Effect of Reduction Conditions on the Swelling Behaviour of Cement-bonded Briquettes

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Cement-bonded agglomerates of by-products generated in iron and steel plants are commonly used as burden material for blast furnaces. It has been observed that under certain conditions the briquettes containing pellet-fines show a tendency to swell catastrophically when reduced at 900–1 000°C using carbon monoxide as reducing agent. This swelling is dependent upon a number of factors like: reducing temperature, reducing conditions and composition of reducing gas. The optical micrographs do not show the formation of iron whiskers as the cause of swelling; instead, the reduced iron particles seem to move apart, thereby causing swelling. This paper describes the effect of various parameters that cause the abnormal swelling of briquettes.

KEY WORDS: cement-bonded agglomerates; blast furnace; swelling; reduction; pilot-plant.

1. Introduction

The reduction of hematite pellets is accompanied by expansion in their volume. About 20% swelling is common and does not adversely affect blast furnace operation in any way. On the contrary, the swelling promotes the reduction process, due to increase in porosity. This swelling is caused mainly due to the phase transformation from hematite (hexagonal)→magnetite (cubic). In some cases, there is volume increase during conversion of magnetite to wustite. The exact mechanism for this expansion is not clear, but it is often attributed to the release of the remnant stresses, generated during the conversion of hematite to magnetite, during conversion of magnetite to the weaker wustite structure.

In some cases, pellets exhibit “abnormal” or “catastrophic” swelling/disintegration/degradation. This results in volume expansion more than the normal 20% and results in drastic reduction of the strength of pellets. This catastrophic swelling is a characteristic of pellets and is not observed either in sinters or in iron ore lumps. It has also been observed in cold-bonded briquettes made from pellet-fines. Hence, it is essential to know the exact mechanism and to prevent it as far as possible.

Most of the time, catastrophic swelling occurs during the last stage of the reduction process (wustite→iron) when iron of fibre-like (whiskers) morphology is formed. The growing whiskers push neighbouring grains and lead to large-scale swelling. In other types of swelling, there is no formation of whiskers; instead, the whole of the pellet expands and big fissures are created.

The degree of swelling of indurated or cold-bonded pellets and briquettes depends upon the mechanism of reduction, which in turn depends upon the:
- Reduction temperature.
- Reduction time.
- Reduction potential.
- Reducing gas composition.
- Flow rate of the reducing gas.
- Change of gas composition with time.
- Impurities in the reducing gas.
- Isothermal/non-isothermal reduction.
- Thermal treatment.

When the pellets show catastrophic swelling due to the formation of iron whiskers, the swelling generally increases with increase in temperature. This may be because at low temperature the metallic iron is formed uniformly over the surfaces of the wustite grains, giving a shell-like growth of iron. On the other hand, at high temperature, the nucleation takes place at favoured sites on wustite grain and continues to grow from these points as nodules or angular projection. The transition from shell-like to nodular iron growth occurs in the temperature range 850–900°C, and marks the onset of abnormal swelling.

The occurrence of swelling without the formation of iron whiskers reaches a maximum at about 900°C. This happens because at that temperature CO dissociates to C and CO₂; the C either dissolves in the produced iron or reacts to form Fe₃C. As the reduction proceeds, the C/Fe₃C reacts with wustite to give CO & CO₂ and Fe. This leads to the formation of bubbles, which exert disruptive force. At high reduction temperature (>900°C), the swelling is less because of low C deposition and greater sintering.

In this paper the effect of various reducing conditions on the swelling of cement-bonded briquettes have been discussed.
2. Materials and Methods

2.1. Raw Materials

The experiments were conducted on cement-bonded briquettes made using pellet-fines (93.5 wt%) with ordinary Portland cement (6.5 wt%) used as binder. Pellet-fines was a mixture of fines of Pellet A and Pellet B, two commercially available pellets collected by sieving before the pellets were fed to a blast furnace. The generation of fines took place due to the breakage that took place during transportation and handling. Structurally pellet-fines is different, since it is mostly the weak—under-fired or over-fired—pellets that break. Table 1 gives the chemical analysis of the raw materials.

2.2. Preparation of Briquettes

900 g of raw mixture was ground in a steel ball mill. 150 g of this mixture and optimum quantity of water (10–15 mL depending upon the particle size distribution of the raw mixture) were then put in a steel trough and mixed for about a minute, so as to obtain a mouldable paste. The plastic paste was put in a cylindrical steel mould of 4.2 cm diameter and compacted first by vibration for fixed period of time (1.0 min) (using a vibrating machine) and subsequently by compression under fixed load (1.5 t) for fixed time (1.0 min) (using a laboratory scale press). The green briquette thus obtained was cured for 28 d in a high humidity chamber. The cured briquettes were dried overnight in an oven maintained at 105°C.

2.3. Reduction of Briquettes

Figure 1 is the schematic diagram of the experimental set-up. The reduction set-up consisted of two parts: the gas supply and the heating furnace. The gases were supplied from cylinders. The supply of nitrogen and carbon monoxide was controlled using needle valves and flow meters. The gases in the required proportions were mixed in a gas mixer consisting of a tube containing glass beads.

The heating furnace consisted of a Kanthal wire wound tube furnace (length: 100 cm, diameter: 12.5 cm). A stainless steel tube (length: 135 cm, outer diameter: 6.5 cm) closed at the bottom end was placed inside this furnace. A K-type thermocouple placed inside the furnace near the briquette monitored the furnace temperature. The gas mixture, either only nitrogen or a mixture of nitrogen and carbon monoxide (N₂:CO=60:40) at a flow rate of 10 L/min entered from the bottom and was burnt at the top by means of an off-gas burner.

For isothermal reduction, the furnace was heated until the desired temperature and then the flow of reducing gas mixture was introduced. A briquette, placed in a high-temperature steel basket, was then lowered into the furnace and suspended from a balance placed above. After the desired time had elapsed, the briquette was raised to the mouth of the furnace and cooled in a flowing-nitrogen.

2.4. Reduction under Load

A high-temperature steel crucible with small holes at the bottom was used. A layer of alumina balls (diameter 10 mm) was laid at the bottom of this crucible. A briquette was then placed over the layer of alumina balls and in the centre of the crucible. The space between the briquette and the wall was then filled with alumina balls and a layer of alumina balls was placed over the briquette. 650 g (arbitrarily decided) of stainless steel balls (diameter 10 mm) was then put over the briquette to apply a constant load (Fig. 2). The crucible containing the briquette was placed inside the hot furnace and reducing gas was blown from the bottom.

2.5. Pilot Plant Tests

Some briquettes were also tested in a pilot blast furnace. The pilot plant has the following specifications: hearth diameter=1.2 m, height=14 m, volume=8.2 m³, production=36 t/24 h, blast temperature=1200°C, coke/coal consumption=510 kg/ton hot metal.

The briquette to be tested was put in a steel basket and surrounded by commercially available Pellet A (Fig. 3).
Just prior to the quenching of the furnace the baskets were introduced into the furnace from the top at regular intervals. The furnace was then quenched by flushing nitrogen from the top. Within minutes the reducing gases were removed and the reduction stopped. After cooling the furnace for ten days the baskets were excavated from the quenched furnace.

2.6. Degree of Reduction

The degree of reduction was calculated according to the formula:

$$R = \frac{\Delta W_T - \Delta W_M}{\Delta W_O}$$  \hspace{1cm} (1)

- \(R\): Degree of Reduction
- \(\Delta W_T\): Total loss in weight
- \(\Delta W_M\): Loss in weight due to the removal of moisture
- \(\Delta W_O\): Total possible loss in weight due to oxygen removal

Total loss in weight was obtained by recording the change of weight of briquettes during reduction. Loss in weight due to the removal of moisture was obtained by recording the weight of similar briquettes heated in a nitrogen. Total possible loss in weight due to oxygen removal was obtained from TGA and cross-checked using the chemical analysis of individual components. An average value of three briquettes per test was accepted. A variation within ±10% of the mean value was accepted.

2.7. Chemical Analysis

Chemical analysis was carried out using a Inductively Coupled Plasma (ICP) Spectrometer.

2.8. Optical Microscopic Examination

A test piece of the sample to be observed was cast in a cold-mounting epoxy resin mould under vacuum. The moulded sample was then ground and polished. The polished sample was then observed using a optical microscope.

2.9. Particle Size Analysis

Approximately 100 g of dried material was dry-sieved to various size fractions using a set of U.S. Standard Sieves conforming to ASTM. In this paper the particle size has been reported as \(d_{50}\), which is the cumulative fifty percent finer than the value.

2.10. Volume Measurements

The bulk volume of briquettes and pellets was calculated under the assumption that they were perfectly cylindrical and spherical, respectively. The diameter and the length were measured using callipers. After reduction, the briquettes and pellets often distorted. Even in this case the diameter and length were measured at several places and an average of the readings was taken. This method of measuring the volume gave only rough values; hence, they should be taken only qualitatively.

2.11. High Temperature X-ray Diffraction Analysis

\textit{In situ} high-temperature X-ray diffraction (HT-XRD) studies were carried out using an automatic diffractometer. The basic units in this system were: a powder diffractometer with a vertical goniometer, a graphite monochromator, a proportional counter for reflected beam and a generator. The heating of the sample was done in a high-temperature attachment. The temperature of the sample was measured with a Type R thermocouple placed close to the sample. The specimens, made by grinding the cured samples into a thin wafer (10 mm \times 7 mm \times 0.7 mm), were heated in a flowing nitrogen. The temperature was ramped at a rate of 8.3°C/min CuKα (50 kV, 30 mA) radiation was employed. The samples were scanned at room temperature and at every 100°C at a rate of 1.2°C/min.

2.12. Scanning Electron Microscopic (SEM) Examination

A test piece of the sample to be observed was fixed into an epoxy resin mould, ground and polished. The moulded specimen was then fixed on an aluminium mount and coated with a thin layer of gold-palladium alloy using a sputter coater. The coated specimen was then examined under a scanning electron microscope. The Energy Dispersive X-ray Analysis (EDXA) was also done on the sample to obtain chemical mapping and line mapping of the sample.

2.13. Effect of Temperature

Two different types of briquettes, A1 \((d_{50}=74 \mu m)\) and A2 \((d_{50}=2512 \mu m)\) were isothermally heated in nitrogen or reduced in \(N_2 + CO\) (60:40) at different temperatures for 5 h at different temperatures.

2.14. Effect of Degree of Reduction

Two different types of briquettes, B1 \((d_{50}<74 \mu m)\) and B2 \((d_{50}=2465 \mu m)\), were isothermally reduced at 950°C. In the first set of experiments, the briquettes, B1 and B2, were
reduced in N$_2$+CO (60:40) for varying periods of time. In the second set of experiments, the briquettes, B2, were reduced using gas mixtures having three different reduction potentials (CO/CO$_2$/H$_2$=12.5, 50, 100 vol.%) at 950°C for 5 h. This was done to reduce the briquettes in steps to magnetite, wustite and iron stages respectively.

2.15. Effect of Reduction under Load

One set of briquettes, C1 ($d_{50}$=359 μm), was prepared in the normal fashion. Some of these briquettes were reduced allowing free swelling and others were reduced under load.

2.16. Effect of Non-isothermal Reduction and Presence of Hydrogen

One set of briquettes D1–D7 ($d_{50}$=1595 μm) was prepared according to the standard procedure using 93.5 wt% of pellet-fines and 6.5 wt% of cement. These briquettes were reduced under isothermal/non-isothermal conditions. The reducing gas contained different amounts of CO and H$_2$. Briquettes D1, D2 and D3 were heated under isothermal conditions by introducing the briquettes into the furnace maintained at 950°C. Table 2 gives the summary of experiments carried out.

2.17. Pilot Plant Tests

Seven different types of briquettes were prepared. Four briquettes of each kind were then introduced at different times into the pilot blast furnace prior to quenching of the furnace. These briquettes were:

- E1: Pellets fines+6.5% cement–Coarsely ground ($d_{50}$=2512 μm).
- E2: Pellets fines+6.5% cement–Coarsely ground ($d_{50}$=2512 μm) put into basket without any pellets to surround them. This was done to allow free swelling of briquettes.
- E3: Pellets fines+6.5% cement–Finely ground ($d_{50}$<74 μm).
- E4A: Pellets fines+2% cement–Coarsely ground.
- E4B: Pellets fines+8% cement–Coarsely ground.
- E4C: Pellets fines+15% cement–Coarsely ground.
- E4D: Pellets fines+25% cement–Coarsely ground.

3. Results and Discussion

3.1. Effect of Temperature

When heated in nitrogen, the briquettes show almost constant volume expansion of about 10%, irrespective of the heating temperature. The expansion is accompanied by the development of many small and large cracks. The cracking is most likely due to the loss of cement bonding, which weakens the structure. At higher temperatures, the degree of sintering is higher, thereby, resulting in less cracking. This is especially true for briquettes made of finely ground materials that expand slightly less than coarsely ground materials. This difference may be due to the greater amount of sintering that takes place with finely ground material as opposed to coarsely ground materials.

Figures 4 and 5 show the effect of temperature on the

Table 2. Summary of tests carried out to study the influence of reduction conditions on the swelling of briquettes (RT=Room Temperature).

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Type</th>
<th>Temperature (°C)</th>
<th>Gas Composition</th>
<th>Heating Rate (°C/min)</th>
<th>Reduction Time (h)</th>
<th>Degree of Reduction (%)</th>
<th>Volume Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Isothermal</td>
<td>950</td>
<td>N$_2$:CO=60:40</td>
<td>3</td>
<td>84.12</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>Isothermal</td>
<td>950</td>
<td>N$_2$:CO=60:40</td>
<td>3</td>
<td>75.18</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>Isothermal</td>
<td>950</td>
<td>N$_2$:CO=75:25</td>
<td>3</td>
<td>54.07</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>Non-isothermal</td>
<td>RT-600</td>
<td>100:0</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D5</td>
<td>Non-isothermal</td>
<td>RT-950</td>
<td>60.35:5:7</td>
<td>2</td>
<td>69.07</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>D6</td>
<td>Non-isothermal</td>
<td>RT-950</td>
<td>60.35:5:7</td>
<td>5.4</td>
<td>58.31</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>D7</td>
<td>Non-isothermal</td>
<td>RT-950</td>
<td>60.35:5:7</td>
<td>4.65</td>
<td>65.75</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 4. Effect of reduction temperature on Mix A briquettes reduced in N$_2$:CO=60:40 for 5 h (a) A1 ($d_{50}$<74 μm); and (b) A2 ($d_{50}$=2512 μm).](image)
swelling of briquettes A1 and A2 reduced at different temperatures. When the briquettes are reduced at low temperature (<800°C), they experience swelling leading to cracking and disintegration. For these briquettes, the measured volume expansion reduces with increase in reduction temperature. This is because at low temperatures the cracks formed are bigger, which gives bigger measured diameter and height and thereby greater volume expansion. If the volume of briquettes were measured by immersion method, perhaps the results would be otherwise. In the temperature range 800–900°C, the swelling is rather low and within the acceptable limit. In the temperature range 850–1 000°C, the briquettes show catastrophic swelling wherein the coarse pellet-fines particles present in the briquettes start pop-ing up like "pop-corn". The overall swelling of the briquettes may be due to the combined effect of loss of strength of the cement matrix and expansion due to the hematite $\rightarrow$ magnetite $\rightarrow$ wustite $\rightarrow$ iron transformations. The popped-up particles are very soft and spongy. XRD analysis of the spongy mass and of material collected from the surroundings shows that the material in the spongy mass is mostly iron, while in the surroundings the material is mostly wustite.

The effect of temperature on swelling may be summarised as:
- 750–850°C: The swelling is rather low and within the acceptable limit. It is due to the formation of large cracks.
- 900–1 000°C: The swelling increases and then falls with temperature so that the swelling reaches a maximum at 950–1 000°C. The swelling is due to the formation of a soft spongy mass of iron.
- At 1 050°C: The swelling is within the permissible limits.

While the above description is true, the figure should not be interpreted quantitatively. This is because the samples were reduced for fixed time, 5 h. However, the rate of reduction is dependent upon the temperature. The rate of reduction increases with temperature up to 900°C and there-

![Fig. 5. Effect of temperature on the volume of briquettes made of Mix A (A1 and A2) reduced for 5 h and Pellets A reduced for 1 h in N₂ : CO (3 : 2).](image)

![Fig. 6. Optical micrographs of briquettes of A2 ($d_{50}=2.512 \mu m$) reduced at different temperatures in N₂ : CO=60 : 40 for 5 h, (a) 750°C (grey particles are iron carbide, white particles are iron); (b) 950°C (white particles are iron); and (c) 1 050°C (white particles are iron).](image)
after it does not increase. Hence, while the briquettes reduced at 750–850°C reduced to 67–77%, those reduced at 900–1050°C had reduced to 81–85%. Since, the swelling increases with the degree of reduction the briquettes reduced at 750–850°C would have shown further swelling had they been reduced to over 80%.

For the sake of comparison, Fig. 5 also shows the effect of temperature on the swelling of Pellet A. It can be seen that under the same conditions the Pellet A does not have the tendency to swell abnormally.

Figure 6 shows the optical micrographs of briquettes of A2 ($d_{50}$=2512 μm) reduced at different temperatures. At 750°C and 800°C, iron carbide (Fe₃C) is the main component and iron is the minor component. The grains are laminar and well connected. At 850°C, even though the iron is the main phase, the grains are large and well compacted. At 950°C, the iron grains are rather small, spherical and scattered. At 1000°C, even though the iron particles are small and spherical, they are not dispersed as in the previous case. At 1050°C the iron grains are large and well sintered.

3.2. Effect of Degree of Reduction

Figure 7 shows the effect of reduction time on the volume of briquettes, when the briquettes were reduced in one step. As can be seen, the reduction time (also reduction degree) has tolerable effect on the briquettes made of finely ground material B1. On the other hand, briquettes made of coarse material, B2, show catastrophic swelling. Visual observations show that in the briquettes, B2, the larger particles of pellets-fines blow up like “pop-corns”. Large-scale formation of a soft spongy iron mass could be seen with the naked eye.

When the briquettes are reduced in steps, the briquettes B2 reduced in an environment having low reduction potentials (CO/CO₂ = 12.5 and 50) show swelling of only 10%.
and 14%, respectively. On the other hand, similar briquettes reduced in an environment with a high reduction potential (CO/CO\(_2\), CO\(_2\)/H\(_2\) = 100) show catastrophic swelling (232 vol%). This clearly shows that the catastrophic swelling takes place during the reduction from wustite to iron. Figure 8 shows the optical micrographs of the samples. It shows that on reduction from hematite\(\rightarrow\)magnetite the large pellet-fines particles develop cracks and disintegrate to smaller and detached grains. On further reduction to wustite, the grains disintegrate even further, as a result of which the wustite grains are much smaller and fragmented. At this stage, the wustite grains are still close to each other and a rough outline of the original particle may still be there. During reduction to iron, the wustite grains disintegrate and disperse even further. The iron is formed as small spheres and appears in well-dispersed patches. At this stage the boundaries of the original particles totally disappear. It seems that the reduction of wustite to iron takes place in a pool of molten slag (comprised of CaO, SiO\(_2\), FeO, MgO, Al\(_2\)O\(_3\)). As a result, the reduced iron is able to move away from the wustite structure and, due to the surface tension, takes a spheroid shape.

### 3.3. Effect of Reduction under Load

Figure 9 is the photograph of a briquette reduced under load. The briquette reduced under load shows, overall, less degree of swelling when compared to a similar briquette reduced without any physical constraints. Figure 9 also shows the optical micrographs of briquette C1 reduced under load. It can be seen that in the centre of the briquette the individual grains of wustite are more densely packed than in the case where the briquettes were reduced allowing free swelling. In an optical micrograph of a sample from peripheral Position 1, the region between two alumina balls, which did not experience much load, shows normal swelling tendencies. On the other hand, in the optical micrograph of sample from peripheral Position 2, the region that was under the direct influence of load, shows denser and bigger iron grains. This shows that the reduction in the degree of swelling is not due to the fact that the briquette has less tendency to swell, rather it is because the applied load has restricted its swelling. On application of load the iron grains tend to sinter into larger grains and do not disperse significantly.

### 3.4. Effect of Non-isothermal Reduction and Presence of Hydrogen

Figures 10 and 11 show the effect of reduction on the
volume expansion. Since the volume expansion depends upon the degree of reduction and particle size, the data for briquettes ($d_{50} = 2465 \mu m$) reduced under isothermal conditions ($N_2 : CO = 60:40, 950^\circ C$) has also been included as a comparison in Figure 11.\textsuperscript{13} As can be seen from the figure, the degree of expansion increases with the degree of reduction. Irrespective of the experimental condition, the points follow almost the same trend (except for sample D2). The consistently lower degree of swelling may be explained by the lower average particle size ($d_{50}$) of samples D1–D7. Taking into account the degree of reduction, briquette D2 showed a lower degree of expansion compared to briquette D1. The reason may be the presence of 5% hydrogen in the reducing gas for briquette D2. Briquette D3 did not show any tendency to swell with the formation of spongy mass, but large cracks appeared in the briquette.

Figure 11 shows that the briquettes reduced under isothermal conditions are less prone to swelling than the briquettes reduced under non-isothermal conditions. This observation is contrary to the ones made when pellets were used.

Figure 12 shows the optical micrographs of briquette D3 reduced in $N_2 : H_2 (75:25)$. It can be seen that the briquette has no tendency to swell, because the iron grains formed are more compact and laminar. This clearly shows that the presence of carbon monoxide is an essential condition for swelling.

3.5. Proposed Model to Describe Swelling

A simple conceptual model has been proposed to describe the swelling mechanism. The model is based on the following premises:

- Pellet-fines contain a significant proportion of under-fired and weak pellet particles that disintegrate to very small
particles of wustite on step-wise reduction of hematite (Fig. 8(c)).

- The calcium silicate from cement reacts with magnesia from olivine, alumina from cement and pellet-fines and wustite to produce a slag having low melting point.
- Figure 13 shows the SEM of a reduced briquette showing the formation of CaO–MgO–FeO–SiO₂–Al₂O₃ phase over a large region.
- The reduction of wustite liberates heat resulting in localized melting of the slag.
- At about 950°C carbon monoxide in reducing gas reacts with wustite to form metastable iron carbide.

Figure 14 is the high-temperature XRD of cured pellet-fines (75%)–cement (25%) briquette sample showing the formation of metastable iron carbide.

During the reduction of a cement-bonded briquette a layer of molten slag envelops the disintegrated pellet-fines particles which has been reduced to wustite. The carbon monoxide reacts with wustite to form iron carbide. The iron carbide oxides to iron and carbon monoxide by taking oxygen from wustite or carbon dioxide. The carbon monoxide thus generated builds up a pressure inside the fragmented particle. This pressure then pushes out the iron particles. Since there is liquid slag present, hence, there is sufficient lubrication for the particles to move out. This outward movement of particles leads to swelling.

3.6. Testing of Briquettes in a Pilot Plant

Examination of the reduced briquettes obtained by excavating the quenched pilot blast furnace reveal that the briquettes do not swell inside the furnace. The difference in the behaviour of the briquettes when tested in the laboratory and when tested in the pilot plant maybe because the laboratory tests do not replicate the actual conditions inside a blast furnace. In the laboratory, all the experiments are carried out in the isothermal condition (950°C) using a fixed environment (N₂ : CO=60 : 40) as stipulated by the reduction test ISO 4695. This test intends to simulate the reserve zone of a typical blast furnace. On the other hand the conditions inside the pilot blast furnace are different in many ways. Two important differences are:

- In the pilot plant the reduction takes place in non-isothermal condition. Basically there are four zones inside the furnace—drying, reserve, cohesive and dripping zones. The reserve zone has a temperature range of 800–1 000°C, retention time of approximately 2 h and 30 min and the temperature gradient of 2°C/min The earlier experiments have shown that the swelling takes place only in the range of 900–1 000°C and since in the pilot plant the briquettes stay in this temperature range only for a short time they may not swell.
- In the pilot plant there is a presence of hydrogen inside the furnace. Experiments have shown that the briquettes have lesser tendency to swell in the presence of hydrogen.

Even though the briquettes excavated from the pilot blast furnace do not swell, the optical microscopic examination of the briquettes shows some similarity to the briquettes reduced in the laboratory. At the hematite stage the structure of pellet-fines particles is well bound. On reduction to magnetite, the pellet-fines structure breaks into small fractions. On further reduction to wustite, the structure completely falls apart. This behaviour matches quite closely to the behaviour of briquettes tested in the laboratory furnace (Fig. 8). In spite of the similarity there are certain differences. Firstly, while in the laboratory-tested briquettes almost all the particles disintegrate, in the pilot plant tested briquettes substantial amount of particles do not disintegrate. Secondly, on reduction to iron, while the briquettes tested in laboratory swell due to moving asunder of the individual spherical iron particles, in the case of briquettes tested in pilot plant this does not happen. Figure 15 shows the optical micrograph of reduced briquette E1. The figure shows two distinct regions. On the left, the iron particles are compactly packed and are probably remnants of a large pellet-fine particle. On the right the iron particles are sparsely packed and are probably from the fine particles that were distributed between the cement matrix.

The briquettes E1 were enclosed in steel basket and surrounded by Pellet A which could have restricted the swelling of the briquettes, but the examination of briquettes E2, which were not surrounded by the pellets, again do not show any swelling tendencies. The optical microscopic examination of the briquettes shows similarity in microstruc-
In spite of the fact that the reduced E1 briquettes do not have tendency to swell they have rather low strength and tend to fall apart. This may be because the bond between the pellet-fines particles are not strong. This is due to the large distance that exist between them.

Figure 16 shows the optical micrograph of the briquette E3. Like the previous case the relatively large pellet-fines particles dissociate and fall apart, so that at the magnetite and wustite stage the iron oxide particles are quite evenly distributed in the briquettes. On reduction to iron, again the iron particles are rather well distributed throughout the briquette. This even distribution of particles could be the cause of better strength characteristics of the briquettes E3.

In the case of E4A–E4D only a few briquettes could be recovered from the pilot plant. These briquettes were from the upper half of the shaft. Among these briquettes, it is observed that the strength of briquettes increases with an increase in the cement content. Also, none of the briquettes show any swelling tendency. Figure 17 shows the optical micrograph of a reduced Pellet A. When Pellet A is reduced in pilot plant the structure of the pellet does not crumble on conversion to magnetite and wustite. Hence, the final iron grains are compact and well bound. This results in strong structure.

From the pilot plant experiments it seems that the quality of briquettes may be improved by grinding the raw material fine or by using only the fine fractions. The strength may also be improved by increasing the cement content in the briquettes.

The conditions inside the pilot plant are very close to those of an actual blast furnace. Still the conditions inside vary from blast furnace to blast furnace depending upon the design and operation. Larger blast furnaces normally have larger isothermal reserve zone having a temperature of about 950°C. Under such condition there may be a possibility for the briquettes to swell. Hence, steps should be taken to reduce this possibility.

4. Conclusions

From the work carried out, it may be concluded that:

(1) The swelling of briquettes reaches a maximum when reduced at 950°C.
(2) The swelling takes place during the transformation of wustite to iron.
(3) During the reduction under load, the briquettes still have the tendency to swell, but applied load prevents the swelling from taking place.
(4) The swelling takes place only when the briquettes are reduced using carbon monoxide. It decreases in the presence of hydrogen.
(5) The swelling of briquettes is not due to the formation of iron whiskers, but rather due to the movement of iron particles away from each other in a bath of molten slag. A model has been proposed to explain the swelling behaviour.
(6) The briquettes do not swell during reduction inside the pilot plant. Like the briquettes tested in the laboratory, the pellet-fines present in the briquettes tend to disintegrate resulting in the loss of strength. The performance of briquettes inside the furnace improves by increasing the fineness of the raw material or by increasing the cement content.

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