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Assessment of Foundry Chromite Sand Crushability under Thermal-Mechanical Loading

J.K. Kabasele [a] *, K.D. Nyembwe [a], H. Polzin [b]

[a] Department of Metallurgy, University of Johannesburg, 55 Beit Street, Doornfontein, Johannesburg, South Africa

[b] Peak Deutschland GmbH, Dresdner Straße 58, 01683 Nossen, Germany

*Corresponding author: E-mail address: kabasele.jonathan@yahoo.fr

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Abstract

When used for sand casting, foundry sand is stressed in several ways. These stresses, thermal and mechanical, compromise the grain integrity, resulting in size reduction and the production of small particles to the point where the sand is no longer viable for sand casting. This study evaluates the crushability of chromite sand, a crucial characteristic for determining how resistant sand is to size reduction by crushing. To replicate the heat and mechanical strain that sand is subjected to during the industrial sand-casting process, a sinter furnace and rod mill were employed. After nine minutes of heat and mechanical stress application, the crushing ratio, which was used to gauge the crushability of chromite sand, ranged from 1.72 to 1.92 for all samples. There were differences in the rate at which fine particles were produced among the samples, with sample E producing the highest proportion of fine particles in the same length of time.

Understanding the properties that control the crushability performance of chromite sand will enable foundries to buy chromite sand with higher recycling yield, reducing the environmental impact of waste foundry sand and eliminating the risk to the workforce's pulmonary health in line with the current industry standards. Foundries will also be able to optimize the current industrial process while continually pushing for innovative foundry technologies and materials.

Keywords: Innovative foundry technologies and materials, Environment protection, Crushability, Chromite sand, Moulding aggregates

1. Introduction

As a moulding aggregate, chromite has several advantages over foundry silica sand. It has a significantly lower coefficient of thermal expansion and a superior thermal conductivity. Chromite sand can be a substitute for silica sand in the casting of high alloy steel since it is chemically inert to alloying elements such as manganese and chromium [1]. In addition, exposure to silica dust puts the workforce at risk of contracting severe pulmonary diseases, such as silicosis and lung cancer. Furthermore, pre-existing pulmonary diseases, like silicosis, put the workforce at higher risk of contracting more severe forms of Covid-19. This should provide a strong incentive for foundries to look for healthy alternatives, such as chromite sand [2].

Most studies on the properties of foundry sand have been conducted on foundry grade silica sand because it is the primary moulding aggregate for foundry applications. Studies have been conducted to a lesser extent on the other foundry aggregates, namely zircon, olivine and chromite. This is also true for the assessment of the crushability performance of foundry aggregates, that was solely focused on silica sand [1,3].

The ability to crush material, such as rocks, sand, and ores, is determined by a property called crushability. Simply put, crushability measures the resistance of material to crushing under standard conditions. As increasing levels of stress are applied to materials, they break into finer particles. Depending on the nature of the stress applied and the material's characteristics (physical and geological), crushability will differ from one material to another [3].

1.1. Relevance of crushability to the sand-casting process

Fig. 1 shows the types of stress on sand grains at different stages of a typical sand casting process, during which the crushability of the sand is significantly affected. At each stage, the sand is subjected to mechanical stress, thermal stress or a combination of both. Firstly, the new foundry sand goes through moulding where it is placed in mixers or mullers and subjected to mechanical stress. Once the sand mould has achieved the required level of strength, molten metal is poured into the mould. The rapid rise in temperature subjects the sand to severe thermal stress and metallostatic pressure, resulting from the heaviness of the metal. The thermal shock experienced by the sand grains weakens their cohesion, causing further breaking. The sand grains experience further thermal stress as a result of the rapid cooling taking place in the heat-diffusing metal. Finally, during reclamation, the sand experiences both thermal and mechanical stress. During reclamation a large amount of sand is lost as fine particles [3,4].

At the end of a sand-casting cycle, depending on the crushability of the sand, foundry sand generates a moderate to a large amount of fines. Investigation into the crushability of moulding sand is important to the foundry industry, since this property has several ramifications for the environmental, economic and health aspects of the industry. The resistance of the sand to crushing affects foundry properties, such as permeability and resin addition. An excessive amount of fines generated increases the percentage of waste, resulting in financial and environmental costs. Even more worrying, the exposure to a large quantity of fine particles is detrimental to the pulmonary health of the workforce [2,5,6].

The generation of fines has negative repercussions on the reusability of the sand. It is not uncommon that fine particles have to be replaced by virgin sand after sand reclamation. In some cases, up to 50% new sand is required. The increasing cost of landfill acquisition and sand waste disposal has forced the foundry industry to develop new methods to improve the reclamation process. The crushability of sand, a good predictor of fine particle generation, should be used to determine sand selection in order to increase the efficiency of sand reclamation and reduce the financial cost of sand waste [5].

Sand handling processes amount to about 5 - 10% of the total energy used in foundries specialised in the casting of steel components. However, almost all of the solid waste generated in foundries are is a result of sand handling processes. While most studies on sustainability focus on the efficiency of the plant as a whole, it is evident that the sand handling process should be given as much if not more attention. Studies on the crushability of chromite sand become even more relevant as they could assist foundries in making an informed selection of higher quality sand based on reusability and sustainability [5].

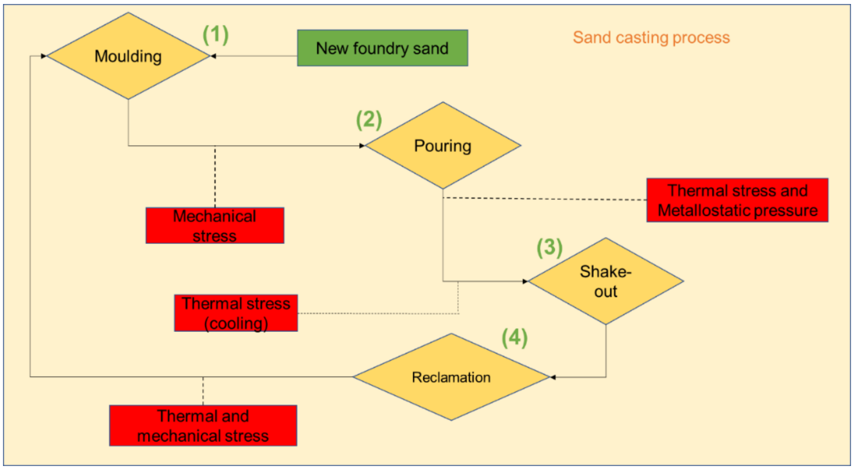


Fig. 1. Types of stress acting on sand grains in a typical sand casting process [3]

1.2. Crushability of chromite sand for foundry application

This work is based on a recent study conducted to assess the crushability of foundry silica sand. The study took into consideration the fact that sand grains subjected to mechanical, thermal, and thermal-mechanical loads during the sand-casting process break into smaller particles. From this observation a methodology was formulated to assess the crushability of foundry silica sand. The methodology involves evaluating the average grain size of the sand prior to and after the application of artificial stress (thermal, mechanical and thermal-mechanical). It was discovered that the larger the variation of grain size, the better the crushing effect [3].

The energy required to crush rocks is proportional to the new surface area [7]. In the field of construction, for example, a significant percentage of the energy consumed to produce construction aggregates of regular size is also spent on generating non-viable fines. This clearly establishes the relationship between size reduction and the resistance of material to crushing. Therefore, in this study South African chromite sand's crushability will be assessed in terms of the variation in the average grain fineness number (AFS number) or crushing ratio/index, the rate of fine particle generation and grain deformation. Each of these three properties affects an aspect of size reduction taking place in the material subjected to stress [3].

This work investigated the crushability of South African chromite sand samples from the top suppliers and exporters in South Africa. The properties of all samples are provided in Table 1. The properties of the South African chromite sand, including the size distribution, the chemical composition and the refractoriness were found to comply with the typical chromite sand specifications for foundry applications. In this study, the sintering temperature was determined using the procedure "Bestimmung des Sinterbeginn Nach VDG-Merkblatt P026" (Determination of the start of sintering according to VDG leaflet P 026). This test method identifies the threshold temperature at which 60% of the sand sample has undergone sintering [8].

Table 1.
Specification of chromite sand samples [8]

Sample	Average grain size (AFS)	%Fine particles (<75microns)	% Chromite content	%Iron content	% Silica content	Turbidity (NTU)	Sintering temperature (Celsius)
Sample A	51.90	0.70	48.735	31.01	0.665	439.00	870.31
Sample B	49.22	0.76	48.395	30.79	0.725	349.33	843.55
Sample C	46.92	0.38	48.405	31.49	0.640	314.00	848.37
Sample D	48.62	0.24	45.975	28.95	0.665	266.00	814.18
Sample E	47.55	0.36	43.920	30.50	1.415	330.67	812.18

2. Methodology

The experimental work in this study followed the methodology adopted by Dai et al. in the published paper investigating the crushability of foundry silica sand [3]. This methodology consists of two components, namely thermal and mechanical stress application to sand grains. The first step of the crushability determination involved the application of thermal stress using thermal-cold cycles. They were carried out in a box-type resistance furnace, which mimicked the thermal load being repeatedly delivered to sand during metal casting and thermal reclamation of spent sand. The sand was put in a box-type resistance furnace at 650°C for one hour before being cooled to room temperature in a well-ventilated area. This process was repeated 10 times to allow the thermal stress to weaken the grains. Thereafter mechanical stress was applied using a planetary ball mill to replicate the mechanical load during the mulling/mixing of sand and the vibration during mechanical reclamation of used sand. The sand was placed in the planetary ball mill for a duration of 40 minutes which was enough time to create a significant reduction in the size of the sand grains [3].

From the experimental method describe above, three properties related to the crushability of chromite sand, as presented in Fig. 2, namely the crushing ratio, the generation of fine particles and the modification of the grain morphology under thermal-mechanical stress were determined. The details of the methodology in terms of procedures, test equipment are explained in the sections below. The test equipment used, shown in Fig. 3, were a SEM TESCAN VEGA3 scanning electron microscope, sintering furnace, AFS sieve set, and sieve shaker, milling container and rod mill.

2.1. Crushing ratio or index of chromite sand

In this test, 1100 g of sand was weighed and screened according to standards AFS 1106-00-S and BCIRA 16-7. Next, the initial sand grain size was recorded as an AFS number. For this research, since the steel rod mill induced a higher level of mechanical stress on the sand grains than a planetary ball mill, a shorter amount of time was required to break the sand grains. The sand was place in the furnace for 30 minutes at 650ºC then cooled to room temperature. The heating and cooling process was repeated 10 times. Thereafter the sand was milled for three, six and nine minutes. At the nine-minute mark, the sand grains were reduced to almost half their size which was sufficient to measure the difference in crushing ratio. The samples were screened one last time to determine the final grain size, as an AFS number. The crushing index of the sand was obtained from the ratio of the final grain size to the original grain size as shown in equation (1).

$$R = \frac{AFS\ final}{AFS\ original} \tag{1}$$

2.2. Rate of fine particles generation

Each time sand is subjected to thermal-mechanical load, the percentage of fine particles increases. Thus, the initial percentage of fine particles must be compared to the final percentage of fine particles after the sand has been subjected to thermal-mechanical stress. The rate of increase in fine particles is the ratio between the final percentage of fine particles over the initial percentage of fine particles as shown in equation (2). Thus, for this test, the sand was heated in a furnace at 650ºC for 30 minutes and then cooled to room temperature. The heating and cooling cycle was repeated 10 times. Thereafter, the sand sample is milled for three, six and nine minutes. The percentage of fine particles increased each time the duration of the mechanical stress increased and was plotted on a curve. From the curve, the rate of fine particles generation was determined.

$$R = \frac{Percentage\ fines\ final}{Percentage\ fines\ original} \quad (2)$$

2.3. Inspection of grain morphology

A scanning electron microscope was used to determine the shape of the sand grains prior to and after the thermal-mechanical load. The results obtained from the SEM were then compared.

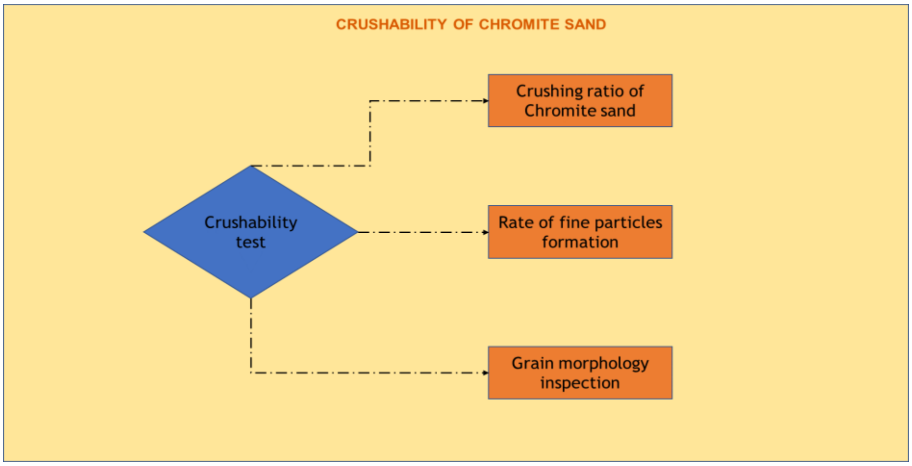


Fig. 2. Experimental design

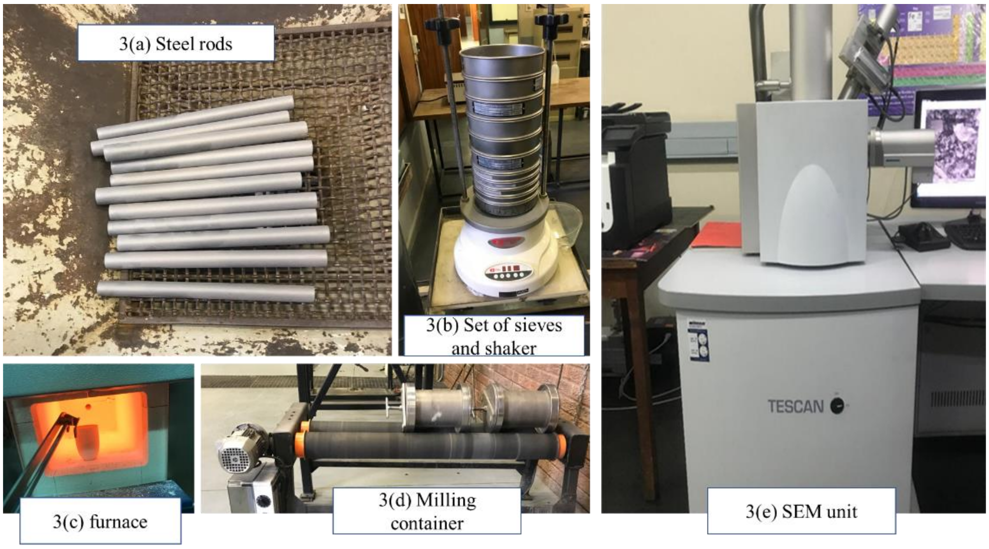


Fig. 3. Equipment used to perform the crushability tests: 3(a) Steel rods, 3(b) Set of sieves and shaker, 3(c) Sinter funace, 3(d) Milling container, 3(e) TESCAN VEGA3 scanning electron microscope

3. Results

The variations observed in the crushing ratios are shown in Figure 4, while Fig. 5 shows the percentage of fine particles generated per minute. As can be seen in Fig. 4, samples A and B show the least variation with respective crushing ratios of 1.70 and 1.75. Sample E, on the other hand, has the weakest resistance to thermal-mechanical stress as is demonstrated by its relatively high crushing ratio of 1.95. According to Fig. 5, sample E had the highest rate of fine particles generated per minute, with a value of 1.92 percentage fines generated per minute under thermal-mechanical load. Samples B and C produce the least percentage of fines generated per minute with respective values of 1.50 and 1.57.

Table 2 shows the change of the grain shape occurring in the chromite samples due to the thermal and mechanical loads. The thermal-mechanical load appears to have produce new grain with higher angularity judging by the number of visible new facets on the grains. Coarser ceramic grains have higher concentrations of flaws and depressions, which make them prone to breaking [3]. The fact that sample E, as shown in Table 2, with its coarser grains, experienced more severe size reduction from AFS value of 47.55 to 92.49 is further confirmation.

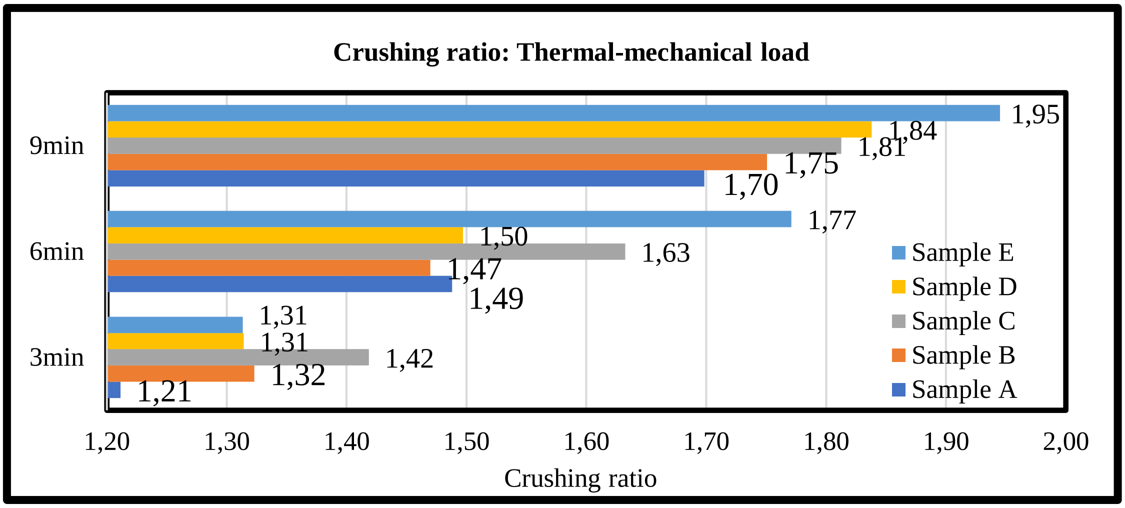


Fig. 4. Variations in the crushing ratios of chromite sand samples under both thermal and mechanical loads (a)

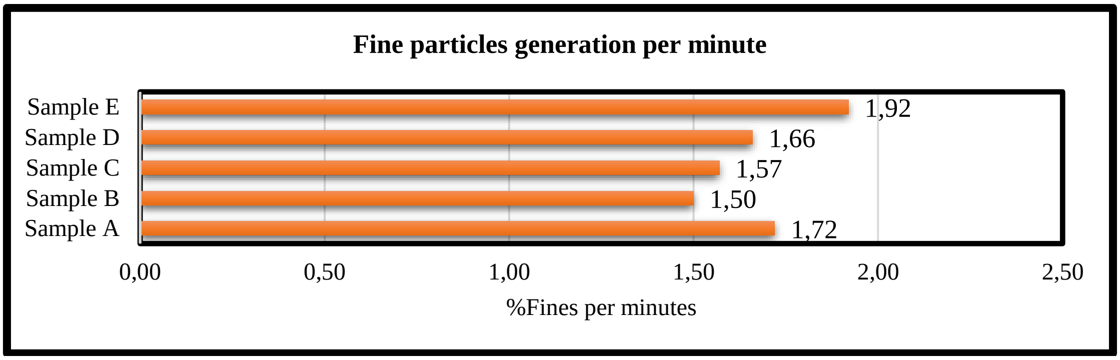
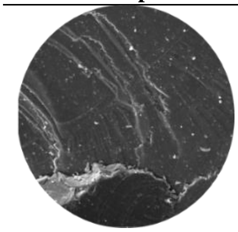
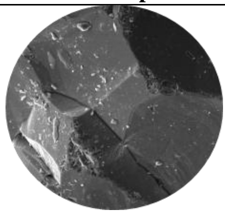
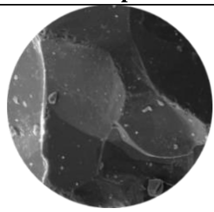
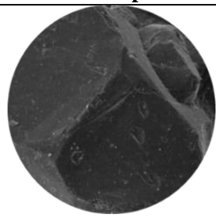
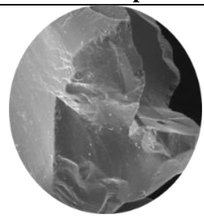
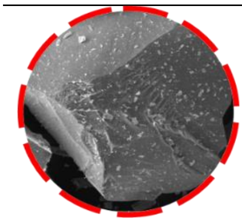
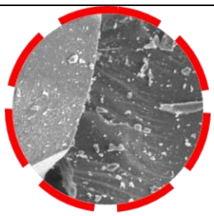
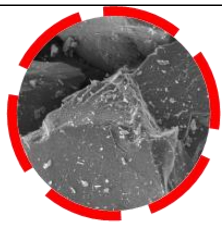
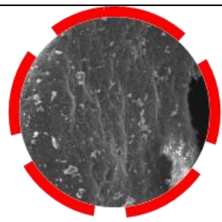


Fig. 5. The amount of fine particles generated per minute by each chromite sand sample under thermal and mechanical loads

Table 2.
Grain morphology of chromite sand prior to and after the application of thermal-mechanical load

Sample A	**Sample B**	**Sample C**	**Sample D**	**Sample E**
				
51.9 AFS	**49.22 AFS**	**46.92 AFS**	**48.62 AFS**	**47.55 AFS**
Thermal-mechanical load application				
				
88.14 AFS	**86.17 AFS**	**85.05 AFS**	**89.37 AFS**	**92.49 AFS**

4. Discussion of results

The evaluation of crushability based solely on the initial sand grain size could be incomplete and therefore misleading. As can be observed in Table 2, Sample C, which had the coarsest grains with an AFS value of 46.92, showed the least variation in its post thermal-mechanical stress AFS average grain fineness number. It is therefore apparent that other properties of chromite sand affect the crushability. The mining site and geological location of the chromite sand, which had a key impact on the variation in the crushing ratio shown in all samples, can partially account for the inconsistencies seen in South African chromite sand. The best attribute to consider which is determined by the chromite sand's geological origin, is probably its chemical makeup. Fig. 6 shows a linear regression study between the crushing ratio and chromite content after nine minutes of thermal mechanical stress; the results show a strong negative correlation between the two variables, further demonstrating their co-dependency [9].

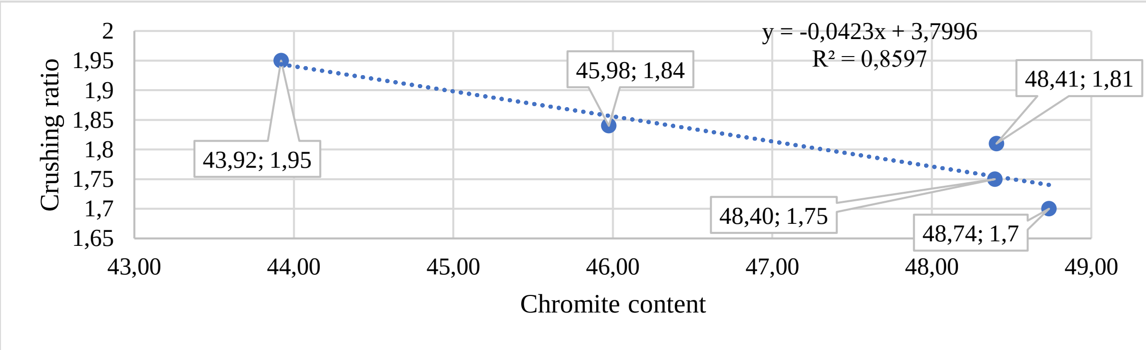


Fig. 6. Linear regression analysis: crushing ratio and chromite content

5. Conclusions

This study investigated the crushability of foundry chromite sand. The results show that chromite samples exhibit appreciable differences in terms of crushing ratio, fines generation and grain shape change during thermal-mechanical loading. These modifications of chromite sand grain size distribution and morphology during stress application, emulating the sand recycling process in the foundry have direct implications on the casting quality and economics of casting production. The authors admit that this methodology only simplistically depict the real intensity, frequency and different thermal stresses to which sand grains are submitted during sand foundry operations and recycling. The stress applications to the moulding sand are indeed very complex. Future investigations could attempt to develop a more realistic model of mechanical and thermal stress, thus refining the one proposed in this study.

Acknowledgements

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