

Article

Coke Substitution with Anthracite in Sintering Production

Pavlina Pustejovska ^{1,*} , Michal Sikora ¹, Simona Jursova ², Kristyna Pustejovska ³  and Edyta Kardas ⁴ 

- ¹ Department of Metallurgical Technologies, Faculty of Materials Science and Technology, VSB—Technical University of Ostrava, 17. Listopadu 2172/15, 708 00 Ostrava, Czech Republic
- ² Department of Computer Science, Faculty of Electrical Engineering and Computer Science, VSB—Technical University of Ostrava, 17. Listopadu 2172/15, 708 00 Ostrava, Czech Republic; simona.jursova@vsb.cz
- ³ Department of Industrial Systems Management, Faculty of Materials Science and Technology, VSB—Technical University of Ostrava, 17. Listopadu 2172/15, 708 00 Ostrava, Czech Republic
- ⁴ Department of Production Management, Faculty of Production Engineering and Materials Technology, Czestochowa University of Technology, J.H. Dabrowskiego 69, 42-201 Czestochowa, Poland; edyta.kardas@pcz.pl
- * Correspondence: pavlina.pustejovska@vsb.cz

Abstract: This article summarises the possibility of replacing the coke breeze sintering fuel with an economically and ecologically more suitable fuel, anthracite. The main focus is on the possibility of replacing coke breeze with anthracite, during which, the replacement process is accelerated and the other properties are also affected. The analyses performed showed that the replacement of coke breeze with different amounts of anthracite does not have a negative effect if the initial permeability of the sintering bed is the same.

Keywords: sintering; coke breeze; anthracite



Citation: Pustejovska, P.; Sikora, M.; Jursova, S.; Pustejovska, K.; Kardas, E. Coke Substitution with Anthracite in Sintering Production. *Processes* **2024**, *12*, 440. <https://doi.org/10.3390/pr12030440>

Academic Editor: Blaž Likozar

Received: 31 January 2024

Revised: 13 February 2024

Accepted: 17 February 2024

Published: 22 February 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The metallurgical industry is increasingly seeking substitutes for commonly used raw materials and fuels [1]. In the iron and steel production processes, it is very important to reduce the amount of fuel used [2]. Most of the atmospheric pollutants released come from the iron and steel industry, and more than 42% of the dust, 65% of the SO₂, and 55% of the NO_x are emitted as exhaust gas pollutants during the sintering process. The S and N content in fossil fuels is high and a large amount of SO₂ and NO_x is released during iron ore sintering [3,4].

Metallurgical research seeks to reduce the energy intensity of processes and minimise environmental impacts. The blast furnace charge consists of three main raw materials: fuel, iron ore (sinter, pellets), and additives. The efficiency of the blast furnace process is affected by both the quality of the blast furnace coke and the quality of the ferrous burden materials [5–7].

Metallurgical firms consume significant energy in the steel production process, and the iron and steel industry is characterised by a high energy intensity and material usage. Almost half of the input material was found to be off-gases, process gases, and solid production residues [8].

Between 2010 and 2022, pig iron production in the European Union (EU) saw a rise from around 94.05 million metric tons to a peak of approximately 95.19 million metric tons. Pig iron production decreased in the following years. In 2022, it was about 73.7 million metric tons. The production of pig iron within the EU is shown in Figure 1. This statistic illustrates the total pig iron production in the EU from 2010 to 2022 [9]. According to the International Energy Agency (IEA), steel production is projected to grow by 30% by 2050 [10].

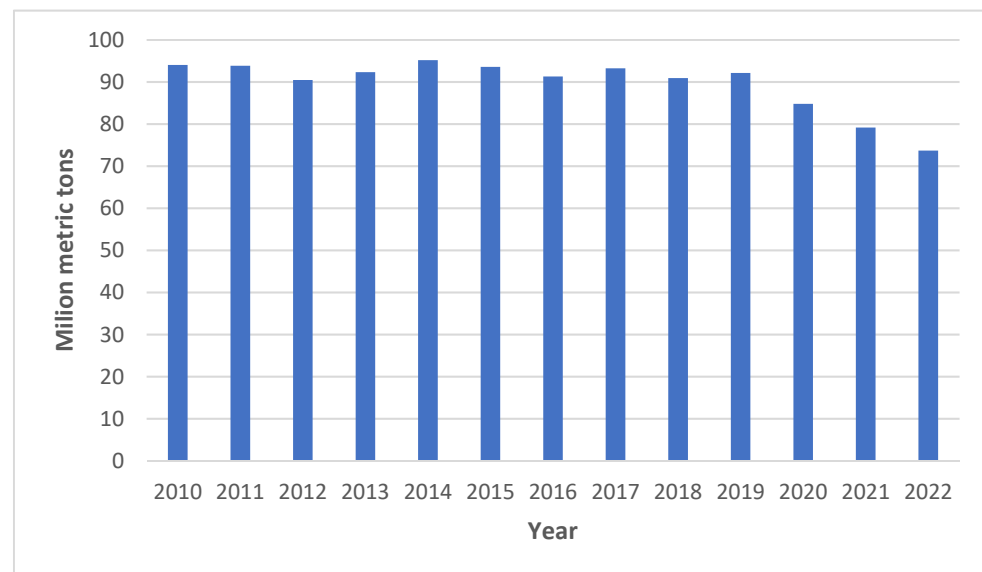


Figure 1. Total pig iron production in the European Union (EU) from 2010 to 2022 in million metric tons [9].

The type of fuel used has an effect on the economy and ecology of production, as well as the properties of the sinter. The price of anthracite is, on average, lower than the price of producing coke (coke breeze). Coke breeze has a non-volatile carbon content of 91%, a volatile content of 4.5%, an ash content of 17%, and a sulphur content of 2%. Sulphur constitutes a significant portion (approximately 65–80%) of the organic component, the remainder being composed of sulphur in various forms such as FeS_2 , FeSO_4 , CaSO_4 , and elemental sulphur. The concentration of SO_2 emissions is 800–2000 g per ton of sinter. The sulphur content of the fuels influences both the quality of the sinter and the amount of SO_2 emissions. The suitable substitute fuel is anthracite according to its chemical composition. The amount of sulphur in anthracite is in the range of 0.25 to 0.48%. The faster combustion reactivity of anthracite leads to a higher maximum temperature and a shorter sintering time. When using anthracite, the strength of the sinter increased in the 0.5–6.3% fraction [4,8].

1.1. Sintering Process

In ferrous metallurgy, the process of sintering fine ferrous compounds, such as fine ores, blast furnace residues, steelwork waste, mill scale, and electrostatic precipitator dust, is known as the sintering process (Babich et al., 2008) [11]. This sinter production is a thermotechnical procedure in which the materials are heated using carbonaceous fuel. Typically, the main carbonaceous fuel used is coke breeze, a by-product of metallurgical coke sorting [12]. Coke breeze is the main fuel used in the sintering process, with a particle size of 1 to 3 mm, and is considered the most favourable for effective sintering [13].

Alkaline additives should have a particle size below 3 mm. During the initial phase, individual grains of alkaline additives may undergo dissociation, and in the subsequent phase, the reaction typically occurs between the CaO decomposition product and SiO_2 from the surface of the molten ore grain [14].

Chemical Reactions during Sintering

During the sintering of the agglomeration mixture, a large number of physicochemical events take place in the layer, which affect the sintering process and the quality of the produced agglomerate in different ways and to varying degrees. Knowledge of the course of individual events and processes is a prerequisite for the economic development of the agglomeration and to increase its quality [2,11].

1. Moisture Removal

Hygroscopic moisture already begins to evaporate intensively at a temperature of around 55 °C. The evaporated water passes from the charge into the gas phase, which ensures its further transport.

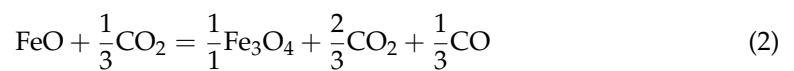
2. Dissociation of hydrate and carbonate

The bound water in the form of hydrates begins to be released only at temperatures above 320 °C. The dehydration process only takes place intensively at higher temperatures, and the complete removal of bound water can occur even at temperatures around 1300 °C.

Carbonates enter the agglomeration batch through the ore part of the mixture, which may contain FeCO_3 a MnCO_3 , and also through basic additives that adjust the basicity of the mixture. The dissociation of siderite requires a temperature of 400 °C to 550 °C and proceeds according to the following equation:



part of the FeO reoxidises according to the equation

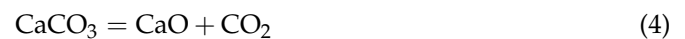


Rhodochrosite dissociates according to the equation



To ensure the necessary basicity of the agglomerate, limestone (CaCO_3), magnesit (MgCO_3), or dolomite ($\text{CaMg}(\text{CO}_3)_2$) is added to the sintering mixture.

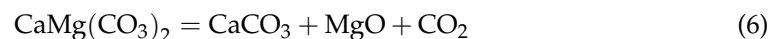
The highest temperature for the dissociation of all carbonates is required for the dissociation of limestone. It decomposes at a temperature of about 900 °C according to the following equation:



Magnesite (MgCO_3) decomposes at a temperature of 620 °C–680 °C according to the reaction



The dissociation of dolomite takes place in two stages. In the first stage, MgCO_3 dissociates at a temperature of around 700 °C:



and in the second stage at 900 °C, the resulting limestone decomposes.

The solid products of the dissociation of CaO and MgO participate in the formation of calcium and magnesium ferrites, respectively, which are a welcome form of agglomerate.

3. Reduction and oxidation processes in the sintering layer

Simultaneously, with the dehydration of the charge with the dissociation of carbonates, a partial reduction of oxides begins to occur in the sintering layer. Reduction processes take place mainly in the immediate vicinity of fuel grains, where there is a significant concentration of CO.

Among the reduction processes, the following can take place mainly in the sintering layer:

- Reduction of Fe_2O_3 to Fe_3O_4 by carbon monoxide and solid carbon;
- Reduction of Fe_3O_4 to FeO by carbon monoxide and carbon;
- Reduction of Mn_3O_4 by carbon monoxide.

Of the oxidation processes that take place in the layer, the most significant are

- Oxidation of fuel carbon to CO_2 or CO;

- Oxidation of CO by oxygen to CO₂;
- Oxidation of FeO to Fe₃O₄ a Fe₂O₃;
- Oxidation of sulphur-containing compounds [2,11].

Coke dust is thoroughly mixed with wetted ore mix, limestone, or dolomite, as well as industrial waste such as the sinter recovery fraction, slag, metallurgical waste sludge, etc. In the first stage of the process, the materials are mixed and carefully layered on a sintering belt by adding waste materials from other ironmaking operations. The last layer is usually composed of coarse material. Coke burning on the sintering belt takes place according to Equations (7)–(10):



and (in part)



As the temperature increases, the subsequent gasification of carbons takes place:



as well as CO oxidation:



Unlike Equations (7) and (8), the other equations are exothermic, which then leads to an increase in the temperature on the sintering belt. This temperature rise can be successfully reduced by the optimal distribution of the fine coke particles. The air intake causes the sintering zone, which has formed at the top, to move downward, and the agglomerate is gradually formed. Cold air drawn through the bed cools the already baked layer, heats, and preheats the layer below the combustion zone. The process is complete when the sintering zone reaches the lowest layer. This is followed by an oxidation zone and a cooling zone. The resulting sinter is further crushed and sieved [11].

The raw material for the sintering process is fine-grained iron ore and iron ore concentrates, which are imported from abroad. Their composition is shown in Tables 1 and 2. The process of sintering iron ores involves the heating of the dust agglomeration mixture (ore, fuel, additives) to such a temperature that the surface of the individual grains of the charge melts. The resulting melt will form liquid bridges between the grains, which after solidification will ensure the formation of a solid porous material, sinter.

Table 1. Chemical composition and grain size of fine iron ore samples.

Raw Material	Composition of Fine Iron Ores (FIOx) (w.%)													Grain Size (mm)	
	Fe	SiO ₂	CaO	MgO	Al ₂ O ₃	P	Mn	S	Na ₂ O	K ₂ O	Zn	FeO	H ₂ O	<0.5 mm	>10 mm
FIO1	56.6–64.0	6.2–17.8	0.02–0.10	0.05–0.34	0.59–0.88	0.015–0.35	0.01–0.04	0.012–0.016	0.090–0.201	0.033–0.053	0.002–0.007	0.14–0.68	3.5–4.5	20–24	<12
FIO2	59.8	12.1	0.06	0.14	0.77	0.026	0.02	0.011	0.148	0.043	0.004	0.37	3.8	35–37	<15
FIO3	62.7	7.3	0.52	0.23	0.84	0.023	0.06	0.020	0.055	0.027	0.004	0.90	4.6	20–23	<10
FIO4	63.1	2.4	0.15	0.04	1.38	0.047	0.27	0.016	0.016	0.011	0.003	0.14	7.0	21–24	<11
FIO5	65.0	3.5	0.08	0.06	0.90	0.042	0.08	0.005	0.005	0.008	0.003	2.02	7.4	30–36	<14
FIO6	65.6	1.1	0.10	0.05	0.89	0.074	0.31	0.014	0.013	0.024	0.003	0.18	6.8	19–23	<16
FIO7	64.5	6.7	0.10	0.05	0.96	0.047	0.16	0.004	0.013	0.015	0.003	3.92	7.5	33–36	<12
FIO8	67.05	1.4	0.70	0.52	0.47	0.001	0.02	0.003	0.001	0.001	0.001	8.04	4.0	20–26	<11
FIO9	64.7	1.3	0.03	0.07	0.77	0.057	0.02	0.007	0.016	0.000	0.006	0.14	5.5	30–34	<13

Table 2. Chemical composition and grain size of iron ore concentrates.

Raw Material	Composition of Iron Ore Concentrates (IOCx) (w.%)													Grain Size (mm)	
	Fe	SiO ₂	CaO	MgO	Al ₂ O ₃	P	Mn	S	Na ₂ O	K ₂ O	Zn	FeO	H ₂ O	<0.5 mm	>10 mm
IOC1	65.54–67.50	5.90–7.83	0.12–0.14	0.35	0.15	0.007–0.008	0.016–0.023	0.022–0.027	0.052–0.059	0.014–0.030	0.003	27.16–27.55	10.1–10.2	8	8
IOC2	64.82	8.01	0.25	0.36	0.1	0.007	0.02	0.035	0.069	0.038	0.003	26.61	9.4	13	4
IOC3	64.90–67.5	5.9–8.49	0.05–0.19	0.32–0.35	0.25–0.31	0.011–0.015	0.032	0.012–0.073	0.025–0.060	0.030–0.042	0.003	26.96–28.0	9.3–10.5	9	11
IOC4	66.36	6.78	0.21	0.44	0.18	0.014	0.041	0.035	0.045	0.049	0.003	28.07	8.8	47	10
IOC5	65.68	7.28	0.23	0.29	0.25	0.013	0.027	0.066	0.032	0.042	0.003	27.05	9.4	62	10
IOC6	67.79	4.92	0.16	0.33	0.14	0.011	0.025	0.044	0.062	0.035	0.002	28.22	9.5	51	9
IOC7	65.61	7.59	0.17	0.28	0.06	0.011	0.015	0.018	0.06	0.181	0.003	26.08	9.5	21	6
IOC8	64.74	0.42	0.23	5.49	1.78	0.038	0.43	0.269	0.026	0.034	0.034	23.75	2.7	15	48
IOC9	69.65	0.97	0.24	0.13	0.78	0.075	0.056	0.02	0.011	0.022	0.005	37.43	7	28	12

Key steps of the sintering process:

The thermal processes in the sintered layer affect mainly the quality of the agglomerate produced.

Ignition of the mixture

The charge is ignited with a mixed gas. A certain amount of heat (about 45 MJ/m²), a certain time (40 s to 90 s), and a certain negative pressure are needed.

Fuel burning

After ignition, a 10–30 mm high combustion front is formed. The speed of the combustion front is 0.03–0.04 cm/s. There is excess air in the bed, and coke carbon burns to produce about 80% CO₂ and 20% CO.

Heat transfer

In the upper zone of heat transfer, the hot sinter preheats the passing air, whereas in the lower zone, the hot flue gases preheat the charge. At the beginning of the process, neither the air nor the charge is preheated, and at the end of the process above the grate, the preheating is at the maximum. Therefore, there is significantly more heat in the lower part of the layer than in the upper part. This is reflected in the mineralogy composition and properties of the sinter produced [2,11].

The absence of coking coal and the environmental considerations for decarbonisation create opportunities for substituting coke with alternative fuels. Anthracite, charcoal, and other types of biomass are used, as the appropriate char obtained from car tyres could be a potential substitute for some of the coke breeze used in the iron ore sintering process [15]. The replacement of coke dust in the production of sinters with alternative fuels has been tested since the 1970s. In Sumitoma's study [16], tests were carried out with different types of substitute fuel and anthracite coal, and the results showed that up to 45% of the coke dust could be substituted. BlueScope Steel, CSIRO, and OneSteel [17] are investigating the replacement of dust coke with biomass-derived charcoal. Research has shown that specially treated charcoal is a potential substitute for coke dust or anthracite. As a result, the sinter made from a 50% charcoal replacement had a lower strength.

The reason for using substitute fuels is to reduce the emission burden of the sintering process. The fuel for sintering must have a high calorific value and, if possible, a low content of ash and volatile substances.

During sintering, the fuel burns only in a narrow area with a thickness of approx. 10 to 30 mm. This region moves toward the grid at a rate of 0.03 to 0.04 cm/s.

The highly flammable fuel will burn in a given layer before the filtered air gives up the heat obtained in the cooling zone of the agglomerate (in the upper zone of heat transfer) at this level. The consequence is a reduction in the maximum temperature and a prolongation of the course of temperature waves. The specific fuel consumption increases and equipment productivity decreases.

If the fuel is not very flammable, it will burn at the given level of the layer at the time when the most preheated air flows over it. In this case, the maximum temperature will decrease and the sintering zone will expand. The optimal fuel flammability lies in the region between these extreme cases. With a low fuel content, the necessary strength of the agglomerate is not achieved, while a fuel content that is too high leads to the formation of an excessive amount of melt, to a decrease in productivity, and to a deterioration of the reducibility of the agglomerate.

Charcoal naturally contains a higher moisture content. An increasing proportion of charcoal increases the vertical sintering rate, while the yield and strength index decrease [8,14,17].

Currently, efforts are underway to enhance the quality of the sinter by reducing the fuel consumption. Fine-grained coke dust or coke pulp is considered a premium fuel for sinter production. A recent trend involves substituting coke dust with anthracite. The fuel used for sintering typically has a particle size of less than 3 mm.

The sintering of iron ores is characterised by significant thermal, mineral, and chemical variations in height and volume. The grain size of the sintering components plays a crucial

role, as it influences the chemical composition of the pellets and the distribution of the solid fuel within the sintering layer, leading to uneven temperature-kinetic sintering conditions. The amount of return sinter fines serves as an indicator of the strength and reducibility of the finished sinter. An increase in the quantity of resulting return sinter fines suggests a decrease in strength and an increase in reducibility and vice versa. Consequently, the sinter mixture exhibits an uneven distribution throughout its volume. The research emphasis has been placed on obtaining more detailed information on the mineralogical composition and mechanical properties of the sinter as a result of the significant importance of its structure.

Some researchers [18] have focused on minimising the coke breeze in the sintering process, exploring its impact on the yield and productivity of the final sinter. Using a basicity of 2.5% and 1.5%, along with a gradual 50% reduction in coke, the yield demonstrated an improvement of approximately 8%. This led to a better production productivity of about $30 \text{ t} \cdot \text{m}^{-2}$ per day.

Scientists from Australia [19] have examined the correlation between the structure and chemical composition, including basicity, and the quality of sinters. As the basicity of the sinter increased, more binding phases were formed, resulting in an enhancement of the pore structure. The strength of the sinter saw an increase with an increase in basicity up to 3. However, when the basicity of the sinter reached 3.5, there was a marked decrease in strength.

2. Materials and Methods

The experiments were performed in a sinter plant in the Czech Republic, where the sintering fuel (coke) was replaced by anthracite. The replacement coefficient ranged from 0–100%.

Raw Materials

The raw materials comprised iron-containing substances (iron concentrates, iron ore fines), fluxes (limestone, dolomite), solid fuels (coke breeze and anthracite), and return fines. In the fine iron ores used in the Czech Republic, the presence of an undesirable coarse fraction exceeding 10 mm typically amounts to approximately 7%. The chemical compositions of the raw materials are presented in Tables 1 and 2 [20].

The choice of fuel for the sintering charge is of significant importance, as it supplies the necessary heat for both the physical and chemical processes and contributes to the formation of sinters with desired properties. Approximately 65% of the iron ore enters the blast furnace in the form of sinter, while around 30% is in the form of pellets [21]. In the Czech Republic, the fuel used for the sintering process includes coke breeze and anthracite. The composition and parameters of these fuels undergo change over the years, and a comparison of their average parameters is presented in Table 3.

Table 3. Comparison of the average parameters of anthracite and coke breeze.

	Anthracite	Coke Breeze
C (%)	85.30	77.20
N (%)	0.71	1.05
H (%)	1.36	0.23
Zn (%)	0.004	0.004
H ₂ O (%)	10.40	15.40
A ^d (%)	13.00	16.30
V ^{daf} (%)	1.33	4.12
S (%)	0.30	0.53
Q _{ir} (MJ/kg)	23.90	23.99
Q _{sa} (MJ/kg)	27.01	28.74

As is clear from the table, the difference in calorific value between coke dust and anthracite is very small (approx. 1.7 MJ/kg) compared to, for example, the calorific value of biomass ($Q = 15.1$ MJ/kg) [15].

Typically, coke breeze serves as the primary fuel in the sintering process due to its high calorific value, low reactivity, and diminished volatile content. However, in recent years, alternative fuels such as brown coal coke, anthracite, and biomass have also been used in the sintering process [22,23].

As part of the technological flow of the material, the ore components and basic correction additives are transported to the dosing tanks by a conveyor belt, and the pulverised fuel is transported through a vibrating screen to the raw fuel tank above two two-roll mills, which grind the fuel to the required grain size (minimum of 85% of grain should be 0–3 mm). Ground fuel is transported by conveyor belts and a bucket elevator to technological fuel storage tanks, where the ore components are dosed using proportional dosing, the basic ingredients are dosed using dosing scales, and ground fuel is dosed by dosing scales onto the conveyor belt, where the warm return sinter is also dosed through the steel passport. Wet anthracite is not suitable for grinding and subsequent uniform dosing; due to its lower roughness, it sticks to the walls of the containers and sticks to the feeding screens.

The preparation of the sintering mixture (charge) begins with the packaging technology. It is produced using a combination of first- and second-stage mixing drums. In the first-stage mixing drum, the mixture is mixed and sprinkled with a set of nozzles. The parameters are checked using an automatic multifunctional sensing device. The monitored parameters include the weight of the dosed raw materials, the opening position of the cap of the added return sinter, the temperature of the return sinter, the amount of water added, the humidity of the mixture, the temperature of the mixture, and its permeability.

In practice, the machinist must take into account three factors that determine the optimal structure of the mixture:

1. The amount of material entering the mixing drum and its properties, mainly with respect to fraction and moisture content. The material then does not have time to fully thaw because of its flow rate. Larger grains formed by contact with frozen water enter the packing drum and, in the mixer (under the influence of heat), they disintegrate during the packing process or in already-formed bales. When the mixture is thawed, the bound water is released and its participation is influenced by the packability of the mixture. Here, it depends on the storage method, the previous condition, and the climatic conditions at the time of the addition of the raw materials.
2. The amount and temperature of the incoming return sinter. The standard cycle of movement of the return sinter is such that, as the quality of the sinter increases, the amount of the returnable fraction decreases. With a relatively constant withdrawal, the level in the reservoir drops. Subsequently, an increasingly hot sinter enters the batch, bringing more heat into the packaging process.
3. Hysteresis of ongoing regulation. The effect of changing the amount of water in the batch mixture is shifted by the sum of two influences. The first is the time required to achieve a change in the mixture in the packing drum. The second is the time delay caused by the distance between the measurement point and the operator's evaluation of the state of the mixture from the ongoing changes in the packing drum.

After reaching the optimal state of the charged mixture, the operator has the option of switching the dosing system to the automatic position. The dosing control system then evaluates the read parameters in real time and makes corrections to maintain the set limits in which the measured parameters of mixture moisture, permeability of the mixture, and its temperature were moving at the time of switching to the automatic mode. This control system is applicable when there are no sudden changes in the monitored system. In general, it can be said that the worse the packing properties of the mixture are, the less realistic the possibility is to keep the automatic water dosage control system at the optimal values of the mixture. After leaving the first-stage mixing drum, the sintering mixture travels through

conveyor belts to a two-part distribution hopper with a distribution valve. From this flap, the material is divided into separate paths for each sintering belt.

Behind the hopper, the mixture enters a pair of second-stage mixers. In them, the mixing and packaging process is completed. Fine dusting absorbs the moisture available from the mixture and is wrapped in bales. The packing process is completed when the mixture is placed into containers. The accumulation of the mixture in the reservoir causes its further compaction. In addition to maintaining a sufficient supply for the sintering process, the reservoirs also serve as a capacity buffer in the event of unforeseeable shutdowns of the sintering belts for the smooth shutdown of the mixing equipment; the quality of the mixture produced decreases during immediate shutdown. The mixture is then dosed onto the sintering belt using a delivery drum. Its amount is controlled by the regulating trowel so that a sufficient discharge of the mixture is achieved throughout the width of the sintering belt.

The sintering of the sinter mixture in the monitored sinter plant was carried out using a Dwight–Lloyd machine. The mixture must form an even homogeneous layer with a thickness of 25–50 mm.

The upper layer of the sinter mixture on the sintering belt is ignited by the ignition head, and because of the negative pressure created by the turbo exhauster, the mixture layer gradually burns through and the dust ores themselves sinter into a piece of sinter.

The individual bands that connect to each other move towards the grid surface at the so-called vertical sintering speed. After that, the layer above the grate surface is sintered and the sintering ends, which occurs above the penultimate 15th suction chamber.

The sinter pieces that fall at the discharge end are crushed by rotary hedgehog crushers to a size of up to approximately 200 mm. This is followed by transport by a steel conveyor to the sorter. Here, the return sinter with a grain size of 0–6 mm is sorted, which is returned to the batch by the conveyor. The finished sinter is transported by conveyors to storage tanks as a charge for the blast furnaces.

The main prerequisite for the correct course of the process is the adjustment of the amount of gas supplied to the ignition nozzles in such a way as to achieve the optimal sintering temperature and the uniformity of the ignition of the upper layer of the sintered charge. The inspection is carried out visually when the charge exits under the ignition unit; at the same time, the condition of the carriage and the sealing of the spaces between the carriages and the entrances to the extraction chambers are checked. Furthermore, the sintering process is monitored according to the temperature value of the outgoing flue gases. An ideal combustion process is characterised by an increase in the temperature of the exhaust chamber and the ability to reach maximum temperatures in the chamber. The temperature values in the extraction chamber signal the ongoing cooling of the sintered layer of the charge. The course of negative pressure values is the main indicator for the breathability of the mixture, that is, the course of changes in the thickness of the burning zone along the length of the sintered strip.

The heat generated by burning fuel increases the temperature of the sintered mixture to 1380 °C–1450 °C. There is gradual burning through the mixture layer and the actual sintering of the dust ores into lumpy sinters [20]. In the sintering process, coke breeze and anthracite with a particle size of less than 3 mm are used as fuel.

The sintering belts have 80 bulk sintering carts with a side height of 40 cm. The extracted area is 75 m², with a cart width of 2.5 m. The technical data of the sintering carts are provided in Table 4.

Table 4. Sintering belt parameters [20].

Length of the working section (m)	30
Width (m)	2.5
Extracted area (m ²)	75
Number of sintering trolley/sintering belt (pcs)	80
Max. layer height (mm)	400

In an effort to intensify the sintering process as much as possible, it was necessary to accelerate the burning in the layer of the sintering mass and thereby ensure the formation of liquid phases. This ensures the fulfilment of one of the main parameters of the sintering process, the compliance with a sufficient vertical sintering speed. This, in turn, is somewhat dependent on the optimal permeability of the sintering mass.

Furthermore, the sintering process is monitored according to the temperature value of the outgoing flue gases. An ideal combustion process is characterised by an increase in the temperatures of the exhaust chamber and the ability to reach maximum temperatures in the chamber. The temperature values in the extraction chamber signal the ongoing cooling of the sintered layer of the charge. The course of negative pressure values is the major indicator for the permeability of the mixture, i.e., the course of changes in the thickness of the burning zone along the length of the sintered strip.

3. Results

In the monitored operation of the company, the sintering charge uses coke breeze as the primary fuel, and since 2013, anthracite has been introduced as an additional component. At first, it was only a partial substitute for the fuel, but its share gradually increased, similar to that of the world [7,15,23,24]. During the years 2020–2022, anthracite was added as part of the sintering charge in different proportions. Table 5 provides a summary.

The advantage of replacing coke with anthracite depends on the current purchase prices of these commodities. As is clear from the table, in some (especially winter) months, anthracite was not added at all. On the other hand, in the summer months, the replacement of coke dust with anthracite reached 100%.

As part of the technical control, sinter samples are taken regularly. The content of Fe, FeO, and other elements and oxides in the sinter produced is determined. Granulometry, strength, and abrasion resistance are determined according to the requirements of the technologists; the evaluation is shown in Table 6.

Table 5. Summary of effects of adding anthracite to the sintering charge in different proportions.

	Production (kt)	Specific Power (t/m ² /d)	Total Fuel Consumption (kg/t)	Anthracite (t)	Coke Breeze (t)
			2020		
1	128,000	28.99	45.70	-	5850
2	117,900	28.60	44.36	-	5230
3	128,300	28.99	46.69	2483	3507
4	129,600	30.73	43.90	3395	2295
5	140,600	31.96	45.59	6410	-
6	127,500	30.71	51.92	3862	2758
7	129,100	29.88	48.64	2933	3347
8	129,700	29.90	45.88	2692	3258
9	121,800	28.86	46.63	1929	3751
10	81,600	27.51	53.86	1194	3201
11	121,300	28.43	44.27	390	4980
12	123,100	28.01	47.03	-	5790

Table 5. Cont.

	Production (kt)	Specific Power (t/m ² /d)	Total Fuel Consumption (kg/t)	Anthracite (t)	Coke Breeze (t)
2021					
1	112,900	28.17	52.83	-	5965
2	115,500	28.98	48.57	-	5610
3	128,400	29.03	47.74	380	5750
4	124,600	29.30	49.36	1835	4315
5	139,000	31.71	47.77	6591	49
6	139,300	33.14	44.58	6086	124
7	134,100	32.01	51.53	6846	64
8	125,900	31.14	50.40	1146	5199
9	73,200	30.42	48.22	-	3530
10	97,600	27.22	48.57	-	4740
11	126,900	30.10	52.48	-	6660
12	108,500	27.28	49.40	-	5360
2022					
1	116,600	27.37	50.34	-	5870
2	119,300	30.26	48.11	-	5740
3	112,400	26.69	46.89	-	5270
4	119,000	28.22	48.82	-	5810
5	132,600	30.06	48.11	-	6380
6	111,100	26.92	42.03	-	4670
7	123,200	28.99	41.96	683	4487
8	121,400	29.50	44.98	1602	3858
9	120,300	29.41	49.71	2366	3614
10	81,100	28.64	46.73	398	3392
11	121,800	30.11	45.16	1366	4134
12	105,000	24.91	44.86	602	4108

Table 6. Comparison of sinter parameters with different types of fuel.

Fraction	Sinter Grain Size (%)			Sinter Strength (%)			Specific Power (t/m ² /d)
	0–5 (mm)	5–25 (mm)	>25 (mm)	0–0.5 (mm)	0.5–6.3 (mm)	>6.3 (mm)	
Coke breeze	8.70	58.92	32.38	4.83	26.21	68.95	26.10
Anthracite	9.33	56.84	33.84	4.54	27.46	68.01	24.90

There are worsening conditions during unloading in the winter months and inappropriate storage (outdoor so-called outdoor field warehouses). During the period of anthracite addition, there was a decrease in sinter production. Sinters made with the addition of anthracite have a higher strength. However, this causes, for example, the wear of the crushers; an increase in consumption of up to 34% can be observed for the crusher bars. The evaluation of the results is shown in Table 6.

As a result of the gradual extension of the period of addition of anthracite, anthracite was supplied with increased moisture, negatively affecting the sintering technology, and wet ground anthracite blinded the surface of the grate and stuck to the walls of the storage tanks. Therefore, the anthracite for the sintering process was supplied in the form of a “rough”.

As evident from the previous results, there was an increase in the strength of the sinter within the 0.5–6.3 mm fraction.

The resulting properties of the sinter produced depend on several factors. Among the most important was the carbonaceous fuel, which affected the resulting product, sinter, as well as the economic and ecological conditions of its production.

When using anthracite, the specific power of the sinter was reduced by approximately $1.2 \text{ t/m}^2/\text{d}$, depending on the moisture content of the anthracite (uneven dosing occurs). The specific power increased with a higher proportion of anthracite but only up to a certain limit, after which, it tended to decrease again. Even with sufficient strength and high reducibility of the sinter, it may not always be a suitable raw material for blast furnaces. In addition to these two properties, compliance with a certain chemical composition is important. There must be no fluctuations, mainly in the content of Fe, FeO, CaO, and SiO₂.

The way it is cooled also had a great influence on the strength of the sinter. The use of hot sinter results in an increase in blast furnace discharge, makes the working conditions around the blast furnace reservoirs more difficult, and wears out the transport equipment used to transport the sinter to the blast furnaces. Therefore, the produced sinter must be cooled. The sinter is cooled by either air or water. Both methods have an effect on the strength of the sinter, especially during cooling with water, when the sinter is disrupted and a significant amount of small particles is formed.

The analysis of the process showed that the full replacement of coke with anthracite did not worsen the process of packing the mixture and pre-pelleting the charge; with an increase in the coefficient of replacement of coke with anthracite, there was a decrease in the temperature of the sintered layer, and an increase in the sintering time was recorded. The replacement of coke with anthracite resulted in a slight reduction in the proportion of the subsieve fraction by approximately 2% in the case of a high degree of substitution. This was also confirmed by the increase in medium grains.

The use of anthracite led to a higher maximum temperature and a shorter sintering time, which reduces quality.

According to the results, the use of anthracite as a substitute fuel affects the quality of the resulting agglomerate, increasing it in the 0.5–6.3 mm fraction, and slightly decreasing it in the other fractions [25].

4. Conclusions

The results can be summarized as follows:

- Substituting coke breeze with anthracite does not compromise the packing and pre-pelleting of the sinter mix. With an increase in the coefficient of replacement of the coke breeze with anthracite, the temperatures of the sintered layer decreased and the sintering time was extended. Substituting coke breeze with anthracite resulted in a minor decrease in the proportion of the subnetwork by approximately 2% in the case of extensive substitutions, as confirmed by the increase in the medium-sized grains;
- Replacing 100% of the coke breeze content with anthracite resulted in a 17% decrease in sintering production;
- In the 0.5–6.3 mm fractions, the strength of the sinter increased, resulting in an increase in abrasion of approximately 0.7%;
- The higher strength of the sinter caused stress and also wear in the case of the crusher bars; an increase in consumption of up to 34% was observed;
- With a 50% substitution, anthracite exhibited more favourable performance parameters compared to the standard sintering process with coke breeze;
- Wet anthracite is not suitable for grinding and subsequent uniform dosing; as a result of lower roughness, it sticks to the walls of the containers.

Due to ecological requirements to reduce the amount of CO emissions during the sintering process and the requirements to reduce the specific fuel consumption, the following measures are proposed:

- Reduce the amount of false air sucked in between rails and carriages;
- Reintroduce the grid, which is common in all world sinters, without exception;
- Increase the suction efficiency with the aim of increasing the layer on the sintering belt;
- Increase the layer in the sintering belt to a value of 600–680 (mm). This requires an increase in the breathability of the sinter mixture, which can be improved by the following measures:

- Better mixing (creating micropellets) by extending the mixers or optimising the wetting of the sinter mixture;
- Fuel filtering to exclude the fraction below 1 mm.

By implementing the measures mentioned above, it would be possible to reduce the specific fuel consumption to 50% of the current value.

The operational testing of the replacement of coke breeze with anthracite proved that the promotion of anthracite significantly affects both the economy and ecology of the sinter production process. The use of approximately 15 kt of anthracite appears to be optimal in terms of fuel savings.

The replacement of coke breeze with anthracite in the sinter production process is beneficial both from an ecological and economic point of view. Coke breeze replacement measures are mainly aimed at reducing energy consumption and the environmental burden, while meeting production and quality requirements for sinter.

Author Contributions: Conceptualization, P.P. and M.S.; Methodology, K.P.; Software, S.J.; Validation, E.K.; Formal analysis, M.S.; Data curation, P.P.; Writing—original draft, P.P. and M.S.; Writing—review & editing, S.J. and K.P.; Supervision, E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bernasowski, M.; Stachura, R.; Klimczyk, A. Fuel Consumption Dependence on a Share of Reduction Processes in Imperial Smelting Furnace. *Energies* **2022**, *15*, 9259. [CrossRef]
2. Legemza, J.; Fröhlichová, M.; Findorák, R.; Džupková, M. Modelling of Mass and Thermal Balance and Simulation of Iron Sintering Process with Biomass. *Metals* **2019**, *9*, 1010. [CrossRef]
3. Liu, C.; Kang, Y.; Zhang, Y.; Xing, H.; Xue, G. Effect of Replacing Coke with Biomass Fuel on Sinter Properties and Pollutant Emissions. *Metals* **2022**, *12*, 1483. [CrossRef]
4. Angalakuditi, V.B.; Gujare, R.; Anbarasu, R.; Gandikoti, T.; Raydurg, S.R.; Singh, L.R.; Baral, S.S. Characterization and In Situ Abatement of SO_x, NO_x, and PCDD/Fs in Iron Ore Sinter Machine Wind Legs. *J. Sustain. Metall.* **2022**, *8*, 742–753. [CrossRef]
5. Kardas, E. The analysis of quality of ferrous burden materials and its effect on the parameters of blast furnace process. *Metalurgija* **2013**, *52*, 149–152.
6. Konstanciak, A. Evaluation of the quality of coke for blast furnace process in chosen metallurgical plant. In Proceedings of the Metal 2015, Brno, Czech Republic, 3–5 June 2015; pp. 1988–1993.
7. Cameron, I.; Sukhram, M.; Lefebvre, K.; Davenport, W. *Blast Furnace Ironmaking: Analysis, Control, and Optimization*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2019. Available online: <http://ebookcentral.proquest.com/lib/vsbtuo-ebooks/detail.action?docID=5967200> (accessed on 16 February 2024).
8. Commission of the European Union; Joint Research Centre; Institute for Prospective Technological Studies. *Best Available Techniques (BAT) Reference Document for Iron and Steel Production: Industrial Emissions Directive 2010/75/EU: Integrated Pollution Prevention and Control*; Publications Office: Luxembourg, 2013.
9. Annual Production of Pig Iron in the European Union (EU-28). Available online: <https://www.statista.com/statistics/550857/pig-iron-production-european-union/> (accessed on 16 February 2024).
10. IEA. Iron and Steel Technology Roadmap towards More Sustainable Ironmaking. 2020. Available online: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf (accessed on 16 February 2024).
11. Babich, A.; Senk, D.; Gudenau, H.W.; Mavrommatis, K. *Ironmaking (Textbook)*; RWTH Aachen University, Department of Ferrous Metallurgy, Wissenschaftsverlag Mainz in Aachen: Aachen, Germany, 2008; p. 402, ISBN 386-13-099-71.
12. Fröhlichová, M.; Ivanisin, D.; Findorák, R.; Džupková, M.; Legemza, J. The Effect of Concentrate/Iron Ore Ratio Change on Agglomerate Phase Composition. *Metals* **2018**, *8*, 973. [CrossRef]
13. Mohamed, F.M.; El-Hussiny, N.A.; Shalabi, M.E.H. Granulation of Coke Breeze Fine for Using in the Sintering Process. *Sci. Sinter.* **2010**, *42*, 193–202. [CrossRef]
14. Legemza, J.; Fröhlichová, M.; Findorák, R. The influence of biomass on ecological aspects of ferri-ferrous agglomerate production. In Proceedings of the 18th International Multidisciplinary Scientific GeoConference (SGEM 2018), Albena, Bulgaria, 2–8 July 2018; pp. 187–194.

15. Niesler, M.; Stecko, J.; Gierad, D.; Nowak, M.; Stelmach, S. Experimental Production of Iron-Bearing Sinters Using Chars from Waste Car Tires. *Processes* **2023**, *11*, 231. [\[CrossRef\]](#)
16. Mitra, D.; Koranne, V.M.; Ambastha, R.; Sinha, S.; Das, B.K. Use of Raw Petroleum Coke in Sinter Plant. *ISIJ Int.* **2009**, *49*, 676–680. [\[CrossRef\]](#)
17. Lu, L.; Adam, M.; Kilburn, M.; Hapugoda, S.; Somerville, M.; Jahanshahi, S.; Mathieson, J.G. Substitution of Charcoal for Coke Breeze in Iron Ore Sintering. *ISIJ Int.* **2013**, *53*, 1607–1616. [\[CrossRef\]](#)
18. Bhagat, P.R. Reduction of solid fuel consumption in sintering of indian iron ore. *Sci. Sinter.* **2015**, *47*, 205–213. [\[CrossRef\]](#)
19. Liming, L.; Ware, N.; Raynlyn, T. Chemistry structure and quality of iron ore sinter. In Proceedings of the AISTech 2015 Proceedings, Cleveland, OH, USA, 4–7 May 2015; pp. 322–332.
20. Sikora, M. Verification of Operation of Experimental Sinter Pot for Sinter Preparation. Diploma Thesis, VŠB-TUO, Ostrava, Czech Republic, 2017; 58p.
21. Kuchin, V.Y.; Detkova, T.V.; Eliseev, A.A.; Reshiotkin, S.V. The Study of the Influence of the Grain-Size Composition of Anthracite on the Agglomerating Index and the Development of Technological Recommendations for the Preparation of Fuel for Sintering for the CherMK Conditions. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *718*, 012009. [\[CrossRef\]](#)
22. Legemza, J.; Fröhlichova, M.; Findorak, R. *Tradičné a Alternatívne Palivá v Metalurgii*; TU Košice: Košice, Slovakia, 2015; 286p, ISBN 978-80-553-2154-7.
23. Zhang, X.; Zhong, Q.; Liu, C.; Rao, M.; Peng, Z.; Li, G.; Jiang, T. Partial substitution of anthracite for coke breeze in iron ore sintering. *Sci. Rep.* **2021**, *11*, 1540. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Cavaliere, P. *Clean Ironmaking and Steelmaking Processes*, 1st ed.; Springer: Cham, Switzerland, 2019. [\[CrossRef\]](#)
25. Sikora, M. Technological Aspects of Using Anthracite to Improve Agglomerate Properties. Ph.D. Thesis, VŠB-TUO, Ostrava, Czech Republic, 2022; 28p.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.