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FOREWORD

Innovation and research into mining technology is necessary to position Africa as a world leader in minerals production and beneficiation. The Young Professionals Council is pleased to host a unique, three-day online conference that will showcase a broad range of emerging research and innovation from young professionals in the metals and minerals industry. Presentations will focus on new technology, tools and techniques relevant to exploiting Africa’s mineral resources safely, competitively and sustainably.

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<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The evaluation of sintering as a cause of duct blockage in a submerged arc furnace in silicomanganese production</td>
<td>M.B. Sitefane, J.D. Steenkamp, and P. den Hoed</td>
<td>1</td>
</tr>
<tr>
<td>Characterization of a rehabilitated gold mine dump with respect to potentially hazardous radioactive elements</td>
<td>S. Mxinwa, G. Freemantle, L. Landu, O. Bazhko, and E.D. Deenanath</td>
<td>13</td>
</tr>
<tr>
<td>Validation of a new density measurement technology</td>
<td>M. Nelwamondo and S. Naik</td>
<td>25</td>
</tr>
<tr>
<td>Optimization of acid-in-agglomeration dosage and curing during percolation leaching of a west African uranium ore</td>
<td>E.D. Deenanath and P. Basson</td>
<td>37</td>
</tr>
<tr>
<td>From taylorism to safety culture and beyond: a review of orthodox and contemporary occupational health and safety management within a South African context</td>
<td>M. Goncalves</td>
<td>57</td>
</tr>
<tr>
<td>Impact breakage devices - the future of comminution technology?</td>
<td>J.S. Theron and S. Naik</td>
<td>71</td>
</tr>
<tr>
<td>The assessment of absenteeism: A case study of a platinum mine</td>
<td>N.M. Chiloane and M. Mpanza</td>
<td>81</td>
</tr>
<tr>
<td>Mineral resource optimization at Leeuwpan coal mine by monitoring the DMS discard qualities</td>
<td>S. Mpofu</td>
<td>91</td>
</tr>
<tr>
<td>Has South Africa done enough to encourage junior mining and to establish something resembling a junior mining sector?</td>
<td>G.T. Malesa</td>
<td>101</td>
</tr>
<tr>
<td>Professionalism in engineering</td>
<td>T.R. Marshall</td>
<td>113</td>
</tr>
<tr>
<td>The application of micro hydropower technology on Matla’s water reticulation system</td>
<td>M.A. Ngobeni</td>
<td>125</td>
</tr>
<tr>
<td>The study of factors influencing mining engineering as a career choice</td>
<td>N.M. Chiloane and T. Mmolah</td>
<td>139</td>
</tr>
<tr>
<td>Developing a concept that can be used to quantify the motion of flyrock, with the intention of eventually producing a measuring tool for future flyrock research</td>
<td>J. van der Walt and W. Spiteri</td>
<td>149</td>
</tr>
<tr>
<td>Improved recovery of gold encapsulated in pyrite mineral using flotation process</td>
<td>S. Nhlapo, E. Makhatha, and S. Lephuting</td>
<td>163</td>
</tr>
<tr>
<td>Title</td>
<td>Page No</td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>Performance recognition of flotation process using K-means clustering algorithm based on froth image analysis</td>
<td>173</td>
<td></td>
</tr>
<tr>
<td>Preliminary evaluation of pre-reduction of carbon-based titaniferous magnetite pellets for reduction of energy requirements in the vanadium and steel co-production process</td>
<td>181</td>
<td></td>
</tr>
<tr>
<td>Investigating the link between human reliability and mine productivity</td>
<td>191</td>
<td></td>
</tr>
<tr>
<td>Iron ore pre-concentration using the Hydrofloat® at the Minas-Rio Complex in Brazil</td>
<td>203</td>
<td></td>
</tr>
<tr>
<td>Identify and evaluate critical disruptive technologies with the potential to simplify the complexity of the mining ecosystem</td>
<td>215</td>
<td></td>
</tr>
<tr>
<td>Healthcare support for employees and local communities by mining companies during the Covid-19 Pandemic, with potential for alignment to municipal integrated development plans and mining social and labour plans</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>Fully automated coal quality control using statistical model predictive and digital twin material tracking for yield optimization during production of semi soft coking- and power station coal</td>
<td>249</td>
<td></td>
</tr>
<tr>
<td>An investigation into the possible use of an existing rotary kiln for the pilot-scale investigation of the PREMA process</td>
<td>261</td>
<td></td>
</tr>
<tr>
<td>Demonstration of experimental methods for determination of thermo-physical properties of molten salt mixtures</td>
<td>277</td>
<td></td>
</tr>
<tr>
<td>Reviewing the implications of electricity costs on the mining industry</td>
<td>289</td>
<td></td>
</tr>
</tbody>
</table>
The Evaluation of Sintering as a Cause of Duct Blockage in a Submerged Arc Furnace in Silicomanganese Production – Method Development

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A leading smelter, producing silicomanganese alloy, has been experiencing repetitive and undesired blockages in its off-gas duct. The cause of blockages is thought to be, albeit without empirical evidence, as a result of sintering of the dust as it moves along the ducts. The current study is aimed at evaluating this postulate by performing laboratory-scale sintering tests, with the view of developing a future innovative solution. As a first step, a methodology which included developing the techniques for collecting representative samples at the smelter, gathering duct temperature data, developing the laboratory-scale pellet press method and developing the laboratory pellet firing method, had to be properly developed so that the outcomes of the future sintering evaluation could be classified as valid and reliable. This paper provides the details of this method development from sampling at the smelter, all the way to firing in the laboratory.

INTRODUCTION

A leading producer of silicomanganese (SiMn) in Southern Africa, utilising Open Submerged Arc Furnace technology, has been experiencing undesirable, but nonetheless recurring, blockages of their furnace off-gas ducts (Steenkamp et al., 2018). When the ducts were inspected, the blockages were observed to comprise dust from the off-gas stream. Data solicited and obtained from both the smelter manager and operational crew revealed that, typically, the blockages are more or less cleared by external contractors during the yearly annual shutdown. Attempts to do this during the short eight-hour long shutdowns, which occur every 2–3 months, have often proven fruitless. According to several key figures at the smelter (i.e., plant manager and engineering superintendent), the former approach to dealing with duct blockages has several disadvantages. The major two disadvantages are complications incurred on the baghouse and the high cost associated with clearing blockages. As a result, the smelter manager was interested in evaluating an alternative, more cost-effective and time-saving solution to this problem.

It was clear to all personnel at the smelter that a good understanding of the cause of blockage was important as a first step in devising a solution. This means that before a solution can be offered to the problem, an investigation needs to be undertaken to understand the cause(s) of the problem. Several personnel at the smelter (including the manager) postulated that the main cause of the duct blockage is the sintering of dust along the inner walls of the ducts. Despite this possibility, no empirical investigation has been conducted to confirm whether or not the dust actually sinters under the conditions encountered in the ducts. The aim of this study is to evaluate this possibility by testing the sintering behaviour of samples of dust in the laboratory. The research questions addressed by this evaluation are—

1. What is the observed mechanism of sintering under the given conditions? Is it solid-state sintering, or liquid-state sintering, or a combination of the two? Does sintering even occur?
2. What is the effect of temperature on sinter formation and strength for a given particle size distribution (PSD)?
3. What is the effect of PSD on sinter formation and strength at fixed temperatures?

As in every laboratory-based investigation, the applicability of the investigation is largely dependent upon a well-structured research method. In this case, it meant that the dust sampling system employed, firing temperatures used for the laboratory sintering evaluation, laboratory-scale test work set-up, amongst other things, had to be designed in such a way that no unintended bias was introduced that would compromise the research outcomes (i.e., to produce valid and reliable data). For this to happen, the research method had to be carefully constructed upfront. In this paper, the research method employed prior to the actual investigation is discussed.

BACKGROUND

In this section, reasons are provided and discussed as to why the method had to be developed.

Operational Improvements
As noted by the smelter personnel, a blockage of the duct has several adverse consequences for furnace operations. Examples include its reducing the effectiveness of the baghouse, increasing the threat of manganism due to increased fugitive emissions (especially around the furnace bed area and dust carried by wind to nearby communities); decreased visibility can obscure workers’ vision around the furnace bed, posing potential safety threats; and potential pollution of air and water. A better solution—one based on information gathering informed by a well-constructed research method—would significantly reduce these problems.

Shutdown Improvements
Similar to operational improvements, an alternative solution would potentially improve the time taken to clear blockages, reduce refractory, shell and electrode damage associated with duct blockage clearance practices, and minimise contractors’ exposure to safety risks associated with clearance practices.

Nature of Laboratory Experiments
Laboratory-scale investigations, whilst having their limitations, are usually a good first step for investigating industrial problems, along with computational modelling. One of the major advantages of a laboratory-scale investigation is that well-designed fundamental test work can be conducted where conditions are under the control of the experimentalist (Geldenhuys and Jones, 2011). Although, as previously mentioned, laboratory experiments do have their limitations, e.g., challenges related to scale up (ibid.), tests conducted using well-structured method can provide useful data and correlations. Geldenhuys and Jones (ibid.) noted that laboratory experiments have been used in past studies to evaluate the viability of new resources for metallurgical applications, as well as for modifications to existing processes.

Technology Transfer
A well-formulated method would produce reliable and useful outcomes with solutions that could be applied to other metallurgical processes.

METHOD

The method development focussed on four primary areas as indicated in Figure 1. The first two areas, known as phase 1, were entirely plant-based. Phase 2 on the other hand was entirely laboratory-based. Details of (1) the reason why each specific area was developed and (2)
the procedure undertaken in each of these areas are discussed for each area.

Phase 1 — Area 1: Smelter Dust Sample Collection

Reasons for Development of the Dust Sample Collection Method
Three reasons are cited to underpin the necessity of method development in this area: (1) the need for the collected sample to be representative of the typical smelter dust despite normal operational changes, (2) the need for a non-biased sampling approach within the given smelter constraints, and (3) the need to collect from each stream samples that represent the PSD of that stream.

Figure 2 shows a diagrammatic representation of the plant flowsheet; it shows the different dust streams where samples were collected.

Procedure Undertaken
In the end, bearing in mind time, smelter, and cost constraints, it was decided that a systematic approach be adopted for sampling. This entailed collecting samples at the smelter over a period of three months. During this period ten days were spent at the smelter; these were broken down into five visits (a visit almost every second week), with each visit lasting two consecutive days.
On each visit, samples were collected at two-hourly intervals between 8 am and 4 pm (i.e., a total of eight hours). A closed scoop was used to draw (from inside the storage bins in the case of stream 1 and stream 2, and from a stockpile in the case of stream 3) between 0.8 and 5 kg of multiple grab samples around the conically shaped sample lot. These samples were then temporarily stored in separate metal drums to allow them to cool. Once cooled, the samples were transferred to their respective labelled plastic bags and then stored for future use. This process was repeated for each interval over the course of the three months. Selected images of the sampling process are shown in Figure 3.

Figure 3. Selected photographs taken during the sampling process: (a) opening of cyclone bin before collection of sample (stream 1), (b) entrance inside the bin, (c) collection of sample using a sample scoop, (d) collection of sample from the silo discharge (stream 3)

**Phase 1—Area 2: Smelter Duct Temperature Data Collection**

**Reasons for development of the dust sample collection method**

The reason for embarking on duct temperature measurements was so that the typical temperatures encountered in the duct where blockages normally occur could be known, and then used in the future laboratory-scale sintering evaluation.

**Procedure Undertaken**

Two possible options were explored as potential procedures that could be used to measure the duct temperature. The first option explored was to insert multiple thermocouples across the duct area where blockages are commonly encountered. However, after consultation with the smelter manager and production superintendent, the high cost associated with this exercise (including the costs of repairing damages to the steel structure caused by drilling into the shell to install the thermocouples), along with fears from previous experience that the installed thermocouples may be damaged by dust-laden off-gas and thus prove ineffective, eliminated this option.

A more feasible option, the one settled upon, was to make estimates of the typical temperatures encountered in the duct by using a combination of methods to approximate the minimum and maximum duct temperature. Using this approach, the furnace bed (i.e., furnace burden), which is the...
point at which the dust-laden off-gas typically vents from the furnace, was taken as the maximum temperature. It is acknowledged that because the furnace bed was 3 m away from the actual duct, its temperature would probably be higher than that actually encountered in the ducts. At the other end, the upper portion of the duct (i.e., duct cap) was used as an estimate of the minimum temperature. Fortunately, the furnace was already equipped with a thermocouple that continuously measured the dust-laden off-gas temperature in that section. Again, as with the maximum temperature, the duct cap was some distance away from the main section of the duct; thus it was acknowledged from the outset that the duct-cap temperatures in reality would be lower than those encountered in the duct. To pictorially illustrate the approaches employed,

Figure 4 shows images of the position of the minimum and maximum temperatures along the duct.

Figure 4(c) is particularly helpful in illustrating this.

![Figure 4](image)

**Figure 4.** Photographs of (a) the hot furnace bed appearance during operations (max temperature) and (b) the duct cap thermocouple positioning (min temperature). Schematic diagram (c) showing the positioning of the maximum and minimum temperature measurements (values represent close approximates based on engineering drawings, in metres).

The procedure used for collecting typical temperature data on the furnace bed and cap end of the duct was as follows:

- For the furnace bed (maximum temperature): A calibrated optical pyrometer, set at an emissivity of 0.7 ⦅ (based on experience as many factors are at play in the furnace bed), and a distance of infinity (to cover the distance of 7 m between bed and probe). Measurements were taken in two-hourly intervals between 8 am and 4 pm, over a total of four days in January 2019 (this period covered every variation occurring in operation, from furnace feeding rate changes to tapping). During each interval, four readings were captured as shown in the results and discussion section.
- For the duct cap (minimum temperature): The production superintendent provided graphical data of the temperature change in the duct cap over a period of five days.
Phase 2 — Area 3: Laboratory Pellet Method Development

Reasons for the Development of the Dust Sample Collection Method
As demonstrated by several authors, the formation of pressed pellets is an effective way of evaluating sintering behaviour (Adell et al., 2007; Romero et al., 2008). Three reasons are given as to why the pellet press method was developed: (1) to determine the water addition, pellet pressure, and days of drying time needed to form a stable pellet; (2) to determine a suitable pellet-pressing pressure that would not alter the dust PSD, especially as PSD is one of the variables in this study; and (3) to determine the pellet compression strength sensitivity to pellet height changes within the same stream - this has an automatic effect on the procedure that must be used for preparing pellets.

Procedure Undertaken
For each stream, 200–400-g samples were weighed and placed in containers. Water to several degrees—i.e., 0, 2, 5 and 10% (calculated as a percentage of the sample mass)—was then added to the sample and the two were mixed thoroughly until a consistent appearance was achieved. From the mixture, a sub-sample was withdrawn and then placed in a cylindrical steel mould, where with a hydraulic press it was pressed into cylindrically shaped pellets. Different hydraulic press pressures were applied, namely, 3.5, 5, 7.5, and 10 MPa. The pellets thus formed were then oven dried at a temperature of 105°C for different time spans—1, 2 and 4 days. After drying, some of the pellets were selected for compressive-strength testing in an Instron instrument. Table I summarizes the parameters applied for each stream during pellet formation.

Table I: Summary of the parameters used during pellet formation as part of the method development

<table>
<thead>
<tr>
<th>Stream</th>
<th>Mass of pellet (g)</th>
<th>Water (%)</th>
<th>Pressure (MPa)</th>
<th>Drying (No. of days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37-40</td>
<td>0, 2, 5, 10</td>
<td>3.5, 5, 7.5, 10</td>
<td>1, 2, 4</td>
</tr>
<tr>
<td>2</td>
<td>30-38</td>
<td>0, 2, 5, 10</td>
<td>3.5, 5, 7.5, 10</td>
<td>1, 2, 4</td>
</tr>
<tr>
<td>3</td>
<td>24-28</td>
<td>0, 2, 5, 10</td>
<td>3.5, 5, 7.5, 10</td>
<td>1, 2, 4</td>
</tr>
</tbody>
</table>

Phase 2 — Area 4: Laboratory Muffle Furnace Firing Test Set-up

Reasons for Development of the Dust Sample Collection Method
Two reasons are given that show the need for developing this area of the method. First, the hot zone of muffle furnace needed to be established such that pellets would not be subjected to different temperatures. Muffle furnaces are notorious for having steep temperature gradients. Secondly to validate the heating profile (especially the consistency for various temperature set-points) as well as the accuracy of the furnace temperature.

Procedure Undertaken
Procedure 1—to determine the heating rate and validate temperatures: A K-type thermocouple was placed through a thermocouple port in the door of the closed muffle furnace (see labelled photograph in Figure 5). The tip of the thermocouple was made to contact the back end of the furnace. The furnace heat-up started at room temperature, with a heating rate of 10°C/minute applied (i.e., the typical heating rate used for muffle furnace operations). Three tests were run to final temperatures of 600, 700, and 800°C. In order to evaluate the heating rate, recordings of the programme, the furnace, and the data logger temperature were taken at 5-minute intervals. From these recordings, graphs depicting the temperature profiles of the furnace chamber were constructed.

Procedure 2—to determine the temperature gradient across the length of the furnace: A temperature gradient measurement at each of the final temperatures stated was commenced once the data logger
temperature had stabilised (i.e., about 10–15 minutes after reaching temperature). As the muffle furnace is 45 cm in length, it was decided that temperature recordings be taken every 5 minutes in 4 cm intervals using the same K-type thermocouple. As such, the temperature recordings were taken at 45 cm (i.e., back of muffle furnace), 41, 37, 33, 29, 25, 21, 17, 13 and 9 cm (close to the furnace door). Recordings at 5 cm and 1 cm were not taken as the furnace was visibly cold in this area. Graphs showing the outcome of recordings are shown in the result and discussion section.

Figure 5. Photograph showing muffle furnace set-up for firing test method

RESULTS AND DISCUSSION

This section discusses the main outcomes of each of the areas highlighted.

Phase 1 – Area 1: Smelter Dust Sample Collection
At the end of the three months a total of ~136 kg, ~299 kg, and ~70 kg of dust from stream 1, stream 2 and stream 3 respectively was collected; this added up to ~505 kg of dust across the three streams for the three months.

Phase 1 – Area 2: Smelter Duct Temperature Data Collection
Table II gives a summary of the main details of the recorded temperatures for the furnace bed as well as the duct bed. From these temperatures, the minimum and maximum decided on for the laboratory sintering evaluation were 600°C and 1300°C respectively. The minimum of 600°C was selected as the average temperature during furnace operation (i.e., when power was in) was slightly above this value. Furthermore, examination of the actual data showed that there were only a few temperatures below this mark. On the other hand, 1300°C was selected as the maximum temperature for two reasons. First, three of the maximum temperatures were found to be above 1300°C, but the 3-m gap between the duct and furnace bed would lower this temperature. Secondly, the average temperature for all the positions was around 1200°C (i.e., below 1300°C). A balance of these two extremes is covered by the 1300°C maximum temperature.

Table II. Summary of the main data gathered for the furnace bed (i.e., position 1–4) and duct cap temperature (i.e., with power in and out)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Phase 2 — Area 3: Laboratory Pellet Method Development

Table III summarises the results obtained during the development of the pellet-press method. From the table it can be seen that the best combination of water, pressure, and oven drying time was 5%, 5 MPa, and one day respectively. Reasons for this were that water additions below 5% and pellet pressures below 5 MPa yielded weak pellets (i.e., pellets that easily disintegrated). The drying time on the other hand was found to have no effect on pellet formation and thus one day was deemed best.

The results of the effect of pellet pressure on the PSD of the pellets are shown as SEM images in Figure 6. It was clear that there was no significant difference in the PSD of the dust material regardless of the pellet pressure applied in preparing the pellets. Minor differences between the as-sampled dusts to that of the pressed pellets were solely as a result of the compaction of pellets (i.e., more particles in the same volume for compacted pellets).

Figure 7 shows graphically the effect of pellet height on compressive strength for material from each stream. It is clear from these graphs that there was no tangible relationship between the two parameters. Furthermore, despite changes in height, compressive-strength measurements fell within a reasonable standard deviation.

Table III. Summary of the tested pellet-formation parameters (best outcome highlighted in comment)

<table>
<thead>
<tr>
<th>Water</th>
<th>Pressure</th>
<th>Drying time</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
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<td>Best</td>
</tr>
<tr>
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</tr>
<tr>
<td>2</td>
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</tr>
<tr>
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<td>7.5</td>
</tr>
<tr>
<td>10</td>
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</tr>
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</table>

(a) Stream 1 – as sampled (b) Stream 1 – 3.5 MPa (c) Stream 1 – 5 MPa
Figure 6. SEM BSE images showing the effect of pellet pressure on the PSD of the pellets for stream 1–3 (stream 1 has predominantly coarse particles with very few intermediate and fine particles, stream 2 has mainly intermediate-sized particles, and stream 3 has very fine particles).
Figure 7. Benign effect of changing pellet height (for the same pellet diameters) on the compressive strength for all the dust streams

Phase 2—Area 4: Laboratory Muffle Furnace Firing Test Set-up
The temperature profiles for heating to a temperature of 600, 700 and 800°C with a 10°C/min heating rate are depicted graphically in Figure 8. It is clear that the 10°C/min set rate was consistently achieved in all tests. One consistent discrepancy observed in all the graphs was that from around 250°C, the data logger temperature was observed to be higher (by about 10–20°C) than both the programme and furnace temperature. This necessitated an adjustment in the programme temperature such that the actual targeted temperature could be obtained. Thus, to achieve, for example, a data logger temperature of 600, 700 and 800°C, the programme had to be set at 580, 680 and 783°C respectively. The same was true for higher temperatures i.e., 900 to 1300°C.

Figure 9 shows graphically temperatures recorded across the length of the muffle furnace when the furnace was at 600, 700 and 800°C (i.e., the data logger temperature). One observes a uniform hot zone that spanned 20 cm (i.e., between 25 to 45 cm) of the furnace. This means that pellets were restricted to this area to ensure that they were all subjected to the same temperature.
Figure 8. Graphs of heating profiles for a targeted temperature of (a) 600°C, (b) 700°C and (c) 800°C. Heating rate of 10°C/min; DL = data logger thermocouple, PT = programme temperature, and FT = furnace temperature.

Figure 9. Temperature gradient across the length of the muffle furnace for targeted temperatures of 600, 700 and 800°C (the front of the muffle furnace was at 0 cm, the back side was at 45 cm; the hot zone was between 25 and 45 cm for all temperatures)

CONCLUSIONS

A useful method was developed by conducting plant-based and laboratory-scale test work. The next steps of the project are to conduct the laboratory-scale test work where sintering of the dust-stream 1 to 3—will be evaluated. The dust will be fired to temperatures from 600 to 1300°C in 100°C steps. All fired product will be examined for sintering using a combination of compressive-strength tests and analysis of phase-chemical compositions by means of scanning electron microscopy coupled with energy dispersive spectroscopy (SEM-EDS), as well as X-ray diffractometry (XRD).

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