphic readout of the variations in temperature, weight, weight variation rate and enthalpy (thermogravimetric analysis TG, differential thermogravimetric analysis DTG, and differential thermal analysis DTA).

Figures 3(a) and 3(b) show the thermoanalysis of ore mixture 1, performed in an inert atmosphere (N2). The endothermal effect recorded between 250–400°C, with a peak at 320°C, leads to an important mass loss due to the release of goethite constitution water, according to the reaction:

$$\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O} \rightarrow \text{Fe}_2\text{O}_3 + \text{H}_2\text{O},$$

which represents 1.8%. The second important endothermal effect is recorded between 600–860°C, with a mass loss of 2.3% (Fig. 3(b)). This effect and the corresponding mass loss represent the loss of CO2 produced by the decomposition of calcite, magnesite and dolomite present in this type of iron ore samples.

The small mass loss recorded on the TG curve between 400–600°C and between 800–1000°C, without a precise effect on the DTA curve, may be due to the release of constitution water from some type of hydrated silico–aluminate present in the ore mixture (Fig. 3(a)). Such silicoaluminates may include kaolinite, gibbsite, pyrophilite and ferrihalloysite. Due to the small amount present in these compounds, they may be considered minor elements which, together with silicon, form the mineral gangue.

Ore mixtures 2, 3 and 4 present similar thermal behaviour to mixture 1.

2.3. Manufacturing of Sinters

Four ore mixtures have been used to manufacture a series of sinters in the pilot plant (Tables 3, 4). In the manufacturing process several of the operating parameters have been kept constant, in accordance with industrial practice, namely:

(i) working depression: 1470 mPa
(ii) calorific contribution during ignition: 12480 kJ
(iii) ignition time: 1.5 min
(iv) overgrate height: 3 cm
while other parameters have been variable:

(i) bed height: 50 and 60 cm
(ii) return fines: 25 and 35%
(iii) basicity index (CaO/SiO2): 1.6 and 1.9

For ore mixes 1 and 2, each sinter is manufactured in duplicate. In other words, sinter S1 is made first and then sinter S2 is made in the same operating conditions. The data in this study always refers to sinter S2, and not the average of S1 and S2. The same then goes for sinters S3 and S4, which are consecutively manufactured in other operating conditions, and so on up to sinters S31 and S32.

Sinter S1 is manufactured with an estimated coke content added to the ore mix. On the basis of the test data, a new coke percentage is then set for the manufacturing of sinter S2, in order to fulfil the balance:

$$B = \frac{\text{return fines generated}}{\text{return fines returned}}$$

and $0.95 \leq B \leq 1.05$

3. Results

Tables 6 and 7 show the sinter process characteristics and results obtained using ore mixtures 1 and 2, respectively.

The best sinters from the viewpoint of strength, with mixtures 1 and 2, were achieved for operating conditions of 60 cm bed height, 25% return fines and 1.9 basicity (sinters S12 and S28, respectively). The Tumbler index was better...
than 72 in the sinters produced in these operating condi-
tions (Table 10). It is supposed that increasing the basicity 
from 1.6 to 1.9 leads to a sinter structure with a more het-
erogeneous texture, (different phases mixed together), con-
ferring greater strength. These operating conditions afford a 
good
R60 reduction grade for mixtures 1 and 2 (Table 10).

The best RDI index (lowest values) is found for the series 
of 8 sinters manufactured with ore mix 1, where the mean 
value, calculated from the results shown in Table 10, is 
37.5%, compared to a mean value of 44.8% for the 8 sin-
ters with mixture 2.

However, in the case of sinters S12 and S28 the differ-
ence in the RDI index is small (Table 11).

By comparing the results obtained with ore mixtures 1 
and 2 it was possible to predict what variables would allow 
better quality sinters to be manufactured with ore mixtures 
3 and 4 (Table 8). The operating parameters for these mixes are:
(i) bed height: 60 cm
(ii) return fines: 25%
(iii) basicity: 1.9

Tables 6–8 show the operating variables and the charac-
teristics of the manufactured sinters. The total ore weight loaded into the sintering pot in-
creases with the bed height from 170 to 210 kg.

### 3.1. Average Sinter Size

Tables 6–8 indicate the weight of the different granulo-
metric fractions of each sinter, whose average size varies 
between 30–42 mm.

### 3.2. Coke Consumption

The coke consumption is a parameter to be taken into ac-
count due to its repercussion on the price of hot metal, 
since the number of tons consumed in ironmaking makes 
this a very important factor in terms of profitability.

Tables 6–8 show that coke consumption varies between 
38 and 45 kg/t sinter.
For ore mixtures 1 and 2 (Tables 6 and 7) it is seen that an increase in basicity leads to a decrease in coke consumption. Consumption rates are further lowered when working with returns of 35% rather than 25%.

3.3. Productivity

Productivity improvement is a primordial objective of sintering plants that need to meet the needs of blast furnaces without affecting sinter quality. Tables 6–8 show that the productivity remains between 34–42 t/m²/24 h.

For ore mixtures 1 and 2 (Tables 6 and 7) it is seen that productivity rises for some sinters when the basicity is increased from 1.6 to 1.9.

3.4. Chemical Analysis of Sinters

Table 9 shows the results of chemical analysis of the sinters. The total iron content is high (55–58%) and the FeO content is low (3.2–5.7%), which indicates the hematitic nature of the iron oxide. The harmful elements content, such as sulphur, phosphorus and alkalis, is low, indicating that the sinters are suitable for use in the blast furnace.

3.5. RDI Test

Sinter degradation during reduction at low temperature is determined by the RDI test (reduction degradation index). The RDI of the manufactured sinters ranges between 33 and 49 (Table 10). Low values are desirable for this index.

Degradation is to a certain extent originated by the transformation that takes place during the reduction of hematite to magnetite, accompanied by an increase in volume that gives rise to the presence of structural stresses within the sinter.

3.6. Tumbler Test

The cold strength of the sinter is determined by the Tumbler Test.
bler test\(^9\) and depends on the strength of each individual ore component, the strength of the bonding matrix component and the ore composition.

Table 10 shows that the sinters present good Tumbler index results, in some cases greater than 70%.

### 3.7. Reducibility Test

Reducibility of the sinter is determined by the ISO test performed at 900°C.\(^5\) Research has been carried out to raise the sinter’s reducibility, in order to achieve greater stability and a saving in coke consumption in the blast furnace.

Table 10 shows that the sinters present good reduction behaviour, with values in the 72–86% range.

### 3.8. Softening and Melting Temperature Test

Softening and melting temperatures have been determined for each manufactured sinter using a LECO AF-600 unit, following the practice noted in point Sec. 2.2.5.

The sinters present melting temperatures in the 1 338–1 370°C range. The differences between melting and softening temperatures are small (<35°C), and the cohesive zone that is achieved in the blast furnace will therefore be narrow, assuring the good operation of the furnace (Table 10).

### 3.9. Characterisation of Structure by Electron Microscopy

The sinters have been studied using a JEOL scanning electron microscope with a microprobe (model JSM-840) connected to a LINK AN-1000 analyser.

The particles of each sinter sample were analysed. Photos were taken showing general and close-up views of the samples, and a number of particles were subjected to spe-
specific quantitative analysis.

Figure 4 shows a randomly-chosen group of particles from a sinter S16 sample.

Figure 5 shows particle P38. This particle is highly heterogeneous (different phases mixed together), as all the sinter particles are in general. An area of the centre of the particle is analysed, with the presence of primary hematite (unmelted) surrounded by a ferrite lattice. Table 12 shows the results of chemical analysis of the identified phases. The oxygen content is calculated by subtracting from 100 the sum of the other elements.

Figure 6 shows a close-up of an area of the centre of particle P39, with the presence of precipitated magnetite, a ferrite lattice and gangue associated with abundant porosity.

Figure 7 shows a close-up of an area of the centre of particle P40, with the presence of the optimised sinter structure, formed by primary hematite surrounded by an acicular ferrite lattice. Particle P40, with the presence of the optimised sinter structure, formed by primary hematite surrounded by an acicular ferrite lattice.

Figure 8 corresponds to a group of particles from a sinter S24 sample.

Figure 9 shows a close-up of the upper part of particle P53, with the presence of a ferrite lattice, gangue and abundant porosity. Figure 10 shows a close-up of the lower part of particle P53, with a similar structure to the upper part.

Figure 11 shows a close-up of an area of the centre of particle P54, with the presence of the optimised sinter structure, formed by a primary hematite nucleus surrounded by an acicular ferrite lattice.

Figure 12 shows a close-up of an area of particle P17, located in a sinter S8 sample, where it is possible to see the presence of highly mixed phases of precipitated hematite, precipitated magnetite, ferrite lattice and gangue.

Table 12. Point chemical analysis of the identified phases of particles of sinter (wt%).

<table>
<thead>
<tr>
<th>Sinter</th>
<th>Particle</th>
<th>Phase</th>
<th>Fe</th>
<th>Ca</th>
<th>Al</th>
<th>Si</th>
<th>Mn</th>
<th>Mg</th>
<th>Ti</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>S16</td>
<td>38</td>
<td>Hematite</td>
<td>69.64</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>30.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ferrite</td>
<td>56.43</td>
<td>6.78</td>
<td>1.06</td>
<td>0.86</td>
<td>0.88</td>
<td>0.71</td>
<td>-</td>
<td>33.28</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>Magnetite</td>
<td>67.67</td>
<td>1.47</td>
<td>0.33</td>
<td>-</td>
<td>0.50</td>
<td>-</td>
<td>-</td>
<td>30.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ferrite</td>
<td>57.75</td>
<td>6.38</td>
<td>1.43</td>
<td>1.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>33.42</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>Hematite</td>
<td>68.51</td>
<td>-</td>
<td>0.19</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>31.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ferrite</td>
<td>56.14</td>
<td>5.87</td>
<td>0.61</td>
<td>0.94</td>
<td>1.20</td>
<td>1.19</td>
<td>-</td>
<td>34.05</td>
</tr>
<tr>
<td>S24</td>
<td>53J</td>
<td>Ferrite</td>
<td>46.92</td>
<td>7.87</td>
<td>0.58</td>
<td>1.85</td>
<td>0.21</td>
<td>0.17</td>
<td>-</td>
<td>42.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gangue</td>
<td>9.76</td>
<td>21.84</td>
<td>12.38</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.68</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>53L</td>
<td>Ferrite</td>
<td>44.25</td>
<td>8.29</td>
<td>0.72</td>
<td>2.19</td>
<td>0.78</td>
<td>0.28</td>
<td>-</td>
<td>43.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gangue</td>
<td>9.21</td>
<td>22.68</td>
<td>0.25</td>
<td>12.55</td>
<td>-</td>
<td>0.42</td>
<td>0.22</td>
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<tr>
<td></td>
<td>54</td>
<td>Hematite</td>
<td>59.07</td>
<td>0.29</td>
<td>0.20</td>
<td>0.21</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ferrite</td>
<td>45.11</td>
<td>7.99</td>
<td>0.69</td>
<td>2.29</td>
<td>0.66</td>
<td>0.32</td>
<td>-</td>
<td>42.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gangue</td>
<td>10.19</td>
<td>21.98</td>
<td>0.52</td>
<td>12.58</td>
<td>-</td>
<td>0.24</td>
<td>0.38</td>
<td>54.11</td>
</tr>
<tr>
<td>S8</td>
<td>17</td>
<td>Hematite</td>
<td>65.12</td>
<td>0.45</td>
<td>-</td>
<td>0.31</td>
<td>0.43</td>
<td>-</td>
<td>33.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnetite</td>
<td>67.71</td>
<td>0.20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>33.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ferrite</td>
<td>53.94</td>
<td>8.19</td>
<td>1.24</td>
<td>1.88</td>
<td>0.33</td>
<td>-</td>
<td>34.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gangue</td>
<td>13.06</td>
<td>22.71</td>
<td>1.33</td>
<td>12.78</td>
<td>-</td>
<td>0.69</td>
<td>0.50</td>
<td>48.93</td>
</tr>
</tbody>
</table>

Fig. 6. Close-up of P39 (×1100). M=magnetite; F=acicular and columnar ferrite lattice. Presence of gangue associated with abundant porosity.

Fig. 7. Close-up of P40 (×750). Optimised sinter structure, formed by a primary hematite nucleus surrounded by an acicular ferrite lattice. Presence of gangue (dark) and pores (black).

Fig. 8. Group of particles from sinter S24 (×40).

Fig. 9. Close-up of the upper part of P53 (×1100). Acicular and columnar ferrite lattice. F=ferrite lattice. Presence of gangue (dark grey) and pores (black).
4. Discussion

4.1. Sintering of Ore Mixtures

The ore mixes used in this study are characterised by a lower alumina content, a higher iron content, and a higher hematite content than those used outside Europe, and their sintering performance and sinter quality is considered good.

In Western Europe, 9 countries operate 36 sintering plants which in 2004 manufactured 100.8 million tons of sinter. Table 13 sets out figures on coke consumption, productivity, and the sinter composition and quality indices of European plants.10) Some plants use an anthracite and coke mixture as fuel, but this data is not included in the table.

In Asia, the ironmaking industry uses porous iron ores imported from Australia, which are of poorer quality than the dense hematitic ores that Europe and North America import from South America. For this reason, Asian ironmakers are striving to develop efficient technologies to produce strong sinter of high reducibility, like the sinter obtained using dense hematitic ores.

The Australian iron ores used in Asia include a high percentage of goethitic type Pisolite and Marra Mamba ores.11,12) A higher goethitic ore content in the sinter bed lowers the bed permeability and efficiency, and consequently reduces sinter productivity.13,14)

Marra Mamba ore has a high fines content which makes its granulation difficult. Goethitic ores also present a high combined water content, which reduces sinter strength due to the formation of a large number of cracks during sintering.15)

Since the 1980’s Japanese steel mills have paid great attention to the development of a suitable sintering technology to allow the use of ore mixes with a high goethitic ore content. Studies have been carried out on melt properties during assimilation, the behaviour of ore mixes with a high goethitic ore content, and the bed structure and permeability.16–20)

In Australia a basic research programme is under way at BHP Billiton’s Newcastle Technology Centre to explore the sintering properties of goethitic ores.

4.2. Sinter Chemical Composition

The manufactured sinters have a total Fe content of 55–58% and a low impurity content (Table 9). These sinters are suitable for processing in the blast furnace.

4.2.1. Sinter FeO

The sinters present a low FeO content (3–6%), which favours their reducibility.

The FeO content is an important control parameter in the sintering plant. When the chemical composition of an ore mixture is fixed, FeO can provide an indication of sintering conditions, in particular the coke rate.21)

It has been found that a 2% increase in the FeO content in the sinter lowers (improves) the RDI index by 8 points. However, when the FeO content increases, reducibility decreases. It is important to find an optimum FeO content in order to improve the RDI without altering other sinter properties.22)

4.2.2. Sinter Al2O3

The sinters have a low Al2O3 content (0.9–1.4%), which is beneficial.

The most harmful effect of alumina is to worsen the sinter’s RDI, which increases as the alumina content rises. Industrial experience with the blast furnace shows that a sinter within a 10–10.5% CaO content range an increase of 0.1% in the alumina content raises the RDI by 2 points.23)
4.2.4. Sinter CaO

The CaO content of the sinters is between 8.6–11.6%. Lime has been added to the ore mixtures in amounts calculated to produce sinters with basicities of 1.6 and 1.9.

4.2.5. Sinter SiO$_2$

The SiO$_2$ content of the sinters has been stabilised at 5–6%, despite the fact that the silica content of the ores used ranges from very low values (0.50%) to very high values (13.43%) (Table 1), because the silica content of the four ore mixtures varies within only a small range (3.46–4.83%) (Table 4).

4.3. RDI Index

The RDI index is a very important parameter that is used as a reference in all sintering work and serves to predict the sinter’s low temperature degradation behaviour in the lower part of the blast furnace stack.

The lowest (i.e. the best) RDI index is found for ore mixture 3 (Table 11), which may be related with the fact that this is the ore mixture with the lowest Al$_2$O$_3$ content (1.02% Al$_2$O$_3$). The series of sinters manufacture with mixture 2 has the highest RDI values (Table 10), which suggests that this may be inherent of the mixture composition used.

4.4. Tumbler Index

This test determines the size reduction due to impact and abrasion of the sinters during their handling, transport and in the blast furnace process.

Cold mechanical strength is directly related with the tendency to form fines during transportation and handling from the sinter machine to the blast furnace throat.

The tumbler index of sinter is dependent on critical flaws in the sinter and the propagation of these flaws through a sinter particle. Flaws are unavoidable because during the cooling cycle the minerals and phases precipitate out of the melt at different times, and changes in volume almost always accompany the transformations of a liquid into a solid.

The best sinters, from the point of view of strength, were achieved with mixtures 1 and 2, with a Tumbler index of more than 72% (Table 11).

4.5. Reducibility Index

In general for the sinters manufactured with ore mixtures 1 and 2 the reducibility increases when the basicity is raised from 1.6 to 1.9, because higher basicity means a higher ferrite content and consequently greater reducibility.

The greater reducibility of the sinters manufactured with mixture 2 compared to those manufactured with mixture 1 (Table 11) may be explained by the higher proportion of goethitic ores in mixture 2, which are more porous and thus more reducible, a fact that agrees with other research where it has been observed that the fine pores produced during reduction lead to an increase in porosity and thus greater reducibility.

The better reducibility of mixture 4 sinters than mixture 3 sinters may be explained similarly (Table 5 and Table 11).

4.6. Softening and Melting

The blast furnace operation is dependent upon the geometry and situation of the cohesive zone, which is delimited by the softening and melting isotherms. The cohesive zone is constituted by alternate layers of soft sinter and coke. The latter, known as “coke windows”, allow the reducing gas to penetrate through to the upper areas of the furnace.

It is therefore important for the cohesive zone to be as

Fig. 13. Relationship between the Al$_2$O$_3$ content and RDI values of sinters made with ore mixtures 3 and 4.
narrow as possible, in order to facilitate the penetration of the reducing gas, and as low as possible in the blast furnace, so that the furnace preparation zone above the cohesive zone is sufficiently large to allow the reduction of iron oxides. In order to fulfil both conditions, the ST and FT must be as high as possible and the difference between them must be minimal. In Table 10 it is observed that with the sinters manufactured, high temperatures have been achieved (1 310–1 370°C), with a minimal FT-FS difference (<35°C).

4.7. Sinter Structure
The structure and composition of a series of sinter samples has been studied by electron microscopy. The presence of primary hematite (non-assimilated or residual), secondary hematite (precipitated), primary magnetite (non-assimilated or residual), secondary magnetite (precipitated), and ferrites has been detected as majority phases, along with a smaller amount of gangue. There is sufficient porosity, with micropores in many cases, to favour the reducibility of the sinter. The structure is always highly heterogeneous with the phases considerably mixed up.

The analysed ferrites are SFCA type (silicoferrites of calcium and aluminium) and form by solid–liquid reaction between the hematite and the Fe2O3·CaO melt, with the subsequent assimilation of SiO2 and Al2O3 in this melt. The chemical formula of SFCA can be written as 5CaO·2SiO2·9(Fe, Al)2O3·39.40. These ferrites are beneficial for the sinter structure because they improve its strength and reducibility.

The presence of acicular ferrites (of a size <10 μm), which are considered to offer optimum conditions, is detected in many cases. The iron content of the ferrites is greater for the sinters with 1.9 basicity than those with 1.6 basicity.

In some sinters the optimum structure for reducibility has been detected, formed by a nucleus of primary hematite surrounded by a lattice of acicular ferrites.

5. Conclusions
A series of iron ores, fluxes and coke have been characterised. Different ore mixtures have been tested in a pilot plant using various operating parameters to establish the best sinter manufacturing conditions. The results obtained in the pilot plant, with regard to the process parameters, and in the laboratory, with regard to characterisation of sinter physical and structural properties, allows the following conclusions to be drawn.

(1) Sinters with good characteristics have been obtained, suitable for the optimum functioning of the blast furnace. The manufacturing of these sinters has been achieved with a low energy consumption, and especially a low coke consumption.

(2) The alumina content is low for all the sinters (<1.40%), which favours their quality. The sinters manufactured with ore mixture 3, with a lower alumina content, have a lower RDI value.

(3) In general the structure of the sinters includes the presence of ferrites with beneficial properties for sinter strength and reducibility. The optimum structure, formed by a hematite nucleus surrounded by an acicular ferrite lattice, has been detected. This structure is favoured when working with a higher basicity.

(4) The sinters manufactured with a greater bed height present better behaviour at high temperatures, with higher softening and melting temperatures and a smaller differential between these.

(5) The information reported in the present work, on the basis of the results obtained on the composition of ore mixtures, will be useful to the operators of the two sintering plants of ARCELOR-MITTAL in Gijón (Spain) to allow improve the sinter manufacturing.

REFERENCES
10) European Blast Furnace Committee, VDEh, Düsseldorf, Germany, (2005).