Original Article

# Impact evaluation of amount of burnt lime, moisture and pellet feed on the sinter fines fraction by utilizing a sintering pilot plant


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**Abstract**

The ironmaking industries are facing challenges concerning the necessity of reducing $CO_2$ emission and the changes in the quality profile of natural iron ore beds. Thus, utilizing sinter pot tests, this work analyzed the impact on the sinter yield by the variation of the amount of burnt lime from 1.8 to 2.8%, and the moisture from 6.0 to 7.0% for two ratios of pellet feed in the iron ore mix, 15%, and 20%. The tests were conducted focusing on producing sinter with higher iron content. It was noted that: i) increasing the pellet feed with low silica content in the sinter mixture raise the total iron content in sinter products and reduced the sinter slag volume; ii) the increase of moisture or burnt lime separately was not effective to minimize the sintering productivity reduction; iii) increasing simultaneously moisture and burnt lime allow achieving levels for sintering productivity close to the standard operational level.



**Keywords:** Sintering; Pilot plant; Pellet feed; Sinter quality.


## 1 Introduction

The ironmaking and steelmaking industries have an important role in the global economy [1], especially because of the observed increase in steel production in the past two decades [2]. This sector has also a significant impact on $CO_2$ emission [1,3,4]. The study developed by the European Parliamentary Research Service [1] indicates that the integrated steelmaking plant is responsible for 1.9 tons of $CO_2$ emission per ton of produced steel. According to Ahmed [5], 90% of the $CO_2$ emission in an integrated steelmaking plant is concerned with the sintering, coking, and blast furnace processes. Based on this scenery, this industrial sector is facing a big challenge concerning the path for the reduction of $CO_2$ emission. The actions to achieve the sustainability requirement for ironmaking and steelmaking industries in the next decades can be divided into two groups. One of them is the development of new ways for reducing iron ore and producing steel for human demands. Research utilizing Direct Reduced Iron (DRI) is well established [6,7] and has gained each time more relevance to facing the actual scenery. Biomass utilization or other energy-renewable sources like hydrogen in iron and steelmaking processes have been also widely observed, as mentioned in [8,9]. The second group of actions observed in iron and steelmaking industries is related to maximize process efficiencies, especially in those processes which are responsible for a high level of $CO_2$ emission [9].

Additionally, the observed changes in the quality profile of natural iron ore beds have been promoting a supplementary challenge for the mining, iron, and steelmaking industries [10-13]. The mining industry has been comminuting more intensively iron ore in order to potentialize the improvement of iron content in the mining products [14]. As a general consequence, the utilization directly of lump ore in the blast furnace process is each time reduced and because of that, the share of aggregated materials has been increasing in the metallic burden of the blast furnace.

The sintering process has a highlighted position among the iron ore agglomeration processes. More than 60% of the metallic burden charged into the blast furnace is sintered ore [15,16]. The iron ore agglomeration process also allows for recycling sources of iron from steel processes. Thus, a second function of the sintering process is the recycling source of iron from steel plants [16,17]. Obviously, for the success of the sintering, several process variables must be well controlled together with the appropriate charge of raw materials which will be sintered. The characteristics of sintering raw materials include chemical and physical aspects. Harvey et al. [15] and Lu [16] pointed out several challenges found in the sintering of iron ore, including the difficult facing in process control. There are other works


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in literature indicating additional challenges in iron ore sintering process [18-20].

Based on the fact that reduced iron content in blast furnace metallic burden decreases the blast furnace efficiency and productivity, additionally increasing the slag rate and the $CO_2$ emission. Thus, an increase in silica content in sinter products raises the blast furnace fuel rate, reducing its efficiency and rising the $CO_2$ emission per ton of hot metal, once the sinter is almost 60% of metallic burden [15,16]. After facing a systematic increase of silica content as a contaminant in the main raw material for the sintering plant (sinter feed), the authors decided to investigate how the sintered product is impacted by a high amount of pellet feed in the sinter mixture, once the silica content in pellet feed is reduced when compared to sinter feed as will be discussed in the following sections. It is well known by mass balance that the increase of silica content in sinter feed directly causes the production of sinter with a lower iron content which is undesirable to blast furnaces.

Therefore, the present investigation analyzed the impact of the amount of burnt lime, moisture and pellet feed on the sinter yield by utilizing a pilot sintering plant. Several sinter pot tests were conducted varying the amount of burnt lime from 1.8 to 2.8%, and the moisture from 6.0 to 7.0% for two ratios of pellet feed in the iron ore mix, 15%, and 20%.

The fraction of sinter fines was measured by fractions higher and lower than 5 mm. Additionally, the sinter plant productivity was calculated based on the test results, and a discussion about sintering permeability together with the impact of FeO and CaO content in the sintered product is presented.

## 2 Materials and methods

### 2.1 Pilot Sintering Plant (Sinter Pot Test)

The pilot sintering plant is located at Volta Redonda (Brazil). The sintering pot has a bed height equal to 0.370 m, a diameter equal to 0.305 m, a processing area equal to 0.073 m$^2$, and a total area of installation equal to approximately 8.10 m$^2$. The processing area is the real sintering area in the pilot sintering plant.

For each test, the mixture mass necessary is about 70 kg by considering the losses during the mixture preparation which will be discussed in the next section. It is also necessary to use a sinter hearth layer with a thickness of about 20 mm. After charging the mixture, the system is positioned to start the simulation by beginning with the ignition through the direct flame for 120 s. After that, the ignition system is removed, and the combustion continues to yield the sintered product from the pilot plant.

### 2.2 Raw materials preparation

The sampling of raw materials for the sinter pot tests can have an intensive impact on the test results due to the quality variation observed in different industrial lots. Thus, in the present investigation, the necessary amount of each material for the whole test was previously calculated. After that, enough amount of dolomite, limestone, burnt lime, sinter feed, pellet feed, mill scale, return sinter fines, coke breeze, and BF dust for the whole pot tests were collected from one industrial lot to avoid a wide range of quality properties. Based on this, the chemical profiles of dolomite, limestone, burned lime, mill scale, return sinter fines, coke breeze, and BF dust were assumed to approximate constant for the whole tests. For sinter feed and pellet feed, the chemical composition is depicted in Table 1 and the range of granulometry is presented in Table 2.

The granulometry distribution of particles has an important role during the sintering process [15,16]. They impact directly the process permeability and consequently the sintering plant productivity.

Thus, the limestone, dolomite, sinter feed, and coke breeze were dried and screened in the following screen sizes: 0.15 mm, 1.00 mm, 3.00 mm, 6.35mm, 9.52 mm, and 12 mm. For each test, the material mass in each range of granulometry was selected rigorously in order to guarantee that all tests have almost the same mass of materials in each granulometry range. Table 3 shows the mass of each material in the different granulometry ranges to the standard test. For the other investigated tests, which will be discussed in the next section, the variation is not higher than 3% in each granulometry range. Thus, by assuming the presented method, the impact of granulometric dispersion exclusively from raw materials can be minimized in the present investigation.

The raw materials preparation for each test started drying of limestone, dolomite, sinter feed, and coke breeze at 110 °C and screening in the grain size mentioned in the previous paragraph. After that, each raw material of the mixture was weighed and added to the intensive mixer to be homogenized. In this step of raw materials preparation, 25% to 35% of the total water necessary for the total moisture was

**Table 1.** Chemical composition of sinter feed and pellet feed

| (%) | Sinter feed | Pellet feed |
|---|---|---|
| $Fe_{tot}$ | 61.74 | 65.20 |
| FeO | - | 0.06 |
| $SiO_2$ | 7.92 | 2.28 |
| $Al_2O_3$ | 1.11 | 0.74 |
| Mn | 0.23 | 0.26 |
| P | 0.066 | 0.049 |
| CaO | - | 0.09 |
| MgO | - | 0.35 |

**Table 2.** Granulometry range of sinter feed and pellet feed

| Material | Grain size (mm) |
|---|---|
| Sinter feed | 0.15 to 6.30 |
| Pellet feed | Lower than 0.15 |

added. The total time of rotation in the intensive mixer was equal to 1 minute following a speed of 60 rpm. A sample of the mixture was collected to analyze the moisture at the end of the rotation of the intensive mixer.

The next step of the preparation was in the drum mixer to generate the micropellets in the sinter mixture [21]. In this step, the fraction of remaining water was added for each test. The total time of rotation in this step was equal to 3 minutes and the moisture of the mixture was measured at the end of the rotation.

After processing the mixture in the drum mixer, the sinter mixture was charged in the pilot sintering plant to be sintered.

### 2.3 Tests description and measurements

Table 4 shows the basic description of realized tests in the present investigation, indicating which variables were changed for each test. The number of tests for each investigation is also indicated in this table. The burnt lime percentage in the sintering mixture is the mass percentage of burnt lime considering the total dried mass of the mixture. The same is valid for the moisture percentage. The percentage of pellet feed was calculated considering the total mass of iron ore charged in the sintering mixture.

The percentage of the other components (coke breeze, mill scale,…) of the sintering mixture was maintained constant for all tests to avoid the influences of other variables in the different investigation lines presented in Table 4. It is also necessary to mention that changes in burnt lime in the mix were compensated by changes in limestone to maintain the same level of $\%SiO_2/\%CaO$ on the sintered product.

By following the tests presented in Table 4, the present investigation was able to analyze the impact of different variables in the sintering process and sinter product quality, measured here by the fine sinter generation. To active this goal, the authors opted by making comparisons between different tests with a standard operational process. It means that three pot tests were conducted in the pilot sintering plant following the values of the variables equal to those observed in the industrial standard operational process.

After conducting each pot test, the sintered product passed firstly by the crushing process in the drum crushing which rotated 50 times utilizing a rate of 19 rpm. Additionally, a sample to be chemically analyzed was collected from each pot test and the rest of the sinter product mass already crushed was screened in grain size of 5 mm. The sinter chemical characterization was by fluorescence of X-ray utilizing pulverized sample and following the preparation method proposed by ABNT NBR ISO 3082 [22].

By following the procedure described above, the contents of total iron ($Fe_{tot}$), FeO, MgO, $Al_2O_3$, $SiO_2$, and CaO were determined for each pot test product. The sinter product yields from tests were determined by the rate of sinter mass higher than 5 mm by the total mass of the sintered product (higher and lower than 5 mm).

Once the fraction of fines in the mixture impacts the sintering productivity, in the present investigation, the time for achieving the maximum sintering temperature was measured for the whole test, and an average time for each investigation line was calculated. The same method was used for the sintering depression measured at the maximum sintering temperature for each pot test.

The relations between $\%SiO_2$, $\%Fe_{tot}$ and %FeO in the sintered product versus the ratio of pellet feed in the mixture were analyzed for each investigation line, as indicated in Table 4. The percentage of sinter lower than 5 mm versus the %FeO and %CaO of the sintered product was also analyzed in the present investigation.

**Table 3.** Mass for each granulometry for the standard test

| Material | Mass for each granulometry (kg) | | | | | | |
|---|---|---|---|---|---|---|---|
| | > 12.00 mm | > 9.52 mm | > 6.35 mm | > 3.00 mm | > 1.00 mm | > 0.15 mm | < 0.15 mm |
| Sinter Feed | 0.047 | 0.517 | 3.174 | 5.984 | 7.012 | 5.956 | 8.671 |
| Limestone | 0.026 | 0.002 | 0.015 | 0.175 | 1.131 | 1.313 | 1.586 |
| Dolomite | 0.009 | 0.001 | 0.006 | 0.269 | 1.489 | 1.110 | 0.510 |
| Coke breeze | 0.002 | 0.006 | 0.392 | 0.226 | 0.500 | 0.608 | 0.526 |

**Table 4.** Experimental tests description of the investigation line

| | Burnt lime of mixture | Pellet feed | Moisture | Nr. of pot tests |
|---|---|---|---|---|
| **Test denomination** | **(%)** | **(%)** | **(%)** | - |
| Standard | 2.3 | 15 | 6.50 | 3 |
| Reduction of burnt lime | 1.8 | 15 | 6.50 | 2 |
| Increase of PF | 2.3 | 20 | 6.50 | 2 |
| Increase of PF + Increase of moisture | 2.3 | 20 | 7.00 | 2 |
| Increase of PF + Increase of burnt lime + Reduction of moisture | 2.8 | 20 | 6.00 | 3 |
| Increase of PF + increase of burnt lime + Increase of moisture | 2.8 | 20 | 7.00 | 2 |

The $\%SiO_2$ of sinter products versus the sinter slag mass was plotted for each investigation line proposed in Table 4. Finally, the present investigation calculated the sinter productivity ($t/m^2 \cdot d$) based on the experimental test results from the pilot sintering plant. For the sinter productivity calculus, it was assumed that a sintered mass higher than 5 mm was good sinter to be directed from the sintering plant to the blast furnace.

Thus, Equation 1 indicates the way utilized for the productivity calculus.

$$\begin{matrix} Sinter \\ productivity \end{matrix} = \frac{\begin{pmatrix} mass\,of\ sinter \geq \\ 5\,mm \end{pmatrix}}{\begin{pmatrix} sintering \\ pot\,area \end{pmatrix}} \cdot \frac{(24)}{\begin{pmatrix} time\ for\ T_{MAX} \\ in\,hours \end{pmatrix}} \tag{1}$$

## 3 Results and discussions

The Table 5 depicts the chemical characterization of sinter products for the different investigated lines. The slag volume is the sum of $SiO_2$ and CaO percentages.

Figure 1 shows the comparison of $\%SiO_2$ in sinter products between the standard process practice and the different investigation lines. It is noticed by the results of Figure 1 that an increase in pellet feed in the sintering mixture results in a decrease in the $\%SiO_2$ of sinter products. The reduction of silica in sinter products was in the range of 0.11 to 0.38% in the investigated tests. As pellet feed has lower silica content, see Table 1, a higher ratio of pellet feed in sintering mixture produces a sinter with lower silica content.

Figure 2 depicts the total iron of the sintered product for the standard operating practice and for the other investigated tests, as presented in Table 5. It is observed that improving the ratio of pellet feed in the sintering mixture produces a sinter with higher values of total iron. From point of view of the iron ore reduction, the highest values of total iron content are always wished for materials to be reduced in the blast furnace process because lower energy will be necessary for the reduction of the metallic burden (reduction of fuel rate). The process slag consumes process energy; thus, a reduction of the slag volume is always sought, and it is reached by improving the values of total iron in the blast furnace metallic burden. Therefore, in the iron ore agglomeration processes, the focus on maximizing the total iron in the product (e.g. sinter, pellet, or briquette) is constant, although product quality factors must be considered in the analysis, e.g. fine generation, reducibility, and son on.

The test which considered only the reduction of burnt lime in the mixture produced a sinter with a higher value of total iron content compared to the standard test. To avoid a significant change in the binary basicity, as mentioned previously, for this test a higher amount of limestone was added in the sintering mixture.

Figure 3 shows the sinter slag volume versus silica content in the sintered product. By the results observed in the present

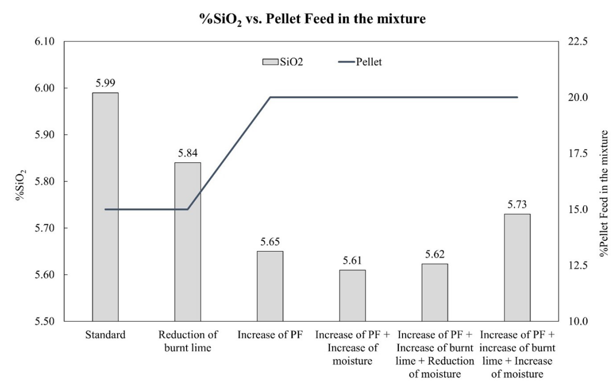


**Figure 1.** Comparison of silica content in sinter product between the standard operational practice and other investigation lines, considering mainly the increase of pellet feed in the sintering mixture.

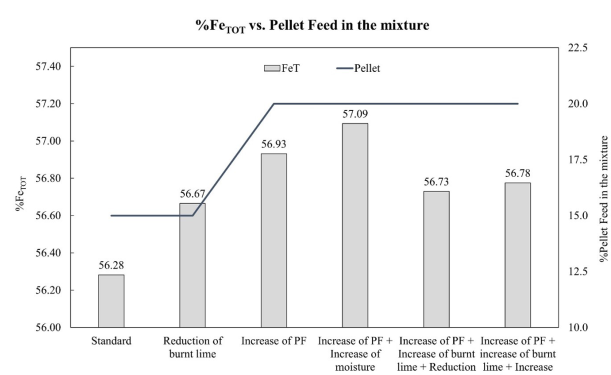


**Figure 2.** Comparison between total iron on sinter product.

**Table 5.** Chemical characterization results of sinter product

| Test denomination | $\%Fe_{tot}$ | %FeO | %MgO | $\%Al_2O_3$ | $\%SiO_2$ | %CaO | $\%CaO/\%SiO_2$ | Slag Volume |
|---|---|---|---|---|---|---|---|---|
| Standard | 56.28 | 9.80 | 1.55 | 1.45 | 5.99 | 10.73 | 1.79 | 16.72 |
| Reduction of burnt lime | 56.67 | 9.87 | 1.47 | 1.36 | 5.84 | 10.54 | 1.81 | 16.38 |
| Increase of PF | 56.93 | 9.90 | 1.38 | 1.47 | 5.65 | 10.15 | 1.74 | 15.80 |
| Increase of PF + Increase of moisture | 57.09 | 9.10 | 1.39 | 1.47 | 5.61 | 10.05 | 1.79 | 15.66 |
| Increase of PF + Increase of burnt lime + Reduction of moisture | 56.73 | 9.17 | 1.64 | 1.56 | 5.62 | 10.32 | 1.84 | 15.94 |
| Increase of PF + increase of burnt lime + Increase of moisture | 56.78 | 9.50 | 1.49 | 1.46 | 5.73 | 10.37 | 1.80 | 16.10 |

investigation, the sinter slag increases approximately linearly with the silica content of the sintered product. The highest value of sinter slag is for the standard process practice.

All results observed in Figures 1, 2, and 3 converge to the principal goals of the present investigation which are: i) reducing the silica content in the sinter; ii) improving the total iron content of the sintered product; and, iii) reducing the sintering slag to allow the best sinter performance in blast furnace process. However, other aspects of the sintered product and sintering process will be discussed to elucidate the impact of the proposed changes.

It is well known that the sintering process is strongly dependent on the transport of gases during the advanced combustion layer throughout the mixture. Thus, adding fine particles in the sintering mixture and/or an inefficient pre-agglomeration of particles can be catastrophic to the sintering process in terms of the productivity and quality of the sintered product [15,16]. In this context, Figure 4 depicts

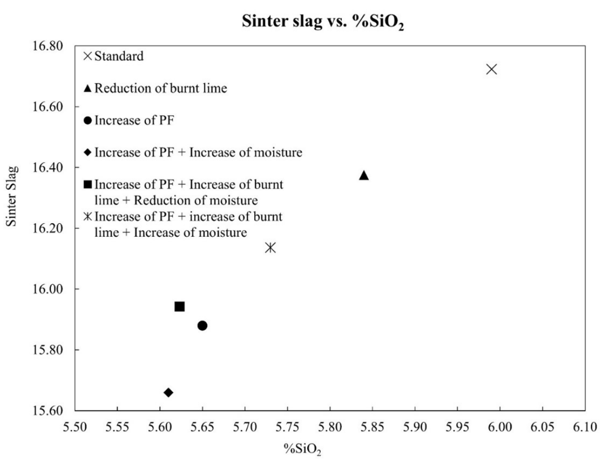


**Figure 3.** Sinter slag versus silica content in sinter product.

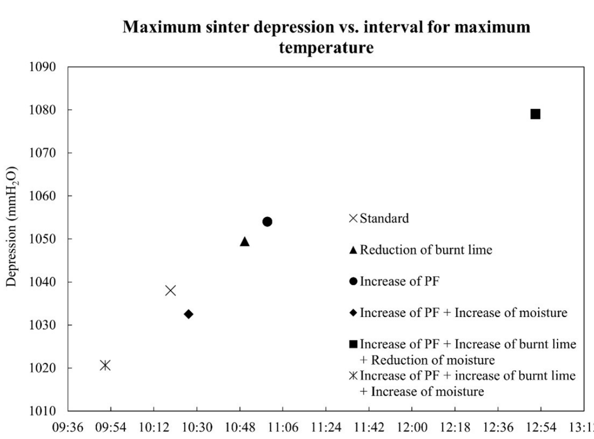


**Figure 4.** Sintering depression at maximum sintering temperature versus time to achievement of the maximum sintering temperature.

the sintering depression at the maximum sintering temperature versus the time interval to the achievement of the maximum sintering temperature. The maximum sintering temperature indicates the moment when the burnt layer is in the lower part of the sintering mixture on the sintering pot in the pilot plant. Based on the outcomes of Figure 4, one can note that the result with the highest depression and highest time to maximum temperature was for the test with an increase of pellet feed, increase of burnt lime, and reduction of moisture, simultaneously. These results can be explained by a combination of two phenomena: i) higher participation of fine particles in the sintering mixture due to the increase of pellet feed; and, ii) a efficiency reduction of pre-agglomeration which is strongly influenced by the moisture content in the mixture pre-treatment [16,23]. This combination of results indicates the difficult of gas passage during the sintering process measured by an elevation of sintering depression and higher time to the maximum temperature.

By analyzing the results presented in Figure 4, it is also possible to observe that both tests, the test of reduction of burnt lime and the test of increase of pellet feed in the mixture, have higher values of sintering depression and interval to the achievement of maximum temperature when they are compared to the standard test. The result observed for the test with an increase of pellet feed can be explained by the increase in the number of fine particles in the sintering mixture. The result of the reduction burnt lime test is related to the fact of the effectivity reduction of the sintering mixture pre-agglomeration, once it is well known that burnt lime is a protagonist in the agglomeration process of fine iron ore particles [15,16,23]. The test which considered the increase of pellet feed together with the increase of moisture has a result similar to the standard test. It is assumed that an increase of moisture gets a better micro pelletizing of the mixture in the pre-agglomeration treatments which compensates the increase of fine particles in the sintering mixture. The last investigation line, the test with an increase of pellet feed plus the increase of burnt lime plus the increase of moisture, has the lower sintering depression together to a lower interval to the maximum sintering temperature. In terms of the sintering process, the result of this test is the best one for the higher speed of the burnt layer.

Figure 5 depicted the outcomes of sinter product yield for each investigation line proposed in Table 4. The sinter pot test with the highest percentage of sinter product higher than 5 mm was the standard test, with a yield equal to 62.9%. The other tests have yields lower than the mentioned one, which indicates that the sinter products of other tests after the sintering process have a higher fraction of sinter fines, assumed in the present discussion as lower than 5 mm. Therefore, reducing the burnt lime in the sintering mixture or increasing the fraction of fines through the improvement of pellet feed ratio in the sintering mixture generates higher fractions of fines of sinter products, even though some isolated compensations have been tested by increasing the moisture content or the burnt lime ratio in the sintering mixture. The investigated test with the worst result was the one which the pellet feed and only the moisture were increased in the sintering mixture.

Figures 6 and 7 show the relationship observed between the percentage of fines in the sintered product versus FeO content and CaO content in the sintered product, respectively. For both figures, it is noted that the sinter product fine percentage decreases with the increase of FeO content or CaO content, even though the shape of the curve between the investigated relations is not well characterized. Although the present investigation does not consider the mineralogy characterization in the sintered product for the several investigated lines, the outcomes depicted in both figures probably can be explained by the formation of phases with high strength during the sintering process as well discussed in many references [11,16, 24-27].

Both investigated components (%CaO and %FeO) are important for the reduction process in the blast furnace (BF). The CaO helps to control the BF slag basicity. The FeO in the BF burden impacts the process energy efficiency concerning the BF coke consumption due to the rate of direct and indirect reduction [28,29].

Finally, Figure 8 depicts the calculated results concerning the sintering productivity based on the sinter pot tests for all investigated lines. In the present investigation, the reference in sintering productivity must be the standard test. This test was utilized to establish a comparison between this one and the others investigated options.

Naturally, as discussed in the above part of this section, there are several impacts on the sintered product quality profile (chemical content of the components in the sintered product), sintering process (measured here for instance by the sintering depression), and cold mechanical resistance of sinter product (analyzed by fraction higher than 5.0 mm) when changes in sintering mixture are carried out. However, the sintering productivity measures the combination of sinter yield with sintering speed. The sintering productivity indicates thus the combination of sinter product mechanical quality and sintering process impacts due occurrences to processes variations.

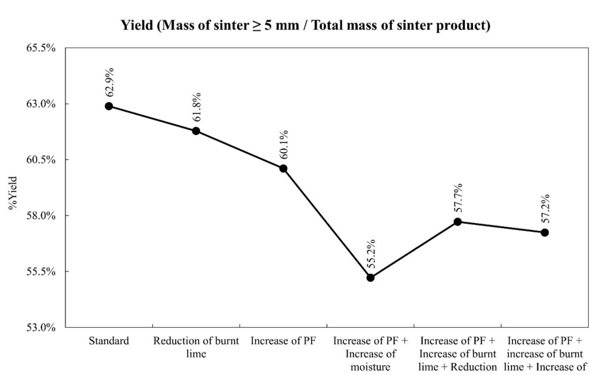


**Figure 5.** Sinter product yields – percentage of sinter product higher than 5 mm.

By analyzing the results presented in Figure 8, the worst sintering productivity result was for the investigated

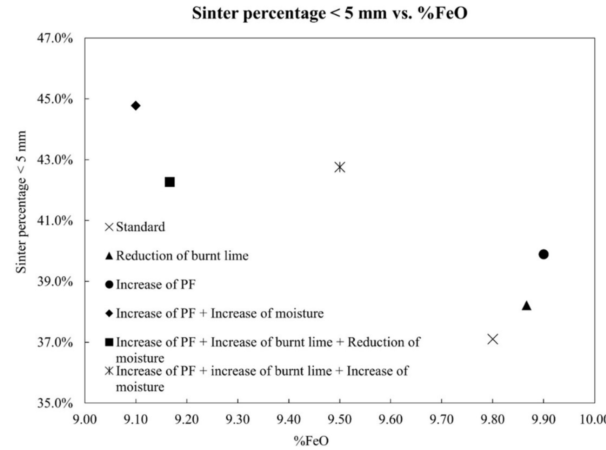


**Figure 6.** The relation between the percentage of fines in the sintered product (percentage lower than 5 mm for the sinter pot tests) and %FeO in the sintered product.

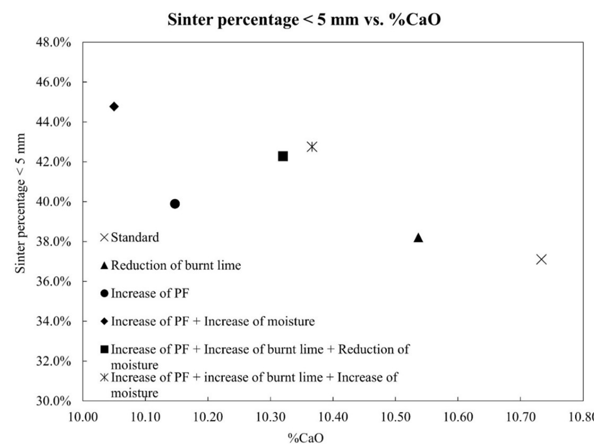


**Figure 7.** The relation between percentage of fines in sinter product (percentage lower than 5 mm for the sinter pot tests) and %CaO in the sinter product.

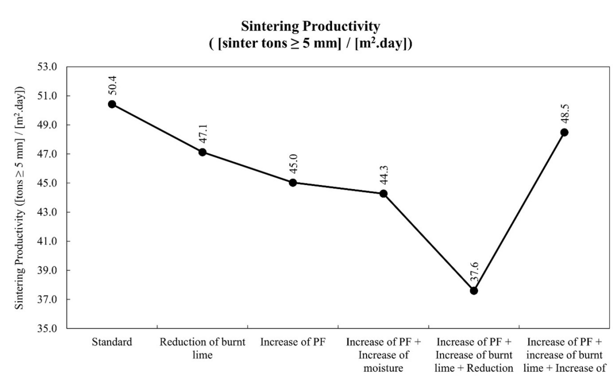


**Figure 8.** Calculated sintering productivity based on the sinter pot tests.

test which combined in sintering mixture an increase in pellet feed, an increase in burnt lime, and a moisture reduction. It is noted that this test has the worst sintering permeability based on the results presented in Figure 4. Although the sintering yield of this test has an intermediate result (see Fig. 5), it is assumed that the present result of productivity is strongly due to ineffective pre-agglomeration of the sintering mixture.

The sintering productivity results closest to the standard test were for the test that considered the increases of the pellet feed, burnt lime, and moisture, according to the outcomes depicted in Figure 8. For this test, it is also observed that it has intermediate values for %CaO and %FeO in the sintered product. Additionally, this test has the second-worst sintering yield results according to Figure 5, even though it has the best sintering permeability result (see Figure 4).

Thus, based on the sinter pot tests, it is possible to affirm: i) this test utilized a higher fraction of fine particles in the sintering mixture compared to the standard test; ii) this investigated test has an efficient pre-agglomeration process for sintering mixture due to the low time for achieving the sintering maximum temperature, associated to the lowest value of sintering depression; iii) this pot test produces sinter with a high fraction of fines. This last point indicates that, in the industrial practical aspect, a higher percentage of return sinter fines must be utilized in the sintering process.

For the other investigation lines, it was observed that all of them have significant reduction of sintering productivity due to reduction of sinter yield or sintering speed, or yet combination of both.

Based on the results of Figure 8, the following points can be inferred: i) the reduction of binder (burnt lime in the present investigation) in the sintering mixture decreases the sintering productivity; ii) an increase only in the ratio of fine particles reduces also the sintering productivity; iii) an increment of fine particles in sintering mixture associated with an increase of moisture in sintering mixture was not enough to maintain the sintering productivity in the standard level; iv) the only way found to active levels for sintering productivity close to the standard level for sintering mixture with a higher ratio of pellet feed was through the combination of increases of burnt lime (2.8%) and moisture (7.0%).

The last inferred point mentioned above is considered very important for the present investigation because it was possible to achieve sinter productivity close to the standard condition and with a sinter slag volume, approximately 3.5% lower, according to the results presented in Figure 3 and Table 5. This result corroborates both aspects of the $CO_2$ reduction, firstly to maximize the blast furnace efficiency by reducing the slag rate and secondly to increase the sintering yield which also minimizes the $CO_2$ emission [30]. Considering the industrial process boundary conditions, the authors decided to stop the variation of binder, moisture, and the ratio of pellet feed in the sintering mixture as presented in Table 4. However, they believe that higher levels of moisture combined with an increase of burnt lime can produce sinter products with lower slag volume due to the higher ratio of pellet feed and best results for sintering productivity, even though these points have not been investigated in the present work.

## 4 Conclusions

Based on the results obtained in the present investigation, it is possible to conclude the following points:

- An increase in the ratio of pellet feed in the sintering mixture reduces the silica and increases the total iron contents in the sintered product. Additionally, the increase of pellet feed in the sintering mixture induces a reduction of the slag volume and changes in the sinter quality profile;
- The results of all investigated lines have sintering yield, measured by the percentage higher than 5 mm, lower than the standard practice;
- Higher percentages of FeO or CaO in sinter products reduce the sinter fine fractions, determined in the present investigation by the fraction lower than 5 mm;
- The result of sintering productivity closest to the standard test was for the investigated test with an increase of pellet feed, burnt lime, and moisture. This test indicates that it is possible to produce sinter with a productivity level similar to the operational standard practice, but with a lower sinter slag volume due to lower silica content in the sintering mixture because of a higher ratio of pellet feed;
- The increase of moisture or burnt lime separately in the sintering mixture was not effective to minimize the reduction of sintering productivity due to the high ratio of fines as a consequence of a high ratio of pellet feed in the sintering mixture, according to the results of the present investigation.

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## References


1 Laguna JC, Duerinck J, Meinke-Hubeny F, Valee J. Carbon-free steel production: cost reduction options and usage of existing gas infrastructure. Brussels: European Parliamentary Research Service – EPRS; 2021. https://doi.org/10.2861/01969.

2 Basson E, World Steel Association. Data Report - Steel statistical publication 2022. Brussels: World Steel Association; 2022. [cited 2022 Nov 3]. Available at: https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2022-1.pdf

3 Brown T, Gambhir A, Florin N, Fennell P. Reducing CO2 Emissions from Heavy Industry: A Review of Technologies and Considerations for Policy Makers. London: Imperial College; 2012. (Briefing paper; 7).

4 Pardo N, Moya JA. Prospective scenarios on energy efficiency and CO2 emissions in the European Iron & Steel industry. Energy. 2013;54:113-128. https://doi.org/10.1016/j.energy.2013.03.015.

5 Ahmed H. New trends in the application of carbon-bearing materials in blast furnace iron-making. Minerals (Basel). 2018;8(12):561. http://doi.org/10.3390/min8120561.

6 Feinman J. Direct Reduction and Smelting Process. In: Fruehan RJ, United States Steel Corporation. Aise Steel Foundation. The making, shaping and treating of steel - ironmaking volume. 11th ed. USA: United States Steel Corp.; 1999. Chapter 11, pp. 741-780.

7 Chatterjee A. Sponge iron production by direct reduction of iron oxide. New Delhi: PHI Learning Private Limited; 2010.

8 Castro JA, Oliveira EM, Campos MF, Takano C, Yagi J. Analyzing cleaner alternatives of solid and gaseous fuels for iron ore sintering in compacts machines. Journal of Cleaner Production. 2018;198:654-661. http://doi.org/10.1016/j.jclepro.2018.07.082.

9 The Technical Society. The Iron and Steel Institute of Japan. Production and technology of iron and steel in Japan during 2020. ISIJ International. 2021;61(6):1739-1757. http://doi.org/10.2355/isijinternational.61.1739.

10 Honeyands T, Manuel J, Matthews L, O'Dea D, Pinson D, Leedham J, et al. Comparison of the mineralogy of iron ore sinters using a range of techniques. Minerals (Basel). 2019;9(6):333. http://doi.org/10.3390/min9060333.

11 Yin J, Lv X, Xiang S, Bai C, Yu B. Influence of CaO source on the formation behavior of calcium ferrite in solid state. ISIJ International. 2013;53(9):1571-1579. http://doi.org/10.2355/isijinternational.53.1571.

12 Osuga K, Adachi T, Miyagawa K, Matsumura T, Nozawa K. Sintering technology using parallel granulation process at high pellet feed ratio. ISIJ International. 2019;59(10):1756-1764. http://doi.org/10.2355/isijinternational.ISIJINT-2018-348.

13 Mežibrický R, Fröhlichová M, Findorák R, Goettgens VS. Ore assimilation and secondary phases by sintering of rich and high-gangue iron ores. Minerals (Basel). 2019;9(2):128. http://doi.org/10.3390/min9020128.

14 Lins FF, Adamian R. Minerais coloidais, teoria DLVO estendida e forças estruturais. Rio de Janeiro: CETEM/MCT; 2000. (Mineral Technology Serie; 78). [cited 2023 July 3]. Available at: http://mineralis.cetem.gov.br/handle/cetem/121

15 Harvey T, Honeyands T, O'Dea D, Evans G. Study of sinter strength and pore structure development using analogue tests. ISIJ International. 2020;60(1):73-83. https://doi.org/10.2355/isijinternational.ISIJINT-2019-247.

16 Lu L. Iron ore: mineralogy, processing and environmental sustainability. 2nd ed. New Dehli: Woodhead Publishing – Elsevier; 2022. p. 489-537.

17 Oliveira VF, Bagatinib MC. Experimental evaluation of the usage of residues for sintermaking. Journal of Materials Research and Technology. 2019;8(6):5781-5789. http://doi.org/10.1016/j.jmrt.2019.09.047.

18. Kim KM, Kim JH, Kwon JH, Lee JA, Han JW. Effect of deflector plate for particle size segregation control. Archives of Metallurgy and Materials. 2019;64(2):495-500. http://doi.org/10.24425/amm.2019.127566.

19. Fröhlichová M, Findorák R, Legemza J, Mašlejová A, Ivanišin D. Iron-ore sintering process optimization. Archives of Metallurgy and Materials. 2015;60(4):2895-2899. https://doi.org/10.1515/amm-2015-0462.

20. Mežibrický R, Fröhlichová M, Mašlejová A. Phase composition of iron ore sinters produced with biomass as a substitute for the coke fuel. Archives of Metallurgy and Materials. 2015;60(4):2955-2963. http://doi.org/10.1515/amm-2015-0472.

21 Niwa Y, Sakamoto N, Komatsu O, Noda H, Kumasaka A. Commercial production of iron ore agglomerates using sinter feeds containing a large amount fine ores. ISIJ International. 1993;33(4):454-461. http://doi.org/10.2355/isijinternational.33.454.

22 Associação Brasileira de Normas Técnicas. NBR ISO 3082:2011: Minérios de Ferro - Procedimentos de Amostragem e Preparação de Amostra. Rio de Janeiro: ABNT; 2011.

23 Campos FLC Jr. Caracterização Tecnológica de Misturas de “Sinter-feed” e de “Pellet-feed” Empregando Diferentes Rotas de Sinterização em Escala Piloto” (tese). Ouro Preto: Universidade Federal de Ouro Preto; 2018.

24 Nicol S, Chen J, Pownceby MI, Webster NAS. A review of the chemistry, structure and formation conditions of Silico-Ferrite of Calcium and Aluminum (‘SFCA’) phases. ISIJ International. 2018;58(12):2157-2172. http://doi.org/10.2355/isijinternational.ISIJINT-2018-203.

25 Pownceby MI, Clout JMF. Importance of fine ore chemical composition and high temperature phase relations: applications to iron ore sintering and pelletising. Mineral Processing and Extractive Metallurgy. 2003;112(1):44-51. http://doi.org/10.1179/037195503225011402.

26 Clout JMF, Manuel JR. Fundamental investigations of differences in bonding mechanisms in iron ore sinter formed from magnetite concentrates and hematite ores. Powder Technology. 2003;130:393-399.

27 Panigrahy SC, Verstraeten P, Dilewijns J. Influence of MgO addition on mineralogy of iron ore sinter. Metallurgical Transactions. 1984;15B:23-32. http://doi.org/10.1007/BF02661059.

28 Biswas AK. Principles of blast furnace ironmaking.  Astralia: Cootha Publishing Hause; 1981.

29 Geerdes M, Toxopeus H, Vliet C, Chaignaeu R, Vander T. Modern blast furnace ironmaking: an introduction. 2nd ed. Netherlands: IOS Press; 2009.

30 Iwami Y, Yamamoto T, Higuchi T, Nushiro K, Sato M, Oyama N. Effect of oxygen enrichment on sintering with combined usage of coke breeze and gaseous fuel. ISIJ International. 2013;53(9):1633-1641. http://doi.org/10.2355/isijinternational.53.1633.

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