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Review paper

Study of the compressive strength of manganese ore waste briquettes with bentonite

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Abstract

The primary raw material for ferroalloy production is manganese ore, which is extracted and charged in beneficiation processes that include granulometric adjustment. In the submerged arc furnace, the charging of fine manganese ore particles must be avoided, as an excessive amount can obstruct interstices and consequently channeling within the charge. The briquetting process is a potential solution, as it consists of an agglomeration process for fine particles through the application of pressure. This study aims to evaluate the compressive strength of manganese ore briquettes with bentonite as a binder, considering a set of conditions to maximize briquette compressive strength. The general objective of this study is to analyze compressive strength about curing time, temperature, binder percentage, raw material particle size, and water/binder rate. The results obtained indicate that the best-performing test specimen was the one cured for 28 days, treated at 400°C, with 7,5 % binder, a particle size of 2,00 mm, and a water/binder ratio of 1,25:1.

Keywords: *briquette; bentonite; density; compressive strength.*

1. Introduction

Manganese ore is considered the primary raw material in the production of ferroalloys, which, in turn, are of paramount importance in steel production, where most of the metal is used as an alloying element in steel [1]. Manganese, for the addition to steel, is produced in the form of ferroalloys [1].
For ferroalloy production, the main raw material in the process is manganese ore. The production of ores involves comminution and sizing stages, which consist of adjusting the particle size of raw materials. Because of this process, during the beneficiation stage of manganese ores, a significant portion of this material is excessively reduced in size [2, 3], forming particles that are too fine for the ferroalloy production process.
The manufacture of manganese-based ferroalloys takes place in submerged arc furnaces (SAF, shown in Fig. 1). The main inputs used in ferroalloy production are ores and/or agglomerates, coke, and fluxes [1].

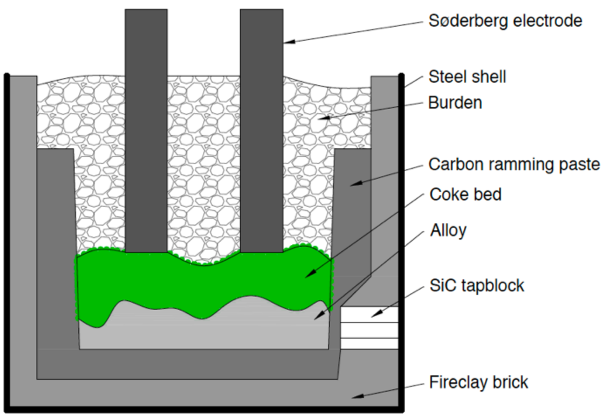

Fig. 1: Schematic diagram of the Submerged Arc Furnace (SAF), modified from Olsen et al. [1].

The submerged arc furnace can be divided into two zones: the pre-reduction zone and the coke bed zone (as depicted in Fig. 2). The pre-reduction zone, which occurs in the upper part of the furnace, is where manganese oxides are reduced to MnO by gases generated in the lower part of the furnace. In the coke bed zone, the melting of oxides occurs, producing slag rich in MnO, which is later reduced to metallic manganese [2].

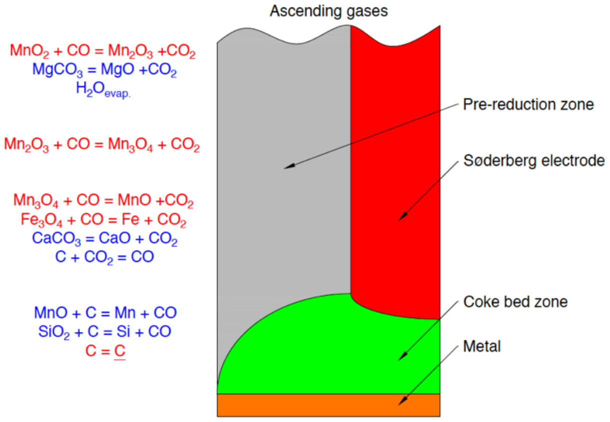

Fig. 2: Schematic diagram of the pre-reduction zone and coke bed with the main reactions occurring in the SAF [1].

In the SAF, the charging of manganese ore fines is undesirable since the particle size must allow sufficient space in the interstices of the particles for gas-solid reactions to occur [1]. Excessive fines can obstruct these interstices, leading to channeling through which gases flow [2, 4].

Briquetting is an agglomeration process of fine particles through the application of pressure, aiming to produce a compact solid with adequate shape, size, and mechanical strength [3]. This process can be presented as a potential solution for the use of such materials, considering that their appropriate chemical composition and the lower mechanical stresses imposed by SAF make these agglomerates a promissing alternative. However, for these materials not to behave as fines, they must withstand the stresses imposed during the charging and ferroalloy production processes in the SAF.

Thus, this study aims to evaluate the compressive strength of manganese ore fines briquettes as a function of binder content (bentonite), curing time, raw material particle size, water/binder rate, and the influence of heat treatment temperature. The study is based on the hypothesis that there is an optimal set of briquette variables that maximizes the compressive strength of the agglomerates.

To achieve the general objective, the following specific objectives were established:

- To study the variation in briquette compressive strength concerning curing time or heat treatment temperature.
- To evaluate the variation in briquette compressive strength concerning binder content.
- To assess the variation in briquette compressive strength concerning the raw materials' particle size.
- To analyze the impact of the binder/water rate on the compressive strength of the agglomerates.

2. Materials and methods

The raw materials used in this study were: fines of manganese ore, supplied by a company in the city of Corumbá/Brazil; bentonite, supplied by the same company; and water. In the briquetting process, the following steps were carried out: preparation of the material to be pressed, mixing, and compression of the agglomerates. Table 1 summarizes the briquettes produced, along with the investigated variables and the parameters that were kept constant.

Table 1: Summaries of the variables and fixed parameters of the briquettes produced through the experimental procedure.

Evaluated parameter	Value	Fixed parameter
Curing time	1 day 7 days 14 days 21 days 28 days	Particle size: < 250 mm Binder content: 10 % Water/binder rate: 1
Temperature	200 ºC 300 ºC 400 ºC	Particle size: < 250 mm Binder content: 10 % Water/binder rate: 1
Binder content	5,0 % 7,5 % 10,0 %	Particle size: < 250 mm Water/binder rate: 1
Particle size	< 0,250 mm < 1,00 mm < 2,00 mm	Binder content: 10 % Water/binder rate: 1
Water/binder rate	0,75 1,00 1,25	Particle size: < 250 mm Binder content: 10 %

For the briquette manufacturing process, the material preparation was conducted using manganese ore, with the addition of water and bentonite in different proportions (with binder content of 5,0, 7,5, and 10,0 %), maximum particle sizes for the ore waste (0,250, 1,00, and 2,00 mm), and water/binder ratios (0,75, 1,00, 1,25).

The mixtures were homogenized using a mechanical impeller to form a uniform charge. Subsequently, the obtained mixture was compacted within a die and punch, with a 10 mm internal diameter, using a uniaxial press. To facilitate the removal of the briquettes from the die, motor oil was used as a lubricant. Once the required compaction pressure was reached, the briquette was held for 30 seconds before being removed from the die. After fabrication, the height and mass of each test specimen were measured for each set of five briquettes. The specimens were then evaluated with regard to its compressive strength.

Initially, 25 briquettes were produced with a maximum particle size of fines of manganese ore < 0,250 mm, 10% binder and a water/binder ratio of 1:1, aiming to assess the change in compressive strength as a function of curing time.
To evaluate the influence of the raw material particle size and water/binder ratio, 30 samples with different ore fines sizes and a fixed water/binder ratio of 1 were produced. The first 10 samples produced were sized < 0,250 mm, with the addition of 7,5 and 5,0 % binder content. Then, another 10 briquettes were produced with particle sizes < 1,00 mm and < 2,00 mm, both with 10,0 % binder content. Lastly, the final 10 test specimens were produced with a particle size < 0,250 mm and 10,0 % binder content, but with a variable water/bentonite ratio, which was adjusted to 0,75 and 1,25.
Finally, 15 additional briquettes were produced with particle size < 0.250 mm of manganese ore fines, 10,0 % binder content, and a water/binder ratio of 1,00. These briquettes were placed in a furnace to evaluate the influence of heat treatment on their compressive strength at different temperatures (200, 300, and 400 °C, respectively). The heat treatment was conducted at the test temperature for 1 h.

3. Results and discussion

The results obtained through the developed methodology are summarized in Table 2. In addition to the compressive strength results, Table 2 also presents the standard deviation of the measurements. The results were also plotted, as presented below.

Table 2: Results obtained through the methodology.

Evaluated parameter	Value	Compressive strength [MPa]	Standard deviation [MPa]
Cure time	1 day	5,3	0,3
	7 days	6,4	0,2
	14 days	5,8	1,1
	21 days	6,9	0,4
	28 days	7,4	0,3
Temperature	200 ºC	21,5	3,8
	300 ºC	24,5	2,9
	400 ºC	36,5	4,9
Binder content	5,0 %	7,8	0,7
	7,5 %	8,8	1,0
	10,0 %	6,4	0,2
Particle size	< 0,250 mm	6,4	0,2
	< 1,00 mm	8,0	1,6
	< 2,00 mm	11,7	0,7
Water/binder rate	0,75	6,8	1,8
	1,00	6,4	0,2
	1,25	12,6	1,2

Figure 3 illustrates the relation between compressive strength and curing time. The general trend in the dataset is an increase in compressive strength with increased curing time. The exception to this trend occurs at the 14-day mark, which, based on possible hypotheses, may be due to insufficient homogenization during the briquetting process or poor surface finishing of the test specimens. These hypotheses are supported by the higher standard deviation of these specimens compared to other measurements in the dataset.

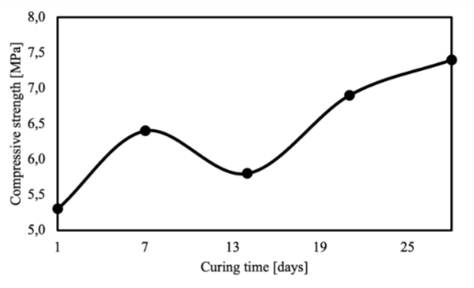

Fig. 3: Compressive strength as a function of briquette curing time.

The hypothesis suggested for the increase in compressive strength with curing time is that the curing mechanism of bentonite and water is like that of cement, meaning it occurs through hydration reactions, which are time-dependent. These reactions were described by Chatterjee [5] for cement and confirmed by observations made by Zhang et al. [6] in studies on binders in briquetting processes.
Figure 4 shows the relationship between compressive strength and heat treatment temperature. Based on the behaviour observed, it is evident that the higher the heat treatment temperature, the greater the compressive strength of the briquettes.

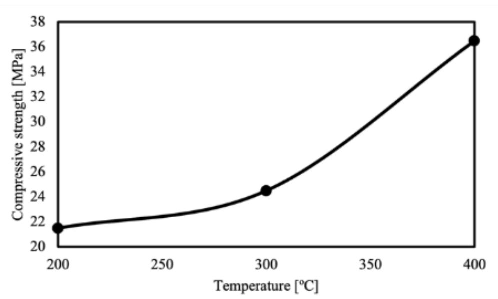

Fig. 4: Compressive strength as a function of briquette heat treatment temperature.

The increase in compressive strength with rising heat treatment temperature may have a prior explanation. The hypothesis suggests that sintering of the test specimens may have occurred, as previously observed by de Jesus [2], promoting the formation of a recrystallized phase, which, in turn, led to an increase in the briquette's compressive strength.

Figure 5 presents the behavior of compressive strength as a function of binder content. A peak in compressive strength is observed at 7,5 % bentonite. The 5,0 and 10,0 % binder percentages presented lower values, particularly the samples prepared with 10% binder.

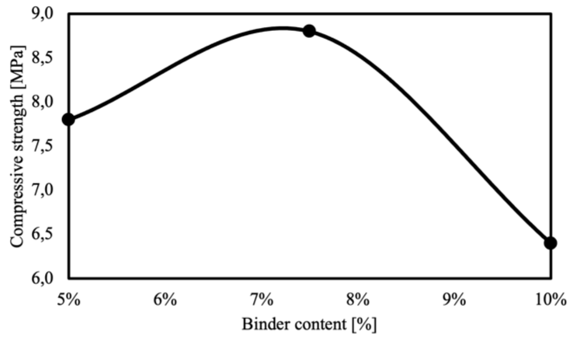

Fig. 5: Compressive strength as a function of binder content.

It is believed that the optimal value of 7,5 % results from a binder content that allows the formation of van der Waals bonding bridges between particles. Lower amounts (such as 5,0 % bentonite) lead to an abundance of sites lacking binder, while higher amounts result in a binder film around the ore waste particles. A deficiency (or excess) of binder leads to a decrease in briquette strength. These mechanisms have been described by other authors in review papers on briquette bonding mechanisms [6, 7].

Figure 6 shows the relation between compressive strength and particle size. It is evident that increasing the maximum particle size positively influences compressive strength.

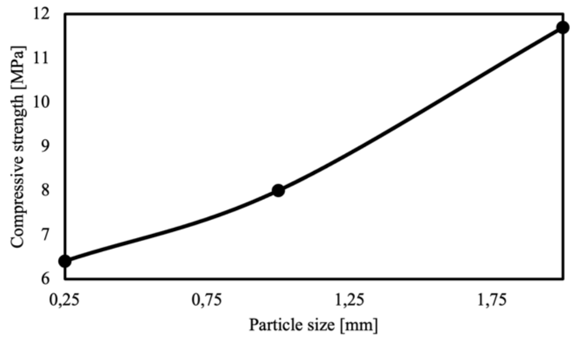

Fig. 6: Compressive strength as a function of particle size.

The increase in compressive strength with larger particle sizes contrasts with observations from other authors who studied mechanical parameters on briquettes [2, 8, 9]. However, El-Hussiny and Shalabi [10] suggested that distributions containing coarse particles can lead to higher packing factors, which may result in stronger briquettes.

Figure 7 depicts the relation between compressive strength and the water/binder ratio. A reduction in compressive strength is observed for a ratio of 1 compared to 0,75. Thus, increasing the water/binder ratio results in increased compressive strength, meaning that the highest compressive strength values were obtained at a ratio of 1,25.

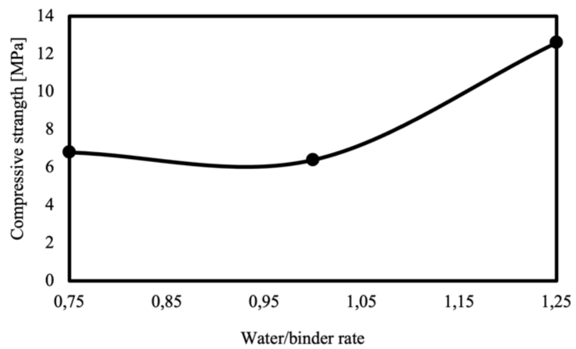

Fig. 7: Compressive strength as a function of water/binder rate.

The increase in compressive strength with a higher water/binder ratio can be explained by the previously mentioned concept that briquette cohesion is ensured by hydration reactions between water and bentonite. This mechanism, described by Chatterjee [5] and observed by Zhang et al. [6], leads to the hypothesis that increasing the water content provides more reactants for the formation of compounds responsible for material cohesion.

Fig. 7: illustrates the relationship between compressive strength and density to analyse the correlation between density measurements and compressive strength.

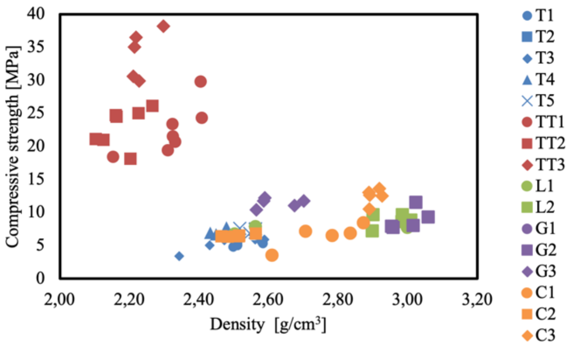

Fig. 8: Compressive strength as a function of density.

Table 3 presents the determination coefficient and the terminology used in the labels of Figure 8.

Table 3: Results obtained through the methodology.

Evaluated parameter	Value	Label	R^2
Cure time	1 day	T1	0,49
	7 days	T2	0,77
	14 days	T3	0,81
	21 days	T4	0,01
	28 days	T5	0,09
Temperature	200 ºC	TT1	0,57
	300 ºC	TT2	0,20
	400 ºC	TT3	0,65
Binder content	5,0 %	L1	0,45
	7,5 %	L2	0,10
Particle size	< 0,250 mm	G1	0,77
	< 1,00 mm	G2	0,33
	< 2,00 mm	G3	0,02
Water/binder rate	0,75	C1	0,74
	1,00	C2	0,77
	1,25	C3	0,17

The analysis of the relations between density and compressive strength indicates that there is no correlation between the two variables studied. Although several authors mention densification as a key factor in briquette compressive strength [3, 6, 7, 9], the hypothesis suggested for the obtained results is that it is possible to densify the material to a point where density differences are not significant enough to markedly impact compressive strength. Thus, as observed by Narita et al. [11], other factors may negatively affect the strength of the specimens, such as homogenization or the binder content. These factors may have influenced the result and, consequently, the determination coefficient.

4. Conclusion

Throughout this study, it was possible to observe the behaviour of the briquettes under different manufacturing conditions. The factors that resulted in the highest compressive strength were heat treatment, indicating that high temperatures positively influence the compressive strength of the samples, and particle size, which an increase in the particle size had a positive effect on briquette strength.

Other important considerations include that the optimal water/binder ratio was 1,25, and the best binder percentage analysed was 7,5%, which represents an intermediate value compared to the other percentages.

Density did not have a significant impact on the compressive strength of the studied briquettes.

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