Evaluation of High Temperature Properties of Blast Furnace Burden

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High temperature properties of blast furnace burden refer to physical and chemical conditions of the burden materials in the high temperature zone, as well as the interaction between the different materials in the burden during slag formation and meltdown. Tests in industrial scale furnaces and in the LKAB experimental blast furnace have shown that all three of these properties must be considered in order to optimise burden properties. The ability of laboratory tests to simulate these behaviours is quite limited and test results from laboratory scale should be treated with caution.

Keywords: blast furnace, ferrous burden, standardized testing

1st International Meeting on Ironmaking, Belo Horizonte, Brazil. September 24-26, 2001.

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1 INTRODUCTION

LKAB has tested numerous pellets types and trim additives in both commercial scale furnaces and in the experimental blast furnace in Luleå, Sweden. A program for the development of a new generation of blast furnace pellets to augment the current MPBO and KPBO olivine pellets was initiated in the early 1990's. Several full-scale blast furnace trials of new pellet concepts were tested in blast furnaces in Sweden in 1994 and 1996, with valuable information provided in each case. The pace of development was limited in testing on a commercial scale, and in 1997 the experimental blast furnace was constructed to accelerate development and provide more flexibility in testing, as well as allow for optimisation of pellet behaviour prior to commercial testing.

The pellet development program has shed much needed light on the relationships between behaviour of burden materials in the laboratory and the blast furnace. The high temperature properties – that is behaviour at temperatures higher than the reserve zone temperature of about 1000°C – have been found to be significant under certain conditions. Reduction strength, swelling and melting-dripping behaviour must all be acceptable, otherwise the furnace becomes unstable and inefficient. However, the laboratory tests sometimes give good or conflicting values for pellets with poor behaviour in the blast furnace.

2 DEFINITION OF HIGH TEMPERATURE PROPERTIES

The high temperature properties of the ferrous burden is being considered as any behaviour occurring after the pellets have passes through the reserve zone, e.g. after about 1000°C.

The evaluation methods for describing high temperature properties can be divided into 3 categories:

1. narrow context to describe the reduction, degradation and softening-melting behaviour in laboratory scale testing;
2. material condition and softening-melting behaviour under operational conditions evaluated by dissection after quenching or by burden probing; .
3. behaviour which can seen directly under normal operation.

The first definition presumes that the behaviour measured in the laboratory is similar to the behaviour under blast furnace conditions and therefore can be related to blast furnace operation. This connection has met with success under some circumstances, such as the case at former British Steel[1] whereby the large amounts of residual material in a meltdown test has been linked to high fuel consumption and poor desulphurisation. A similar case was presented by China Steel[2] whereby high resistance to gas flow in the blast furnace was linked to high temperature permeability and large amounts of residual material in a laboratory meltdown test. In extreme cases of catastrophic swelling or very poor reducibility the behaviours are also related.

The second definition relies on data from blast furnace dissections and in-burden probings. The data may be difficult to transfer and apply to other situations due to differences in furnace construction, blast conditions, charging, materials, and so on. The data are, however, more reliable but require much more effort to obtain and methods are not easily standardised. The LKAB experimental blast furnace is well equipped for these types of evaluations and methods have been developed to give standardised results for comparison of material behaviour determined after quenching and excavation.[3]

The third definition is perhaps the most useful, as it describes what the operator sees during normal operation of a blast furnace. Several examples will be presented from our work on pellet development. Some types of pellets with greatly differing high temperature properties show no difference in blast furnace operation. If the high temperature properties of two materials are different as measured in the laboratory, but no one can see the difference in the furnace, does it matter? Perhaps it does, when the furnace conditions change, or when materials are mixed.

2.1 Categories of high temperature properties and behaviour

High temperature properties of ferrous burden reduced in the blast furnace can be divided into 3 areas:

- physical condition of burden at high temperature
- chemical condition of burden (e.g. reduction extent, alkali pick-up)
- melting and dripping behaviour, including interaction with coke and slag formers

These areas are related as the reduction rate affects breakdown and melting behaviour, for example. For simplicity the behaviours will be described individually. Examples of blast furnace behaviour with pellets of different high temperature behaviours will be shown. Work in full scale furnaces in the early and mid-1990's with experimental high iron content fluxed pellets, followed by experiments in the experimental blast furnace, has identified critical factors for LKAB pellet quality.

3 IMPACT OF HIGH TEMPERATURE PROPERTIES ON THE BLAST FURNACE

3.1 Physical condition of burden

The most common laboratory scale tests for evaluating the physical condition of pellets during high temperature reduction are swelling and reduction strength. The following evaluations of swelling and reduction strength are examples of tests that can give false information.

The swelling test used internally in LKAB, called SW1000, is similar to the standardised swelling test ISO 4698, but with rougher testing conditions to make the test more decisive. Test equipment is the same for the swelling tests, using a platinum basket for 18 pellets kept separately in a tube furnace, but with test temperature higher and gas composition with a stronger reducing power for the SW1000 test. After the tests the swelling degree of pellet samples are determined according to ISO standard, i.e. examination of volume change during reduction. The main differences between the swelling tests are shown in Table I.

Table I: Comparison swelling tests ISO 4698 and SW1000.

	ISO 4698	SW1000
Test temperature, °C	900	1000
Gas composition, % CO/N_2	30/70	40/60
Gas flow, Nl/min	15	20
Reduction time/extent	20 min	to 80 % reduction degree
Swelling measurement	Volume change	Volume change (exactly as the ISO test)

At LKAB the reduction strength, called ITH, is determined by a mechanical treatment of pellets reduced in the standardised reducibility test ISO 4695. The sample (with a mass of just over 400g, initially 500 g before reduction) after the ISO 4695 reducibility test is reloaded into a 130 mm inner diameter drum of 700 mm length. The drum is then revolved at 20 rpm for 600 turns such that the sample falls from one end of the other (700 mm fall) 1200 times. After mechanical treatment in the ITH drum the sample is sieved for +6.3 mm and –0.5 mm. The result is presented as the fractions (%) +6.3 and –0.5 mm respectively.

Figure 1 shows an example of a relationship found between swelling and reduction strength for pellets produced in pot scale and for some pellets produced in industrial scale. The swelling test does show strong differences between pellets. These results are, however, extremely misleading.

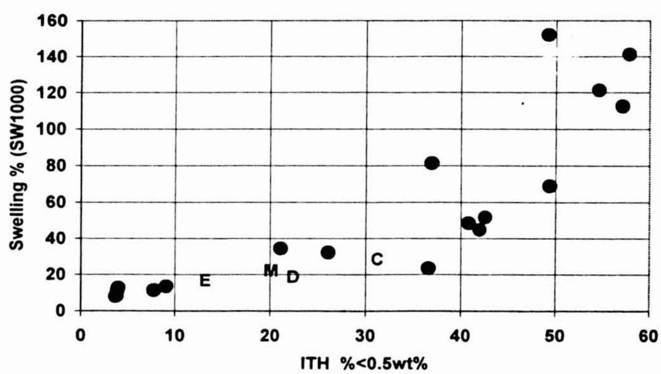


Figure 1. Relationship between swelling and reduction strength
Legend: • : a series of test pellets produced in a laboratory pot furnace
C, D, E : pellets produced in production scale and tested in the experimental blast furnace
M : commercial MPBO pellets (olivine-fluxed pellets)

Drawbacks to using the swelling or ITH to determine quality, as well as the importance of these properties in the blast furnace can be seen in Figure 2. The experimental pellets A1 are shown after reduction in a blast furnace shaft[4], showing significant swelling and cracking. The experimental pellets B in Figure 3, taken from the same blast furnace shaft, show much less swelling and cracking, but the both types of pellets showed low swelling values in the laboratory. Figure 4 shows MPBO pellets taken from the lower shaft of the experimental blast furnace. The behaviour of MPBO pellets is consistent between the laboratory and the blast furnace, with good reduction strength and low swelling.

A small amount of sulphur added to the gas in the swelling test caused catastrophic swelling behaviour in pellet type A. However, sulphur compounds, as well as other potentially important trace components, are not included in the standard swelling test, or any standard tests, thus severely limiting the tests' reliabilities.

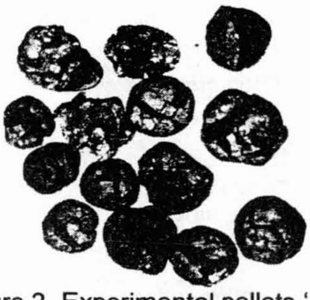


Figure 2. Experimental pellets 'A1' taken from a blast furnace, extreme cracking and swelling.

Figure 3. Experimental pellets 'B' taken from a blast furnace, limited cracking

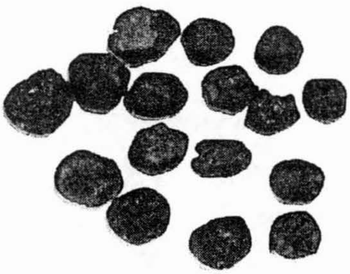


Figure 4.MPBO olivine pellets taken from the experimental blast furnace, with no evidence of swelling.

The behaviour of the blast furnace when severe swelling occurs can be seen in the stability of the gas utlilisation, Figure 5. The pellets used in Figure 5, marked as type C in Figure 1, exhibit similar swelling behaviour to the pellets shown in Figure 2. The experimental furnace went through cycles of rapid reduction, the high EtaCO peaks, followed by poor gas distribution and burden descent. Once the burden slipped rapid charging occurred, followed by rapid reduction and swelling in a clear cycle.

Figure 6 shows a pellet with much lower swelling tendency, type D. The gas utilisation was far more stable. Figure 7 shows a pellet with very good reduction strength and low swelling, type E. The gas utilisation is much more stable, and overall furnace operation was quite good.

In Figure 8, showing the commercial MPBO pellets, the furnace is extremely stable. The olivine pellets show no tendency for swelling in the blast furnace.

3.2 Chemical Condition of Burden

The chemical condition of the burden is determined by the combination of phases present, and how they react at high temperatures. A simplification of this is in the reduction extent of the burden, which measures the Fe/O ratio in partly reduced ore and is usually compared on the basis of reduction rate. Other, more complex behaviour such as alkali pick-up and sulphur pick-up cannot be simulated in the laboratory.

In the laboratory, reducibility in standardised test, the ISO 4695 for example, is measured by weight loss while burden material is being reduced using CO/N_2 mixture at a fixed temperature. These tests tend to show extreme differences between materials, with several materials listed in Table II.

Table II. ISO 4695 reducibilities for several materials

	ISO 4695 R40 %/min
Pellet C	1.22
Pellet D	1.10
Pellet E	1.12
KPBO pellets	0.75
MPBO pellets	0.50
Lump ore A	0.81

Figure 5. Variation in gas utilisation for experimental pellets, Pellets C in Figure 1, which showed extremely high swelling and low reduction strength in the experimental blast furnace

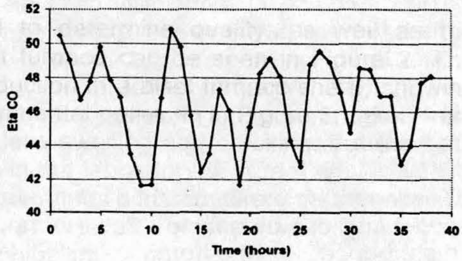


Figure 6. Variation in gas utilisation for experimental pellets, Pellets D in Figure 1, which showed reasonably good reduction strength and low swelling in the experimental blast furnace

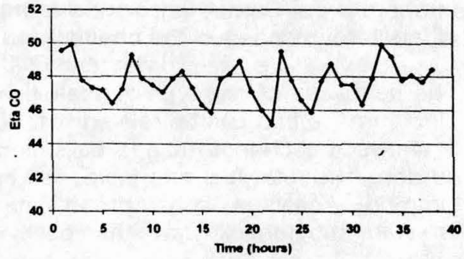


Figure 7. Experimental pellets, Pellets E in Figure 1, which showed good reduction strength and low swelling in the experimental blast furnace

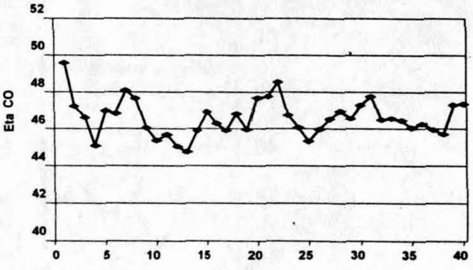
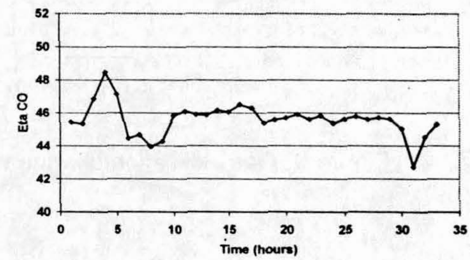


Figure 8. Variation in gas utilisation for commercial MPBO pellets in the blast furnace. In the furnace they exhibit very good reduction strength and little or no swelling, but in the laboratory test they do show a higher tendency to swell than Pellet E above.



The difference in reducibility of LKAB pellets has not had a measurable effect on blast furnace performance, except perhaps that pellet C, with a high reducibility, had poor reduction strength and swelling which resulted in the unstable operation shown in Figure 5. When the pellet properties were good, such as for MBPO and Pellet E, the blast furnace fuel rates were not measurably different despite the great difference in reducibility.

Testing in the experimental blast furnace and experiences at SSAB have shown that pellet size can be a factor. Pellets +16mm which discharge as bins empty have led to disturbances in the furnace including changes in burden permeability and gas utilisation. These disturbances have been partly attributed to lower reducibility increasing the FeO content of the pellet at meltdown and lowering the meltdown temperature. [5] Sampling from the experimental blast furnace verified the conclusions of laboratory studies of the phenomena.

The behaviour of one type of goethitic lump ore has shown to have an effect on the blast furnace that can be related to reducibility under blast furnace conditions. Figure 9 shows the change in gas utilisation with the introduction of lump ore into the burden. The total fuel rate increased by over 20 kg/thm due to the addition of 24% lump ore. Analyses of shaft probe sample showed that the reduction extents of lump ore were substantially lower than pellets, shown in Figure 10.

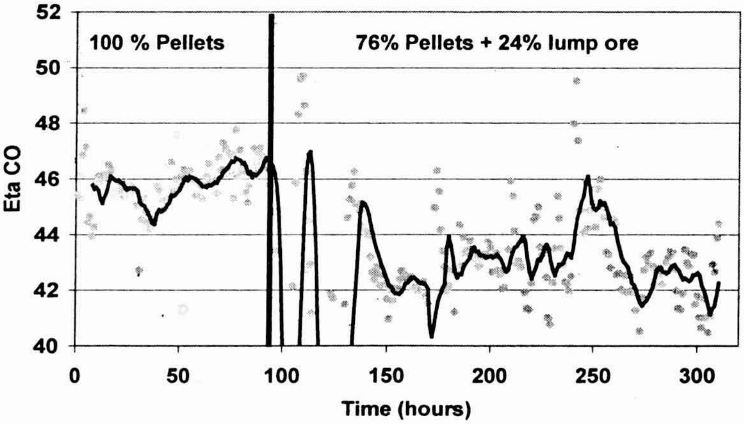


Figure 9. Gas utlilisation change with introduction of lump ore.

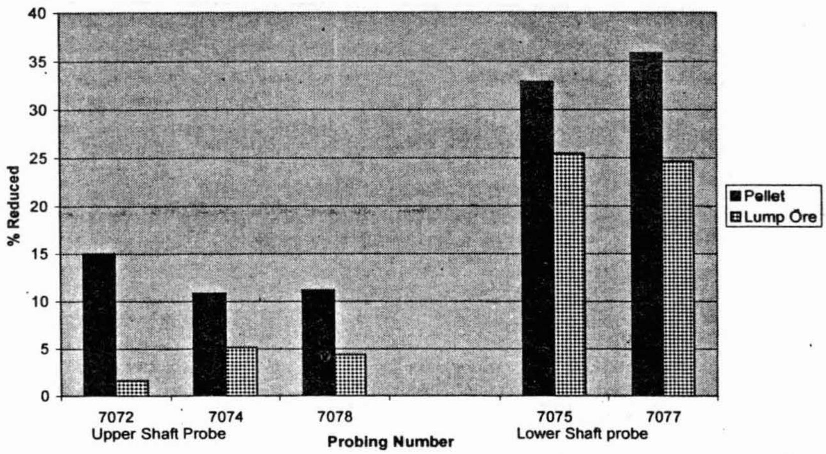


Figure 10. Comparison of the reduction of lump ore and pellets

3.3 Melting and Dripping Behaviour

Melting and dripping behaviour of the ferrous burden are perhaps the most complicated to test in the laboratory. Interactions between all burden components, e.g. pellets, sinter, lump ores, limestone, BOF-slag, coke, may be important. Therefore any laboratory testing must identify how each interaction might affect the blast furnace as well as test the material according to the physical and chemical condition to be expected in the blast furnace at meltdown. In some cases there may be successful tests for materials, as mentioned earlier.

Pellet – slag former interaction

One example of interactions affecting blast furnace operation is in test conducted on experimental pellets in a commercial furnaces in 1994 which has been described in more detail in earlier papers.[6,7] The aims were to reduce slag rate using fluxed pellets and try to utilise the higher reducibility of the flux pellets. Experimental pellets replaced standard olivine pellets in a blast furnace, and the slag rate was lowered from 155 kg/thm to about 125 kg/thm. The furnace response to the introduction of the experimental pellet and the lowered slag rate is clearly shown in Figure 11, with immediate increase in PV-bosh, where:

$$\text{PV-bosh} = (Pb^2 - Pt^2)/Vbosh^{1.7} * k$$

Where Pb = blast pressure, bar
Pt = top pressure, bar
Vbosh = bosh gas flowrate nm3/min
k = scaling constant

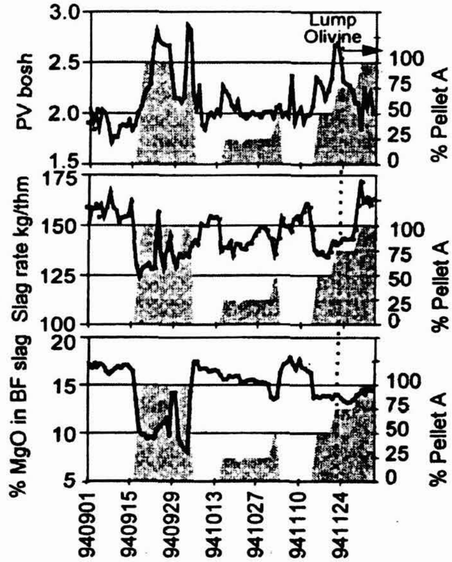


Figure 11. Trial of experimental pellets in a commercial furnace
% of experimental pellets in burden (replacing standard olivine pellets) shown by the grey shading.

In addition to the high pressure drop, tapping became difficult as there was significant hold-up of material. The addition of lumpy olivine towards the end of the test restored the furnace to a normal permeability, as noted on Figure 12. Olivine is quite unreactive and is assimilated in the dripping zone. Because olivine alleviated the permeability problem, the behaviour was associated with residual FeO being reduced from molten slags formed in the cohesive zone and dripping zone.

Laboratory testing of the pellets showed rapid meltdown and carburisation in reduction under load, marked as Pellet A in Figure 13. The melting was rapid at about 1370°C when the pellets melted and carburised taking graphite from the crucible. When a very small amount of limestone, only 10 g limestone per 600 g pellets, was added the pressure drop increased dramatically after the start of melting, shown as the simultaneous drop in temperature and increase in pressure drop, marked as Pellet A + limestone. The actual pressure drop was higher than indicated in the figure as the test had to be stopped due to an extreme pressure drop. Some small hot metal droplets were blown up through the graphite crucible in the melting chamber and into the gas outlet tube, a reaction never before seen in the equipment. Figure 13 shows the bosh slag chemistry with and without olivine. In the case of 100% experimental pellets without olivine addition, Pellet A, the bosh slag liquidus points were reaching over 1500°C in the dicalcium silicate phase field, and the addition of olivine lowered these substantially. Under normal operation the bosh slag liquidus remained close to the periclase primary phase field.

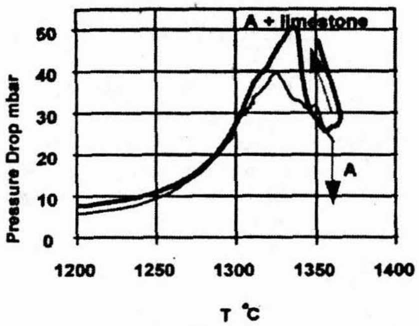


Figure 12. Laboratory meltdown test showing rapid carburisation and melting of a pellet at 1360°C, and a second test showing rapid increase in pressure drop upon the start of melting when there was a small amount of limestone added to the pellets.

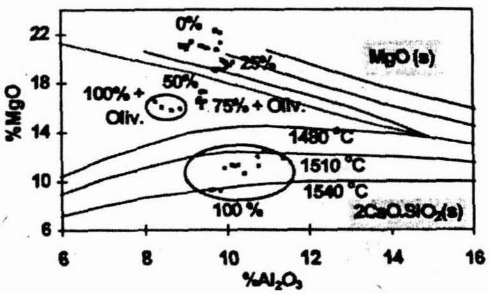


Figure 13. Primary phase fields shown for bosh slags formed with varying mixtures of pellets and lumpy olivine corresponding to the blast furnace tests in Figure 11. At 100% test pellets, without lumpy olivine addition, the primary phase field shown is dicalcium silicate with liquidus temperatures as high as 1540°C.

To alleviate the problem of high melting point slag formation, injection of BOF-slag mixed with pulverised coal was performed in the experimental blast furnace. This enabled the bosh slags to be much less basic and therefore more easily melting and less viscous as described by Ma[7]. The test was successful and a slag rate as low as 100 kg/thm was achieved using the fluxed pellets.

Sinter-Pellet Interaction

Testing of sinter has been done in two campaigns in the experimental furnace, using 2 types of commercial sinters. It is common practice to use acid pellets with sinter in order to keep the sinter more basic thereby improving sinter quality. One objective of the pellet development program was to produce a new type pellet that improves the sinter-pellet burden. LKAB olivine pellets (KPBO, MPBO), while acid in the sense that the CaO/SiO_2 ratio is very low, have much higher meltdown temperatures than acid pellets and have different behaviour.

Several compositions of olivine and quartzite fluxed pellets were tested with the sinters and sinter-flux pellet mixtures. In all cases the overall burden behaviour was reasonably good, as shown in Table III. Gas utilisation was reasonably stable, shown as the standard deviation in Eta CO, except in the case of sinter + fluxed pellets + olivine pellets, which showed slightly higher deviation. Resistance to gas flow was the same in all cases and the behaviour of Sinter + KPBO olivine pellets and of Sinter + KPB experimental acid pellets was virtually identical according to these measurements. The KPB experimental pellets were the final stage in the development of the acid pellet prior to successful industrial trails. This type of pellet is now the commercial product called KPBA.

Table III. Basic evaluation of experimental acid pellets mixed with: a) sinter and b) sinter plus flux pellets.

Test Period	Eta CO		PV-Bosh		Comment
	Average	Std.	Average	Std.	
a) Sinter + FP + KPBO	45.7	2.9	6.6	0.25	Reference
a) Sinter + FP + KBP	47.2	0.7	6.7	0.17	Improved stability (and possibly efficiency)
b) Sinter + KPBO	45.1	0.8	6.3	0.16	Reference
b) Sinter + KPB	45.8	1.0	6.4	0.14	No significant difference

KPBO = LKAB commercial olivine pellets; KPB = LKAB acid pellets;
FP = commercial fluxed pellets

However, there were some very clear differences in other relationships, for example:

- Hot metal silicon content and PV-bosh
- Hot metal silicon content and top gas temperatures

The hot metal silicon content has been chosen as a measure of the heat level in the furnace. As a measure of heat level it should also determine the pressure drop through the furnace as a high heat level should also have a wider cohesive zone with higher resistance to gas flow. The heat level could also be reflected in the top gas temperatures, with a high heat level showing higher gas temperatures, provided no serious channelling occurs.

In the case of mix of sinter, flux pellets and KPBO olivine pellets, the relationship between the PV-bosh and hot metal silicon is not very clear, as shown in Figure 14. When the furnace went from a cold to hot condition the pressure drop increased rapidly before returning to the normal operating level. In the case of sinter mixed with fluxed pellets and KPB experimental acid pellets, the relationship between PV-bosh and hot metal silicon content is clear and does not appear to display unusual peaks during transition from low to high heat level.

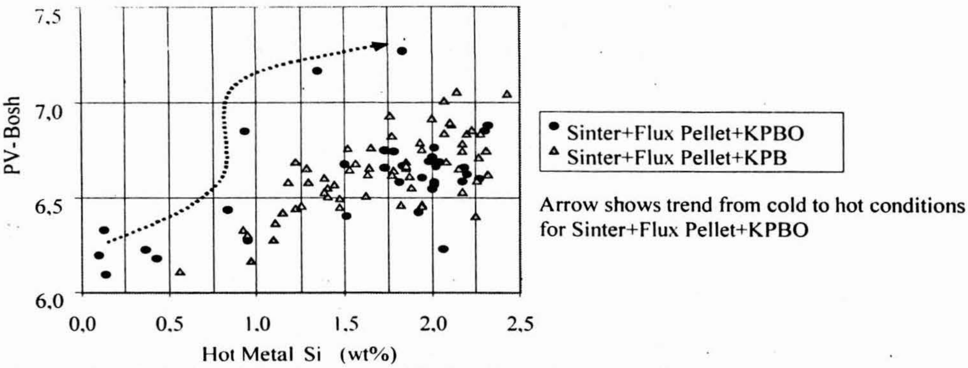


Figure 14. Relationships between PV-bosh and hot metal silicon content for sinter-pellet burdens showing a difference in behaviour between using acid and olivine pellets in the burden mix.

The relationship between hot metal silicon content and top gas temperatures can be seen using cross-correlations, which relate correlate variables according to time. These indicate that when the top gas is hot and the hot metal silicon tends to be high or low at the same time the cross-correlation at Lag 0 should be close to 1, whereas if it is no correlated the correlation should be close to zero. If there would be a consistent delay in response the curve would be shifted from Lag 0.

Figures 15 – 18 show the cross-correlations for the mixtures of sinter, fluxed pellets and acid or olivine pellets listed in Table III. It was clear from both tests that the heat level in the furnace was being reflected in the top gas temperatures for the mixtures containing the acid pellets, whereas no correlation was found for mixtures containing olivine pellets. This result, combined with the better correlation between hot metal silicon content and resistance to gas flow when using the acid pellets with sinter, led to the conclusion that the furnace was behaving in a more predictable, stable fashion due to interactions in the cohesive zone.

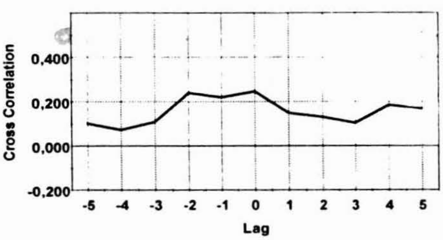


Figure 15. Cross correlation between top gas temperature and hot metal Si content burden of sinter +fluxed pellets + KPBO olivine pellets.

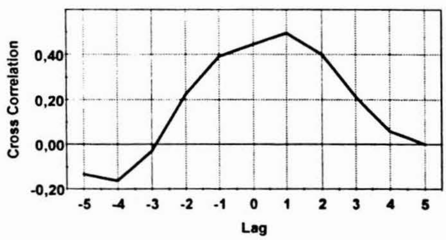


Figure 16. Cross correlation between top gas temperature and hot metal Si for content for burden of sinter + fluxed pellets + KPB acid pellets.

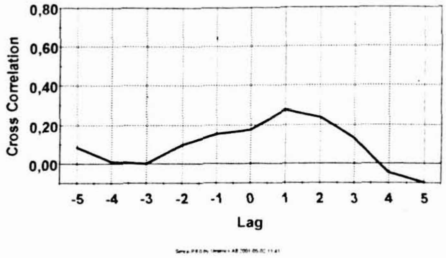


Figure 17. Cross correlation between temperature and hot metal Si content for burden of sinter + KPBO.

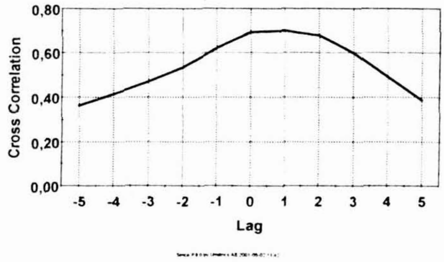


Figure 18. Cross correlation between top gas temperature and hot metal content for burden of sinter + KPB.

Pellets and lump ore

In many instances there are not necessarily any immediately visible changes despite large changes in burden mix. For example Figure 19 shows the PV-bosh for the same period as gas utilisation in Figure 9. The trial consisted a change from 100% LKAB olivine pellets to lump ore (circa 24%) mixed with a commercial fluxed pellet (circa 23%) and the balance being LKAB olivine, acid or experimental fluxed pellets. Despite of large differences in properties between 100% pellet operation and the mixtures pellets and lump ore, the furnace did not show any significant change in resistance to gas flow. Further investigation is necessary to determine the effects on the relationships between hot metal silicon content and PV-bosh or top gas temperature, for example.

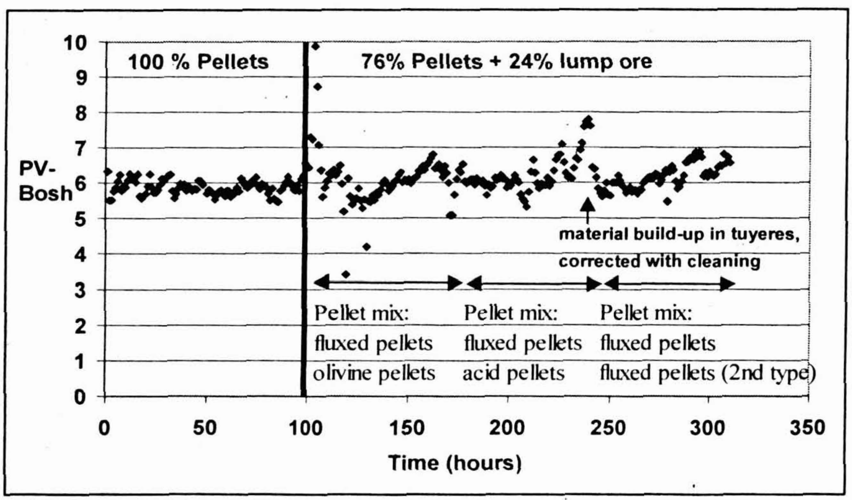


Figure 19. Reasonably stable PV-bosh for operations with 100% KPBO pellets and various mixed burdens of lump ore and pellets.

4 CONCLUSIONS

The three categories of high temperature properties of burden must be considered when evaluating blast furnace performance: physical properties; chemical properties; and melting and dripping behaviour. Laboratory scale testing can give indications of material behaviour provided the correct behaviours are evaluated under the right conditions. Laboratory scale testing is, however, never going to be 100% reliable due to the inability to reproduce complex blast furnace reduction and meting conditions.

High temperature properties of the ferrous burden must meet the following criteria *in the blast furnace* for optimised blast furnace operation:

- high reduction strength and low swelling;
- an acceptable level of reducibility, but above a certain point there is no improvement and at high pellet reducibility the reduction strength and swelling properties may worsen;
- softening, melting and dripping behaviours which give stable burden descent and reasonable pressure drops during both stable operation and typical disturbances, e.g. stops, variations in heat level. These behaviours must take into account interaction between burden components.

The interaction of burden components should be evaluated when changing mixtures to determine which furnace behaviours are changed and if the changes are significant to the blast furnace operation.

The LKAB experimental blast furnace is an effective tool for evaluating blast furnace burdens and has been extremely successful in supporting pellet development.

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