The softening and melting test is widely used to assess the behaviour of ferrous materials in the cohesive zone of a blast furnace. It is generally agreed that the performance of lump ores is inferior to sinter in the test. To understand the factors determining material behaviour, tests were terminated by quenching samples at different temperatures. The samples were then studied under an optical microscope. The formation of a low temperature liquid fayalite caused beds of lump ores to rearrange and contract earlier. Beds of fluxed sinter remained essentially intact with reduction until higher temperatures. The study also showed that results obtained for a mixed burden of 80% sinter and 20% lump ore – a ratio used in many blast furnaces – are not different to results obtained from tests using only sinter. This difference increases as the lump ore level is increased. These findings indicate that there is significant interaction between the material types in the test and that results from single material tests should not be used in isolation assess material performance in a blast furnace. Any prejudice against lump ores as a blast furnace feed material based on softening and melting test results for single materials is clearly incorrect.

KEY WORDS: softening and melting tests; ferrous burden materials; lump ores; fluxed sinter; blast furnace.

1. Introduction

The iron-bearing materials – termed the ferrous burden and is generally composed of sinter, lump ores and pellets – are charged into a blast furnace together but coke is charged separately. The alternate charging of these two materials gives the furnace stack a layered structure: coke layers interspersed between ferrous material layers (Fig. 1). The coke undergoes little change until it has descended into the high temperature regions where reactions (e.g., solution loss) rates become significant. These deleterious reactions occur below the cohesive zone and they cause coke to breakdown physically. The iron-bearing materials undergo reduction reactions at much lower temperatures and these reactions can also result in the generation of fines. On reaching the cohesive zone they soften and melt while the coke remains virtually intact.

An important property of the furnace bed is its permeability, which determines how much gas can be forced through the bed. The stack will have a certain permeability value that is different to that of the cohesive zone. Likewise, the region between the tuyeres and the cohesive zone will have a value that could be quite different to the stack and cohesive zone. Of the three, the region with the lowest permeability value will control gas flow through the furnace. If the cohesive zone has the lowest permeability value then it will be the controlling resistance or ‘bottleneck’. In the literature, there is clearly belief that this is indeed the case because the ferrous layers are no longer permeable and the only path available for gas flow through the cohesive zone is through the coke slits (for example).1,2) This assumption is made because
a ferrous burden undergoing softening and melting is a compliant mass, which can easily be compressed and densified under load rendering it impermeable.

In the literature, stack permeability is also cited as being important (for example).\(^3\)\(^,\)\(^4\) If the physical properties (size distribution and shape) of the charged coke and ferrous materials remain unchanged then stack permeability will essentially depend on degradation in the ferrous layers. For this reason, many plants control the reduction degradation index (RDI) of their sinter. If the coke slits in the cohesive zone are the controlling resistance then the permeability of the stack will be less important. It is possible that the ferrous layers in the cohesive zone are not completely impermeable. In a blast furnace, as gas flow velocity is very large, it is highly probable that flow channels in the ferrous materials will be kept open in the cohesive zone by the flowing gases. If this is the case, then the ferrous layers in the cohesive zone could have a large influence on furnace permeability. The condition of the ferrous material could also have an effect on the properties of the coke slits. The quicker the ferrous material deforms and compresses, the quicker it will be able to penetrate into the voids of the coke slits. The permeability of the coke slits will decrease quickly if the softening temperature of the reduced ferrous mass is low. A finer ferrous burden size distribution descending from the furnace stack can also result in more significant choking of the coke slit voids.

Whichever is the true reason, it appears that softening and melting behaviour of the ferrous materials in the cohesive zone is important. Laboratory softening and melting tests have been formulated to assess this property of ferrous materials. These tests involve subjecting the material to heating and reducing gases while under a normal load. The experimental rig used in our work is shown in Fig. 2. The rig has been described in detail in a previous publication\(^5\) and a typical set of results is shown in Fig. 3. Pressure drop across the sample and the contraction of the sample are the two main parameters determined during a test. Reduction degree is also determined in each test but results are not shown. To facilitate the comparison of test results, material behaviour is often characterized by a softening temperature (\(T_s\)) which is usually defined as the temperature at which the bed has contracted by 50 vol.% (see Fig. 3). Melting temperature (\(T_m\)) is also considered to be another important parameter and is commonly defined as the temperature at which the pressure drop across the bed is similar in value to that obtained at \(T_s\) (see Fig. 3). Other parameters considered relevant are the melting range (\(T_m - T_s\)) which could reflect the thickness of the cohesive zone, and the S-value which is an integrated pressure drop value over the melting range and the maximum pressure drop \(\Delta P_{\max}\). From Fig. 1 it can be seen that increasing the thickness of the cohesive zone will increase the width of the coke slits, making the flow of gases through the cohesive zone more difficult. The S-value is believed to reflect the total pressure drop across the cohesive zone, but measured values can vary quite significantly.
i.e., poor results repeatability. A low $T_s$ value is also believed to indicate that the cohesive zone may be higher up the furnace and this can have a negative impact on the stability of the furnace.

The aim of this paper is to study material behaviour during a softening and melting test rather than just determine the standard test parameters. There is considerable benefit in understanding the fundamental factors causing the bed structure to change – because it is this change that allows the bed to densify under load and reduce in permeability. In this study the changes in bed structure of three lump ores and a sinter are studied.

2. Experimental

A distinctive feature of this study is that for each material several tests were carried out. Some tests were carried to completion but a large number of tests were aborted on reaching different thermocouple temperatures. This was done by turning off the heating power and replacing the flowing gas mixture with nitrogen. The aim of such tests was to provide frozen ‘snap-shots’ of the material at the different stages of the test. Through studying these samples, the causes of bed changes can be inferred. The position of the thermocouple is shown in Fig. 2. Because the thermocouple is not in the sample, quenched temperatures would probably not fully reflect sample temperatures. Nonetheless the difference between the two temperatures should not vary greatly in the temperature range studied.

The cooled graphite containers holding the samples were removed, set in resin and sectioned across a diametrical plane to obtain two blocks, each with a large surface for microscopy studies. The blocks were further trimmed so that they could fit into the sample holder of the microscopes and their surfaces were polished.

3. Results

In Table 1 a summary of the experimental conditions is shown. In a blast furnace the gases flow up a bed but in this rig the gases flow downwards. This is not considered to be important because the rig is not meant to simulate an operating blast furnace. In addition, the bed is only relatively shallow and gas composition should not vary significantly across the bed. Flow rates are also small and should not exert significant forces on the bed regardless of the flow configuration used. The ferrous material – shown as sinter in Fig. 2 – is enclosed in a graphite reactor and above and below the test sample are two layers of coke particles. The sample is reduced by a flowing gas stream composed of 30 vol.% CO:70 vol.% $N_2$ stream flowing at 14 l min$^{-1}$.

The normal load acting on the sample is kept constant at 10 t m$^{-2}$ (or 1 kg cm$^{-2}$).

Three lump ores and a fluxed sinter were considered in this study. Ore A is a porous Australian hematite ore. Ore B is an Australian hematite-goethite ore and is more porous and reducible than Ore A. Ore C is a very dense hematite ore from South Africa and is not as reducible as Ore A or B. The chemical compositions of these ores are shown in Table 2. Ore C has a much higher silica content compared to the other two ores.

Results obtained from a softening and melting test can be quite variable. This is not surprising because no two iron ore lumps are identical and their shapes have a large influence on the packing of the bed. The presence of denser particles also means that there will be a greater mass of solids in tests as the initial bed height for these tests was kept constant. These two factors will have an influence on the compaction behaviour of the bed and the pressure drop across the bed. For this reason our usual approach is to carry out five softening and melting tests for each material. All bed contraction and pressure drop results given in this paper are averaged values for the five tests.

3.1. Bed Changes

For the four ferrous materials considered this study, a set of softening and melting results for each is shown in Table 3. Other than in Table 3 all results for bed contraction and pressure drop (i.e., Fig. 4 onwards) are averaged results for five tests. The bed contraction results as a function of bed temperature for the four ferrous materials are shown in Fig. 4. At 50% contraction the lowest $T_s$ value is obtained for Ore B followed by Ore A and then Ore C. The fluxed sinter results for the full temperature range are very similar to that of Ore C. Sinter is the most porous of the four materials; in

### Table 1. Test conditions used in a softening melting test.

<table>
<thead>
<tr>
<th>Items</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample bed diameter</td>
<td>60 mm</td>
</tr>
<tr>
<td>Initial sample height</td>
<td>70 mm</td>
</tr>
<tr>
<td>Sample weight</td>
<td>About 450 g</td>
</tr>
<tr>
<td>Coke and ore size</td>
<td>10–12.5 mm</td>
</tr>
<tr>
<td>Upper coke layer</td>
<td>15 mm</td>
</tr>
<tr>
<td>Lower coke layer</td>
<td>25 mm</td>
</tr>
<tr>
<td>Reduction gas flow direction</td>
<td>Top to bottom</td>
</tr>
</tbody>
</table>

### Table 2. Chemical composition of the lump ores and sinter.

<table>
<thead>
<tr>
<th>Ore</th>
<th>Total Fe</th>
<th>FeO</th>
<th>SiO$_2$</th>
<th>CaO</th>
<th>MgO</th>
<th>Al$_2$O$_3$</th>
<th>P</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore A</td>
<td>64.31</td>
<td>0.25</td>
<td>3.65</td>
<td>0.03</td>
<td>0.08</td>
<td>1.64</td>
<td>0.044</td>
<td>2.29</td>
</tr>
<tr>
<td>Ore B</td>
<td>63.38</td>
<td>0.29</td>
<td>2.68</td>
<td>0.12</td>
<td>0.06</td>
<td>0.89</td>
<td>0.048</td>
<td>5.57</td>
</tr>
<tr>
<td>Ore C</td>
<td>65.32</td>
<td>0.29</td>
<td>4.22</td>
<td>0.06</td>
<td>0.03</td>
<td>1.18</td>
<td>0.058</td>
<td>0.34</td>
</tr>
<tr>
<td>Sinter</td>
<td>59.31</td>
<td>0.29</td>
<td>4.24</td>
<td>7.70</td>
<td>1.51</td>
<td>1.56</td>
<td>0.042</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 3. Typical softening and melting parameters.

<table>
<thead>
<tr>
<th>Ore</th>
<th>$T_s$, °C</th>
<th>$T_m$, °C</th>
<th>$T_{m}-T_s$, °C</th>
<th>$\Delta P_{max}$, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1180</td>
<td>1432</td>
<td>251</td>
<td>2.58</td>
</tr>
<tr>
<td>B</td>
<td>1135</td>
<td>1512</td>
<td>376</td>
<td>4.53</td>
</tr>
<tr>
<td>C</td>
<td>1339</td>
<td>1384</td>
<td>45</td>
<td>12.0</td>
</tr>
<tr>
<td>Sinter</td>
<td>1357</td>
<td>1497</td>
<td>140</td>
<td>2.6</td>
</tr>
</tbody>
</table>
spite of that it is capable of maintaining its bed structural integrity on reduction.

Figure 5 shows the relationship between pressure drop and contraction. Of the three ores, although Ore C has the lowest reduction rate and the lowest contraction in the temperature range of around 1000 to 1300°C, it gave much higher pressure drop values than Ores A and B. This graph shows that for Ore C changes in contraction (up to 80%) have the greatest effect on pressure drop. The relative positions of the upward sloping sections of these graphs are in line with the porosity of the materials. Ore C is the densest of the four materials and Ore B is more porous than Ore A. Sinter gave the lowest pressure drop value even though it has a contraction behaviour similar to that of Ore C.

Figure 6 shows the structure of the ore beds on quenching at different temperatures. At temperatures of around 1100°C (top row in Fig. 6) all the Ores A and B particles have all been reduced to wustite and some have a thin periphery of metallic iron – as indicated by the lighter colours. For Ore C some (three in particular) particles still have a rounded hematite core and this is indicated by the lighter colours. Surrounding each hematite core would be a thin rim of magnetite. Further out from the core the material has been reduced to wustite. Metallic iron is observed on some particle peripheries.

Figure 6 shows that at 1300°C the differences in behaviour of the ores are very evident. The beds for Ores A and B have compacted much more compared to Ore C. Ore C still has abundant wustite while metallic iron is more abundant in Ores A and B. On the right hand side of the Ore C bed there is still a particle with a hematite core.

At around 1410°C the bottom row of Fig. 6 shows that the beds have undergone further contraction. It would appear that Ore B has contracted the most and Ore C the least. The large uniform dark regions in Ore C are voids and the large dark material regions are wustite. This wustite is different to the wustite obtained at lower temperatures in that they are granular, have precipitated out from melt and the original ore structure is lost. The large dark regions in Ores A and B are predominantly voids with an occasional gangue particle from the ore. Almost all the Ores A and B particles have been reduced to metallic iron but the Ore C sample has predominantly mixes of metallic iron and wustite.

3.2. Mixtures of Lump Ore and Sinter

The next phase of this study involved mixtures of sinter and lump ore. Figure 7 shows bed contraction results for mixtures of Ore A and sinter while Fig. 8 shows the pressure drop results at the different levels of contraction. As the level of sinter in the mixture increases bed contraction decreases. Contraction results for beds with 50 and 80% sinter are very similar and are slightly inferior to those obtained for tests involving only sinter. At these levels, pressure drop results are comparable to those obtained for the sinter only test. However, the position of the highest pressure drop appears to be more sensitive to the level of lump ore in the blend. This means that a pressure drop of 0.5 kPa across the samples is obtained at a higher contraction levels when the amount of sinter in the mix increases.

Figure 9 shows the bed contraction results for mixtures of Ore B and sinter. For a mix of 80% sinter and 20% lump ore results are very similar to those obtained from the sinter only tests. Results obtained for 30 and 50% sinter are very
similar. The tests involving only lump ore clearly contract at the lowest temperatures. Figure 10 shows that the test involving only Ore B gave the highest pressure drop values. The maximum recorded pressure drop decreases significant on introducing sinter into the lump ore and the differences in values measured for the blends containing 0, 20, 50 and 70% lump ore are not significant. As in Fig. 8, at a pressure drop of 0.5 kPa across the bed the same trend of a higher contraction with increasing sinter levels is indicated. However, Figs. 7 to 10 demonstrates very clearly that bed contraction results give much more reliable trends compared to pressure drop results; the variation in pressure drop results for a set of five repeat tests can be quite large.

Figure 11 confirms that the introduction of Ore A into sinter at the 20% level did not visually affect bed compaction behaviour. At 1300°C the height of the bed obtained for this mixture is very similar to that for the only sinter test. This is in agreement with the results of Fig. 7. Figure 12 shows that blending in Ore B at the 20% level also gave very similar results to those obtained for Ore A. This figure could indicate that behaviour of Ore C is slightly different in that the bed has compacted more. However, plots of bed contraction over the full temperature range show that Ores A and C gave very similar results when mixed with 80% sinter (Fig. 13). Despite similarities in contraction behaviour, pressure drop results for the test involving Ore C are higher (Fig. 14). It is interesting that this difference in pressure drop behaviour is also observed for the ores only test results given in Fig. 5. Figure 15 shows that as the levels of Ores A and B in the sinter and lump ore mixture increases the temperature difference between softening and melting...
also increases. However, results obtained for only sinter and 20% lump ore in a mix could indicate that the cohesive zone formed has a very similar thickness to that formed using only sinter.

These results for mixed ferrous materials would indicate the importance of carrying out softening and melting tests using more realistic conditions. Just because results obtained from lump ore only tests are inferior does not mean that their introduction in a blast furnace together with fluxed sinter will have a deleterious effect on cohesive zone behaviour. Past studies\textsuperscript{6–11)} have also shown that the softening and melting properties of lump ore and acid pellets can be improved by mixing with sinter. This could be the reason why many blast furnaces around the world, including the larger ones, use lump ore at levels around 20% in their ferrous burden. For example a recent paper reports that lump Ore B was successfully added to a blast furnace at a burden average of 17.3% for one year, reaching a high of 22% for one month.\textsuperscript{11)} During this extended trial, BF permeability remained in the normal operating range with no indications of non-uniform gas flow conditions or abnormal cohesive zone issues and gas utilization efficiency even improved slightly. This allowed high productivity rates to be maintained during the year with no adverse effects of lump softening and melting on operations.

4. Causes of Lump Ore Bed Contraction

Results indicate very clearly that beds of lump ores contract much earlier than fluxed sinter. A major reason for this is the formation of fayalite (Fe\textsubscript{2}SiO\textsubscript{4}), a liquid at low temperatures. The formation of fayalite as the primary slag for acid pellets and lump ore has been observed and discussed in many publications.\textsuperscript{10,12–14)} For sinter, in spite of its high porosity, changes caused by reduction – and this includes the formation of fine pores caused by oxygen removal leading to decreased solids content and melt formation – did not severely decrease its load bearing strength and cause bed compaction. No fayalite forms in sinter and at higher temperature melts that are generated appear to be more viscous, resulting in less bed deformation under load. Even with significant reduction to metallic iron the original macro-structure of the sinter is maintained. For example, fibrous silico ferrite of calcium and aluminum (SFCA) regions still have the fibrous structure at 1 300°C even though their walls are now composed of metallic iron, dicalcium silicate and slag. It would appear that dicalcium silicate, which is widely scattered through the structure, limits the coalescence and growth of metallic iron grains. The structure stays reasonably intact and remains resilient to compression. At the end of a softening and melting test carried out on sinter, a large amount of powdery dicalcium silicate is left at the bottom of the container.

Formation of fayalite

Figure 16 shows the surface of two lump ore particles in close proximity with each other. Like many other regions observed this is an outcome of particles deforming into each other. Even at 1 080°C, inter-particle contact points have become large ore-ore interface areas (bottom micrograph of Fig. 16). Fayalite melting temperature is normally considered to be around 1 177 to 1 205°C.\textsuperscript{15)} This would suggest that the actual sample temperature is slightly higher than the temperature indicated by the thermocouple or possibly that other lower melting temperature fayalite eutectic compounds are formed. A magnified view of the interface (top micrograph of Fig. 16) shows a densified wustite region, probably caused by the external compression force. Fayalite is scattered around the porous metallic iron grains and this region is quite porous. It would appear that this region is the periphery of the top ore particle. It is more porous compared
to the bottom ore particle and has reduced much more.

**Figure 17** shows a metallic iron region for Ore C at 1150°C. The fayalite is very well distributed within the region. Such a structure is deformable because the iron is basically immersed in liquid fayalite. The high silica content (Table 2) of Ore C means the formation of increased fayalite levels. This could increase the deformability of Ore C particles, resulting in more bed compaction. However the bed deformation of Ore C is delayed until higher temperatures because of the slower reduction and it is also a strong function of ore porosity and this will be discussed in a later section.

**Particle-particle interfaces**

The two micrographs in **Fig. 18** also show the compliant nature of the ore particle periphery on reduction. The top micrograph shows an ore-coke interface and the bottom micrograph show an ore-sinter interface. In both cases the ore particle has ‘wrapped around’ the other particle. The metallic iron adjacent to the coke particle is present as a dense rim. The higher carbon content could have lowered its melting point to cause the formation of this dense rim. The bottom micrograph shows very clearly that at 1300°C the macro-structure of the sinter particle still has the typical original sinter structure. A dense metallic rim is present at the ore particle interface but this is not as dense as the one in the top photograph. When the sinter and lump ore particles are pushed into each other by the external force the contact regions will bear the brunt of the force and, hence, will experience the greatest compaction.

**Ore porosity, size and shape**

All laboratory characterization tests for ferrous materials uses a closely sized fraction (10 to 12.5 mm) and a fixed material bed height of 70 mm. This means that for a dense material like Ore C the intra-particle pore volume of the bed will be lower and the solids content will be higher. Bed packing will essentially be a function of particle shape and size distribution and this will also determine the inter-particle voidage. The bed height and inter-particle voidage of the original ore bed will have an influence on how the bed contracts. A high inter-particle voidage bed means that particles are not jammed together tightly and so they can rearrange easier under load and this should result in greater bed com-
paction. When particles in a bed are rearranging, the movement of one particle could influence the behaviour of a large number of surrounding particles. Increasing inter- and intra-particle porosity means that generated melts have more spaces to deform or flow into and should facilitate the rearrangement of particles.

In softening and melting tests it is likely that intra-particle porosity could have a greater influence on softening and particle rearrangement. Firstly, lower porosity ores like Ore C tend to have lower reducibility and the slower reduction rate means that both wustite and fayalite formation and particle deformation is delayed. When Ore C reacts a thin layer of wustite/metallic iron/fayalite is formed on the periphery of the particles. As this layer is compliant, the particle will change in shape slightly under load and the process of rearrangement is triggered. Ores A and B have higher intra-particle porosities and the thickness of the reacted layer will be much higher. In addition, the presence of intra-particle pores also mean that softened material can enter into these pores as well, greatly increasing the ability of these particles to change in size and shape under load. This explains why bed contraction is so dependent on parent ore porosity.

Contraction and pressure drop

Results for the three lump ores indicate that there is no proportional relationship between bed compaction and pressure drop across the bed. For the same compaction the pressure drop obtained for Ore C is much higher. This could be because Ore C particles have a different shape resulting in much lower inter-particle voidage to start. This is a possibility which will have to be investigated further. The other possibility is that the wustite/fayalite/metallic iron formed is much more flowable (more fayalite in structures shown in Fig. 17). Even though the particles deform more slowly because of the reasons given earlier, the melt is capable of sealing off or hindering access to more inter-particle voids once it forms. The structure of wustite and metallic iron was observed to change considerably with temperature and this is an indication of the fluidity of the reacted products.

Figure 19 shows the changes in wustite structure from 1080 to 1300°C. At the lower temperature the structure of the parent ore is retained and wustite is dense and amorphous. At the higher temperature of 1300°C the wustite is granular and appears to have been precipitated from melt. Wustite has been quoted to melt at around 1371 to 1424°C, which is much higher than the temperatures recorded by the thermocouple at quenching. Changes in metallic iron structure were also observed to accompany the described changes in wustite structure. Figure 20 shows that the grain sizes of the iron increases considerably with increasing temperatures. The top micrograph shows that mixtures of wustite and metallic iron still have the parent ore structure but with the formation of metallic iron and significant fayalite a denser structure is obtained.

The ability of wustite and metallic iron to transform structurally at the temperatures studied is a clear indication that the reacted products are fairly fluid. Around inter-particle voids the transformation of coordination points into ‘wrap-around’ regions, as illustrated in Fig. 18, can easily hinder their role as gas channels. The photograph for Ore C at 1300°C in Fig. 6 shows a bed with much lower porosity and

![Fig. 19. Changes in wustite structure when Ore B is heated to 1080°C (top) and 1300°C (bottom). Widths of both micrographs are 0.90 mm.](image1)

![Fig. 20. Changes in metallic iron structure when Ore A is heated to 1050°C (top) and 1300°C (bottom). Widths of both micrographs are 0.90 mm.](image2)
pore connectivity compared to the other two ores. However, it is not possible to draw firm conclusions about pore properties from a single 2D bed structure micrograph. More work will be carried out in future to understand this area.

5. Conclusions

The softening and melting behaviour of three lump ores and a fluxed sinter was determined. Tests were also carried out using mixtures of lump ore and sinter. On their own beds of lump ores contracted at lower temperatures than the bed of sinter. The pressure drop across the beds was also higher because contraction of the beds during a test was a direct result of particle rearrangement leading to the densification and the loss of inter-particle voidage. Fayalite, a low temperature liquid, forms on the periphery of lump ore particles early and the deformation of this layer facilitates the rearrangement of particles. The fluxed sinter, although a more porous material, remains structurally intact until higher temperatures are reached.

Results obtained for mixes of sinter and lump ores showed that the contraction behaviour of a bed composed of 20% lump ore and 80% sinter was very similar to the results obtained for the sinter only test. It is clear that there is interaction between the two ferrous materials during a test. Fluxed sinter has been able to retard the early deformation of the lump ore particles. Because of this the pressure drop across the bed has also reduced.

Softening and melting tests are used very widely to provide assessments of how ferrous materials perform in the cohesive zone of a blast furnace. The standard test involves using only single materials. This means that a common conclusion obtained from standard tests is that lump ores are inferior furnace feed materials compared to fluxed sinter. Results obtained using mixes of lump ores and fluxed sinter indicate that at the 20% lump ore level results are as good as those obtained for the sinter only test. It is clear that tests involving only single materials can give misleading results because the ferrous material types interact in the test. Fluxed sinter is able to ‘carry’ 20% lump ore with no adverse effect. This could explain why many blast furnaces around the world operate with around 20% lump ore in their ferrous burden without cohesive zone or permeability problems.11)

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