Master's Thesis

Factors Affecting Briquetting Quality of Hot Briquetted Iron

for

voestalpine Texas LLC

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Katharina Gruber

Abstract

Factors Affecting Briquetting Quality of Hot Briquetted Iron

This thesis analyses factors affecting briquetting quality of hot briquetted iron (HBI). Therefore, a testing plan was developed and executed at the voestalpine Texas LLC plant in Corpus Christi, Texas. The impact of the cooling method (air/water quench), of the feed leg temperature, of the roller speed, of the press torque as well as of the segment wear on the briquette quality was tested by changing these parameters at the briquetting press. The briquette quality was determined by the apparent density and the chips generation during a tumble test. For each test, briquette samples were taken and analyzed in the laboratory.

During these tests it is found that air cooling results in significantly less chips generation during the tumble test compared to water quenching. The feed leg temperature positively impacts the apparent density as well as the briquette strength. No correlation was found between roller speed and apparent density. However, the chips generation during the tumble test increases with increasing roller speed. Another result is that briquettes get lighter with increasing roller speed. This suggests that the screw feeder speed is not perfectly aligned with the roller speed. With increasing press torque, the briquette apparent density increases. Moreover, the chips generation decreases, and the briquettes get more abrasion resistance. With increasing press torque, the physical appearance of the briquettes also changes, and they get heavier. This, again, suggests that the screw feeder has to be adjusted. The segment wear does not influence the apparent density of HBI. Nevertheless, there is a higher chips generation during the briquetting process itself. Increasing segment wear leads to changes in the form of the molds, they get deeper and the webbing around the briquettes gets thicker. This is also clearly seen during testing. As a result, the mass of the briquettes increases with increasing segment wear.

Kurzfassung

Faktoren, die die Brikettierqualität von heiß brikettiertem Eisenschwamm beeinflussen

Diese Arbeit analysiert Faktoren, die die Brikettierqualität von heiß brikettiertem Eisenschwamm beeinflussen (HBI). Dafür wird ein Testplan entwickelt und bei der Firma voestalpine Texas LLC in Corpus Christi, Texas, durchgeführt. Es werden fünf verschiedene Tests durchgeführt. Getestet wird der Einfluss der Kühlmethode (Luft/Wasser gekühlt), der Presstemperatur, der Walzengeschwindigkeit, des Drehmoments auf den Rollen, und der Einfluss des Segmentverschleißes auf die Brikettqualität durch Ändern dieser Parameter an der Brikettiermaschine. Die Brikettqualität wird bestimmt von der Dichte und der Festigkeit, bzw. der Bildung von Chips und Feinmaterial während eines Tumble Tests. Die Briketts werden im firmeninternen Labor untersucht.

Die Kühlmethode hat einen großen Einfluss auf die Bildung von Chips während des Tumble Tests. Wassergekühlte Briketts erzeugen wesentlich mehr Chips und Feinmaterial als luftgekühlte. Weiters zeigt sich, dass eine steigende Presstemperatur sowohl die Dichte als auch die Festigkeit der Briketts positiv beeinflusst. Zwischen Walzengeschwindigkeit und Dichte kann kein Zusammenhang festgestellt werden. Mit steigender Walzengeschwindigkeit erhöht sich allerdings die Bildung von Chips während des Tumble Tests. Weiters kann gesehen werden, dass die Briketts mit steigender Walzengeschwindigkeit leichter werden. Dies lässt darauf schließen, dass der Schneckenförderer nicht optimal auf die Walzengeschwindigkeit eingestellt ist. Ein steigendes Drehmoment auf den Rollen resultiert in einer höheren Dichte und Festigkeit, es werden weniger Chips gebildet. Weiters werden die Briketts mit zunehmendem Drehmoment schwerer, was wiederum darauf hinweist, dass der Schneckenförderer besser abgestimmt werden sollte. Der Segmentverschleiß hat keinerlei Einfluss auf die Dichte der Briketts. Allerding steigt der Anteil an Chips, die während des Brikettierprozesses erzeugt werden. Durch Verschleiß werden die Segmente tiefer und deren Form verändert sich. Als Resultat werden die Briketts schwerer.

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1 Introduction

With an increase in crude steel production to 1,689 Mt in 2017 (+3.7 % compared to 2016) the iron and steel industry is continuously growing [1]. Costs and availability of raw material and energy sources as well as restrictions of greenhouse gas (GHG) emissions pose new challenges for the industry. The most relevant greenhouse gas for the production of steel is CO_2. Society as well as governments put continuous pressure on the steel industry to improve efficiency and decrease gas emissions. While Europe's blast furnaces have been optimized during the last decades and are now working close to their theoretical limits, a further decrease in CO_2 emissions by increasing efficiency is extremely difficult. As a result, new, alternative process routes for the production of iron and steel are necessary [2].

One alternative method to minimize the CO_2 emissions is the direct reduction of iron. Direct reduction refers to a removal of oxygen without melting [2]. In October 2016 voestalpine Texas LLC opened the world's largest direct reduction plant in Corpus Christi, Texas. The plant uses methane instead of coal to produce direct reduced iron (DRI). The DRI can be used as a substitute for scrap in an electric arc furnace (EAF) for the production of iron and steel. The DRI/EAF route achieves with 1200 kg CO_2/t crude steel, a 35 % reduction of total CO_2 emissions compared to the traditional blast furnace route with 1700 kg CO_2/t crude steel [3]. This is particularly important because, since the production volume is high with 2 million tonnes per annum, there is a large potential to reduce CO_2 emissions using this technology.

Direct reduced iron (DRI), or also called sponge iron, is a very reactive and unstable material and has to be passivated before storage and transport. The passivation is done with briquetting machines, where two counter-rotating rollers compress the DRI at high temperatures (typically around 700 °C). The product of this briquetting process is called hot briquetted iron (HBI) [4].

Apart of the chemical composition, the most important quality aspects of the HBI is its strength and abrasion resistance which ensures minimum chips and fines generation during material handling. This is of special importance for transportation and in all downstream processes, especially in the electric arc furnace (EAF). In addition to that, an apparent density of 5 g/cm³ is a requirement to ensure its chemical inertness during shipping [4].

The present thesis focuses on the determination of factors affecting the briquetting quality. Improved briquette quality leads to reduced material losses and even has a potential to reduce overall energy consumption during the use of HBI downstream thereby increasing its attractiveness in the industry.

2 Problem Outline

In the following two sections the statement of task as well as the objectives of this thesis will be further described.

2.1 Statement of Task

Austria's biggest steel producer voestalpine has recently built and commissioned a direct reduced iron (DRI) plant in Corpus Christi, Texas. The plant uses natural gas instead of coke to produce iron briquettes and thereby is able to reduce CO_2 emissions. The production volume of this new hot briquetted iron (HBI) plant is with 2 million tons per annum high. Prior to shipment, the DRI must be pressed into a briquette in order to provide a stable unreactive material for shipment. This is accomplished by using several briquetting presses which compact the material at very high temperature. The quality of the briquettes is critical in order to ensure sufficient density, to minimize corrosion and to reduce the quantity of fines and chips generated from the briquettes. A high-quality briquette with minimal corrosion and low fines has the potential to minimize the overall energy input in subsequent steps during which the HBI is converted into steel. The quality of briquettes can be influenced by a number of factors. Incoming DRI material properties into the briquetting press (carbon content, iron content, temperature) as well as materials handling practices and briquetting machine parameters including machine wear all play a role. This thesis will deal with the question of quantifying and qualifying the relevant factors affecting briquetting quality of HBI.

2.2 Objectives

The hot briquetted iron has to fulfill specific physical and chemical parameters in order to meet shipping regulations as well as for economic reasons. These HBI quality parameters include the apparent density and its resistance to the generation of chips and fines during handling and can be influenced by various process factors as well as controlled using various methods (e.g. briquetting press operating parameters).

The main objective of the thesis is to relate briquetting machine parameters and relevant process variables to their impact on briquetting quality. Following research questions should be answered:

- Which factors affect the briquetting apparent density?
- How do different machine parameters influence the briquetting quality concerning chips generation?
- What are ideal operating parameters to achieve a high product quality?
- Do results from the literature research correlate with the results gained from testing on the plant?

This will be accomplished by the design and execution of a series of plant trials, which will relate the impact of specific process parameters to key briquette quality parameters. The tests will be planned together with the voestalpine Texas LLC plant operations group. Moreover, the briquette properties (e.g. density, strength, etc.) will be determined in the production laboratory by conducting standardized tests (e.g. tumble test for identifying the chips generation). The results gained by these tests will then be compared to the results from the literature research and recommendations for optimal process conditions and control methods will be made with the goal of improving the quality of the briquettes produced at the facility in Corpus Christi.

3 Theoretical Part

The theoretical part of this work is structured as follows: First, a definition of Direct Reduced Iron (DRI) and its products is given. Next, the physical and chemical properties as well as the use of DRI in steelmaking are discussed. Furthermore, direct reduction processes with a closer look to the Midrex Process are explained. As a next step, Hot Briquetted Iron (HBI) and its material properties are explained. Afterwards, the thesis treats the agglomeration by compaction and the different types of briquetting, with a special emphasis on hot briquetting and the typical equipment involved. Different influencing factors for briquetting quality are discussed next. Finally, tests to evaluate the physical quality of briquettes are further explained.

3.1 Direct Reduced Iron (DRI)

Direct reduction describes any process in which oxygen is removed from iron ore pellets, lumps or fines in the solid state and where metallic iron is produced. The result of this process is a spongy structure of the product, which is called “sponge iron”. DRI can be used in electric arc furnaces (EAF) as well as in blast furnaces (BF) as feedstock for steel production. There are various types of DRI products which are further described in the next paragraphs. The type of product is dependent on the characteristics of the reduction process used as well as of the incoming iron ore. In section 3.1.4, some processes for the production of direct reduced iron are further described [4],[5],[6].

3.1.1 DRI Products

DRI is available in three different product forms: Cold DRI (CDRI), Hot Briquetted Iron (HBI) and Hot DRI (HDRI). They are shown in Figure 1.

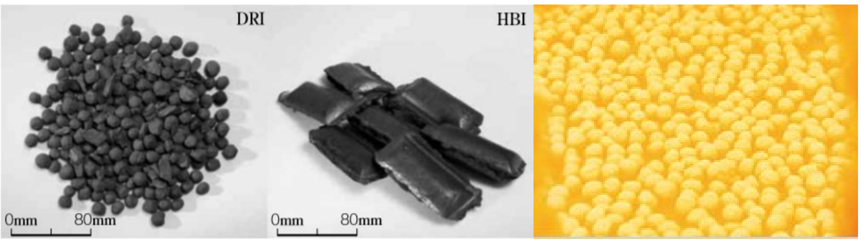


Figure 1: Cold DRI (CDRI), Hot Briquetted Iron (HBI) and Hot DRI (HDRI) [7], [8]

CDRI is produced by most MIDREX plants built today by cooling of DRI in the lower part of the shaft furnace to about 50 °C (122 °F). Typically, this product is used in a nearby EAF. In order to prevent reoxidation and loss of metallization, the CDRI must be kept dry [8]. Metallization is defined as the percentage of iron present as Fe to total iron [9].

HDRI is transported to an adjacent EAF at up to 650 °C (1200 °F) to take advantage of the sensible heat. Because of this, the steelmaker can increase productivity and reduce the production costs.

The third product is HBI. The DRI discharged from the furnace is compressed into pillow shapes. Therefore, this product is much denser than CDRI, which has a positive impact on the reduction of the reoxidation rate [8]. The voestalpine plant in Corpus Christi produces HBI, which will be further described in section 3.1.5.

The typical chemical and physical characteristics of HBI, as well as of CDRI and HDRI are shown in Table 1 [8].

Table 1: Typical characteristics of HBI, CDRI and HDRI [8]

	HBI	CDRI	HDRI
Fe Total (%)	90 - 94	90 - 94	90 - 94
Fe Metallic (%)	83 - 90	83 - 90	83 - 90
Metallization (%)	92 - 96	92 - 97	92 - 96
Carbon (%)	0.5 - 1.5	1.0 - 3.0	1.0 - 3.0
P* (%)	0.005 - 0.09	0.005 - 0.09	0.005 - 0.09
S* (%)	0.001 - 0.03	0.001 - 0.03	0.001 - 0.03
Gangue (%)	2.8 - 6.0	2.8 - 6.0	2.8 - 6.0
Mn, Cu, Ni, Cr, Mo, Sn, Pb and Zn (%)	trace	trace	trace
Bulk Density (kg/m³)	2,400 - 1,900	1,600 - 1,900	1,600 - 1,900
Bulk Density (lbs/ft³)	150 - 175	100 - 120	100 - 120
Apparent Density (g/cm³)	5.0 - 5.5	3.4 - 3.6	3.4 - 3.6
Product Temperature (°C)	80	50	600 - 700
Typical Size (mm)	30 x 50 x 110	4.0 - 20.0	4.0 - 20.0

The quality of the DRI products is defined by four different factors:

The amount of iron oxide and metallic iron - Metallization

Depending on the amount of iron oxide present, extra energy and reducing agent may be required for reduction. The higher the degree of metallization of the DRI, the lower the energy required to reduce remaining FeO (wüstite) present in the structure [9].

The carbon content:

The amount of carbon content for an EAF is dependent on various steelmaking conditions. The carbon is required to achieve a specific steel quality, for the reduction of remaining FeO and it is an additional energy source to support the melting process. The higher the metallization of the DRI, the smaller the required amount of carbon for reduction. As an example: at 96 % metallization, less than 1.0 % carbon is required, while a metallization degree of 93 % requires about 1.5 % carbon for the reduction of FeO. Additional carbon can be used to minimize the tap to tap time and increase the efficiency of the EAF. Even though extra carbon can be seen as extra energy, there can also be too much carbon in the DRI. Too much carbon leads to decarburization and therefore to a decrease of the productivity of the EAF. The removal of carbon from steel results in the production of CO. CO leaves the steel through the formation of bubbles and floats through the slag which starts to “boil”. Too much CO can lead to unsafe conditions in an EAF due to too strong “boiling” [10].

The costs for extra carbon which has to be fed into the EAF for low carbon content DRI can be high. Nevertheless it has to be kept in mind that there are many ways to add carbon to the EAF, but there is only one way to remove it and long removal times reduce the productivity and therefore cost money. [11], [12], [10].

The amount of gangue components

The amount of gangue components determines the amount of slag formed in the EAF. The amount of slag determines the extra amount of energy and residence time required to melt it [9].

The amount of fines:

The amount of fines affects the energy efficiency of the EAF operation. It may cause contaminations of the electrical parts. Moreover, it causes problems concerning handling and loading of DRI through the production of dust [9].

Despite these factors, there are also physical and chemical properties which define the quality of the DRI. These are further described in the following chapter.

3.1.2 Physical and Chemical Properties of DRI

One important parameter is the degree of metallization. As already mentioned, metallization is defined as the percentage of iron present as metallic iron to total iron, as can be seen in Equation 3-1 [13].

$$\%\,Metallization = \left(\frac{Fe_{met}}{Fe_{tot}}\right) * 100 \qquad [\%]$$

Equation 3-1

As can be seen in Table 2, a favorable degree of metallization for DRI is between 90 – 95 %.

Since there is no melting during the direct reduction, the gangue is not separated from the structure. The formation of the slag is based on the reactions of the gangue minerals, which are inherent to the feed stocks, with the aid of flux materials. Because of that, the DRI chemical composition depends on the raw materials composition [9].

Another important parameter is the reduction degree (RD). It can be calculated by the following equation:

$$RD = \left(1 - \frac{X}{1.5}\right) * 100 \quad with \quad X = \frac{O}{Fe_{tot}} \qquad [\%]$$

Equation 3-2

where O is the oxygen content and Fe_{tot} the total iron content. Oxygen and total iron content have to be converted into moles for Equation 3-2 [14]. Table 2 shows some important physical and chemical properties of DRI.

Table 2: Some important physical and chemical properties of DRI [9]

Property	Direct reduced iron (DRI) values
Density	1.5 - 4.0 g/cm³
Bulk density	1.5 - 1.9 ton/m³
Specific surface area (Porosity)	0.5 - 4.0 m²/g
Chrushing strength	50 - 110 kg/cm²
Degree of metallization	90 - 95 % (average 91 - 93 %)
% Metallic iron	~ 85 %

3.1.3 Use of DRI in Steelmaking

The use of DRI has been tested in many melting systems (e.g. blast furnace, open hearths, basic oxygen furnaces, electric arc furnaces (EAF)). Most of the DRI (about 80 %) is used in electric arc furnaces nowadays as a complete or partial substitute for ferrous scrap [3]. There are many advantages of using DRI in an EAF: The composition of the DRI is known exactly and is uniform, there is only a small number of undesirable metallic impurities in DRI, handling and transport of DRI are easy, continuous charging is possible and the price structure of the DRI is more predictable than the one of scrap and many others [5]. In 2016, the world DRI production was 72.76 Million Tons, most of it produced in the Middle East/North Africa with 34.19 Million Tons. The annual production of the three different DRI products can be seen in Figure 2. In 2016 the amount of CDRI produced was 57.74 Million Tons, while HBI production was 5.29 Million Tons and HDRI production 9.73 Million Tons [15]. CDRI as well as HDRI can only be used in an EAF, while HBI can be used in an EAF, in a BF as well as in a BOF [8].

Year	CDRI	HBI	HDRI	Total
2007	55.79	8.34	2.99	67.12
2010	56.60	7.21	6.47	70.28
2013	62.50	6.17	6.25	74.59
2016	57.74	5.29	9.73	72.76

Figure 2: Overview of DRI products in million tons [15]

3.1.4 Direct Reduction Processes

here are several processes for the direct reduction of iron. According to the utilization of the reducing agent source, one can subdivide the reduction processes in two categories. Processes which use hydrocarbon gases such as hydrogen, carbon monoxide or methane (natural gas) as fuels and reducing-carburizing agent are called natural gas-based direct reduction. Processes which use coal, gasified coal or coke breeze are called coal-based DRI production processes. An overview is given in Table 3.

Table 3: Direct reduction processes [9]

<table>
<tr><td rowspan="4">Natural gas-based direct reduction processes</td><td rowspan="3">Catalytic natural gas reforming</td><td>Catalytic steam gas reforming</td><td rowspan="4"></td></tr>
<tr><td>In situ gas reforming</td></tr>
<tr><td>Reductant off gas reforming</td></tr>
<tr><td>Partial oxidation natural gas reforming</td><td></td></tr>
<tr><td rowspan="4">Coal-based direct reduction processes</td><td>Processes where the gasification and reduction take place in a single reactor</td><td></td><td></td></tr>
<tr><td rowspan="3">Processes where the gasification and reduction take place in separate reactors</td><td rowspan="2">Slagging coal gasifiers</td><td>Entrained bed coal gasifiers</td></tr>
<tr><td>Fixed bed coal</td></tr>
<tr><td>Dry ash coal gasifiers</td><td></td></tr>
</table>

According to the different reactors utilized in the process, a further classification can be done. Vertical shaft and retort (batch) furnaces and fluidized bed reactors are commonly used in natural gas-based direct reduction processes, whereas vertical shaft, multiple and rotary hearth furnaces, rotary kiln and fluidized bed reactors are used in coal-based direct reduction processes. Table 4 and Table 5 give an overview of the different processes according to the reactor types utilized [9]. As the plant in Corpus Christi is based on the MIDREX process, this thesis will predominantly focus on this type of process.

Table 4: Natural gas based processes according to the reduction reactor type being utilized [9]

Natural Gas Based Direct Reduction Processes (According to the Reduction Reactor Type)		
Vertical Shaft Furnace	**Retort (Batch Furnace)**	**Fluidized Bed Reactor**
Midrex	Hyl I & II	Fior
Armco		Finmet
Hyl III & IV		Circored
Arex		H-Iron
Purofer		HIB Process
		Iron Carbide

Table 5: Coal-based processes according to the reduction reactor type being utilized [9]

Coal Based Direct Reduction Processes (According to the Reduction Reactor Type)				
Rotary Kiln Furnace	**Fluidized Bed**	**Vertical Shaft Furnace (Retort Process)**	**Multiple Hearth Furnace**	**Rotary Hearth Furnace**
SL/RN	Cirofer	Kinglor-Metor	Pirumus	Inmetco
Krupp-CODIR		Hoganas		Fastmet
DRC				Sidcomet
ACCAR/OSIL				Comet
TISCO (TDR)				IDI
Krupp-Renn				ITMk3
LS-RIOR				DRylron

3.1.4.1 MIDREX Process

About 64.8 % of the world DRI production in 2016 was produced by the MIDREX process [15]. As can be seen in Table 4, the MIDREX process uses natural gas. Originally, Midland-Ross Co. developed the process and the first pilot plant was built in Toledo, Ohio in 1967. In 1969, the first commercial plant with a production capacity of 150,000 tons/year was built in Portland, Oregon. Through the 1980s, many improvements were carried out [7].

Figure 3 shows a flow chart of the MIDREX process. The feed product is either lump ore or pellets and it enters the shaft furnace at the top. The reduction takes place inside the shaft furnace. The reduction gas enters the furnace from about the middle of the shaft, reduces the raw material and exits the furnace from the top. Therefore, this process is based on counter-current flow. The reduced iron is discharged from the bottom of the furnace. Seal gas seals the charging and discharging dynamically which allows a continuous charging of raw material and discharging of DRI.

The exhaust gas exits the shaft furnace at the top and is cleaned and cooled by a wet scrubber. To be able to recirculate and reuse the exhaust gas, it is pressurized by a compressor, mixed with natural gas, preheated and fed into a reformer furnace. The exhaust gas consists mainly of CO_2 and H_2O as well as CO and H_2. Inside the reformer furnace are many tubes filled with nickel catalyst. As the top gas is passing through these tubes, the mixture is reformed to produce reductant gas, which consists of CO and H_2 [7].

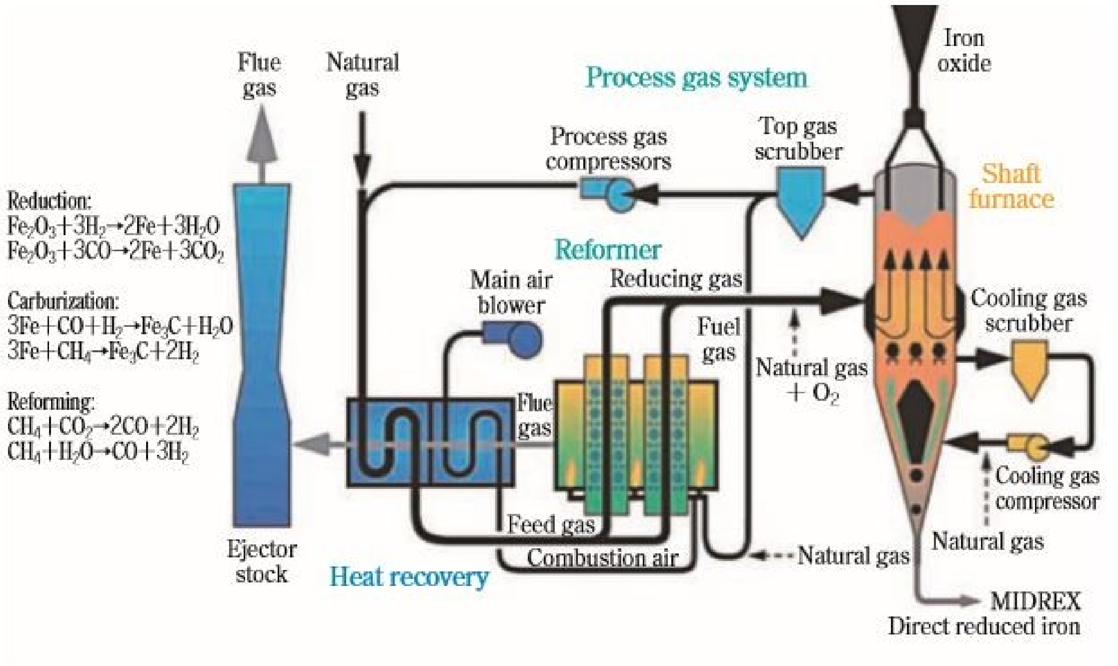


Figure 3: MIDREX process flow chart [7]

The reactions within the shaft furnace are shown in Figure 4. The overall reduction reactions are (calculated with FactWeb): [8]

$$Fe_2O_3 + 3\,H_2 \longrightarrow 2\,Fe + 3\,H_2O \quad (\Delta H_{1073K} = +641.6\,kJ)$$

Equation 3-3

$$Fe_2O_3 + 3\,CO \longrightarrow 2\,Fe + 3\,CO_2 \quad (\Delta H_{1073K} = -38.0\,kJ)$$

Equation 3-4

While the reduction with hydrogen is endothermic (see Equation 3-3), the reduction with carbon monoxide is exothermic (see Equation 3-4). Both equations are equations of equilibrium. There will always be residual H_2 and CO in the exhaust gas to make sure reduction can take place up to the top of the furnace. Thermodynamically, the gas pressure will not have an impact on the reactions above, since the gas volume doesn’t change (number of gas moles is the same on both sides of the reaction). Under process conditions, the equilibrium composition can be expected to lay on the right side for both reactions.

REACTION	HEAT	DESCRIPTION
$3Fe_2O_3 + CO \longrightarrow 2Fe_3O_4 + CO_2$	Exothermic	Reduction by CO
$3Fe_2O_3 + H_2 \longrightarrow 2Fe_3O_4 + H_2O$	Exothermic	Reduction by H_2
$Fe_3O_4 + CO \longrightarrow 3FeO + CO_2$	Endothermic	Reduction by CO
$Fe_3O_4 + H_2 \longrightarrow 3FeO + H_2O$	Endothermic	Reduction by H_2
$FeO + CO \longrightarrow Fe + CO_2$	Exothermic	Reduction by CO
$FeO + H_2 \longrightarrow Fe + H_2O$	Endothermic	Reduction by H_2
$3Fe + CH_4 \longrightarrow Fe_3C + 2H_2$	Endothermic	Carburizing Reaction
$3Fe + 2CO \longrightarrow Fe_3C + CO_2$	Exothermic	Carburizing Reaction
$3Fe + CO + H_2 \longrightarrow Fe_3C + H_2O$	Exothermic	Carburizing Reaction

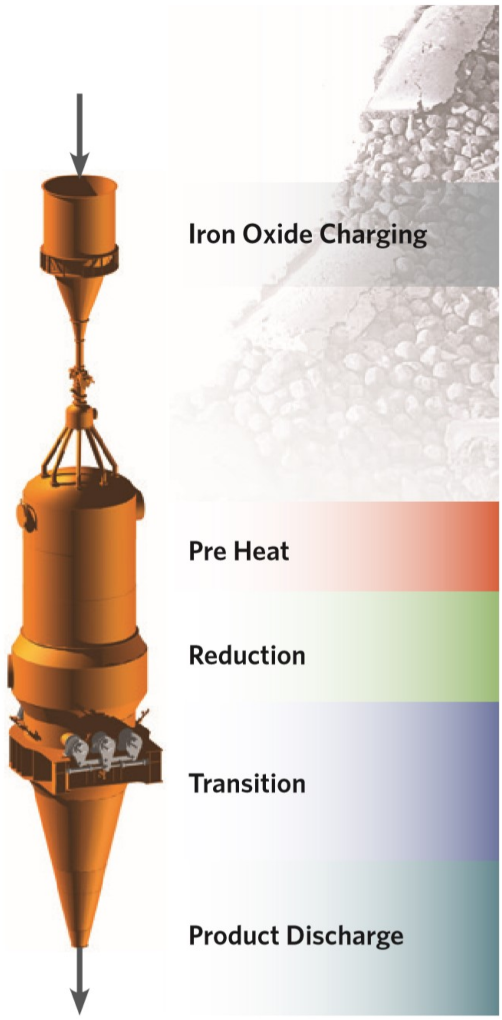


Figure 4: MIDREX shaft furnace overview [8]

3.1.4.1.1 Feed Materials

For the MIDREX process, both iron ore pellets and lump ore can be used (see Figure 5). The most important factors that determine which type of feed material is used within the DRI plant are cost, availability and productivity. At the beginning of the technology of direct reduction, there was a clear difference between iron oxide pellets intended for blast furnace use (BF - grade pellets) and iron oxide pellets used to make DRI to feed an EAF. Higher iron content, less silica, alumina and other gangue constituents typically mark a “DR-grade” pellet. Products from “DR-grade” pellets are more likely used for EAF, because of their low gangue content, the meltshop does not have to worry about excessive slag formation. In Table 6 the typical characteristics of “DR-grade” pellets and lump ore used in EAF steelmaking and of “BF-grade” pellets and lump ore are shown [8].

Figure 5: Lump ore and pellets used in MIDREX process [8]

Table 6: Typical characteristics of DR-grade pellets and lump used in EAF steelmaking and BF-grade pellets and lumps [8], [16]

Chemical Characteristics				
	DR-grade		BF-grade	
	Pellets	Lump	Pellets	Lump
Fe (%)	67 - 69	66 - 68	≥ 65	≥ 58
SiO_2 (%)	≤ 4	≤ 3 - 4	< 4	< 6
Al_2O_3 (%)			-	3 - 4
S (%)	≤ 0.008	≤ 0.025	0.05	0.1
P (%)	≤ 0.03	0.03 - 0.06	< 0.02	< 0.07
Physical Properties				
	Pellets	Lump	Pellets	Lump
Tumble Index (% + 6.75 mm)	≥ 90 - 95	≥ 85	> 93 - 95	> 70
Abrasion Index (% - 5 mm)	≤ 3 - 4	≤ 5	< 7	< 5 - 10
Reduction Characteristics				
	Pellets	Lump	Pellets	Lump
Metallization (%)	93 min.	93 min.	-	-
Reducibility (%/min)	-	0.92	0.8 - 1.4	0.5 - 1.0

3.1.4.1.2 Reducing gas

In the MIDREX process, natural gas, coal, coke, coke oven gas and process syngas can be used. The production of reducing gas using natural gas is done with a traditional steam reformer or an unparalleled stoichiometric MIDREX reformer. If the plant is operated with natural coal including high sulfur coals or Coke Oven Gas (COG) then a gasifier or a thermal reactor system can be used to produce reducing gas. Since the plant in Corpus Christi is operated with natural gas, this thesis will focus on this kind of process.

The gas quality, which is defined as reductant / oxidant ratio (see Equation 3-5), is an important property of the reducing gas to measure the potential for the gas to reduce iron oxide. The higher the gas quality, the less gas has to be used, which has a positive effect on the efficiency of the process.

$$gas\ quality = \frac{\%\ H_2 + \%\ CO}{\%\ H_2O + \%\ CO_2} \qquad [-]$$

Equation 3-5

To be able to use natural gas, it has to be reformed into hydrogen and carbon monoxide first. Typically, natural gas is used for the MIDREX process and it is reformed in the MIDREX reformer. This reformer converts recycled off gas plus fresh natural gas into hydrogen and carbon monoxide. A mixture of recycled top gas and natural gas is heated in a refractory lined furnace and is catalytically reformed. Due to the fact that recycled gas and hot reformed gas, without quenching and reheating, can be fed in the shaft furnace, the process is very efficient. The largest MIDREX reformers produce about 400,000 Nm³/hr of reducing gas. With this amount of reducing gas, an annual production of 2.0 million tons of DRI is possible [8]. The typical composition of the reducing gas is shown in Table 7.

Table 7: Typical gas composition [8]

	Inlet	Outlet
H_2 (%)	35	55
CO (%)	19	35
CO_2 (%)	15	2
H_2O (%)	13	6
CH_4 (%)	17	1
N_2 (%)	1	1
Temp. (°C)	580	980

3.1.5 Hot Briquetted Iron (HBI)

If the DRI is compacted, the product is called Hot Briquetted Iron (HBI). Since DRI has a large specific surface area it reacts very easily with water (especially sea water) and/or oxygen. The occurring reaction is exothermic and therefore heat is produced. Moreover, because of the spongy structure, DRI is an excellent insulator, meaning that the excess heat, produced in a DRI storage pile, produced for example through the reoxidation with sea water, does not easily dissipate. During the reoxidation of iron H_2 is generated which further contributes to the heat generation. A result of this heat is the meltdown of DRI in piles, silos or ship holds. Because of this, many methods for passivation of the product have been developed and tested [4]. Some developed methods are natural aging, air passivation or coating [13]. The most reliable and likely economical process for this task is hot briquetting, however. Figure 6 shows, that freshly produced DRI is extremely reactive, while the reactivity of HBI is relatively low.

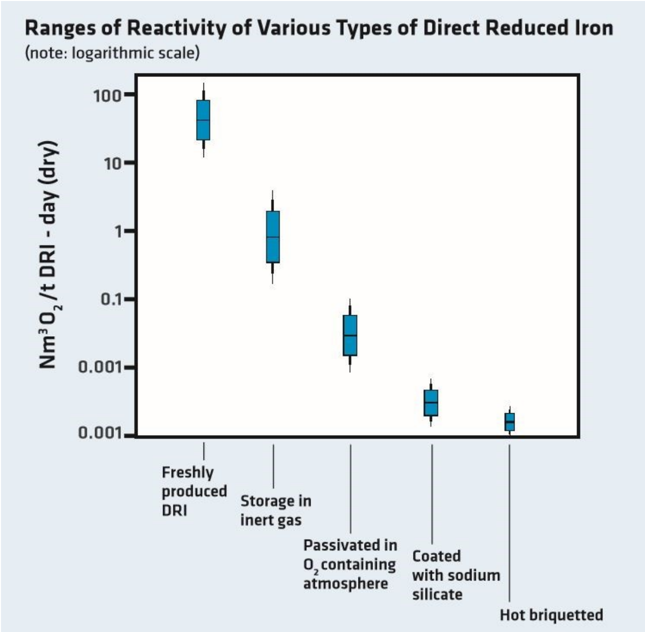


Figure 6: Ranges of reactivity of various DRI products [13]

The hot DRI is intensified and compacted immediately after the reduction at high temperatures with very high pressures [4]. Through the briquetting, internal pores are closed, the accessible surface is lowered, the apparent density is increased, and the thermal conductivity is improved, which all reduce reactivity. In Figure 7, a comparison of the structure of DRI pellets and HBI is given. Because of the compaction, reoxidation and overheating of HBI is very unlikely, which improves the conditions for storage and transport characteristics. Some other advantages are for example the reduced fines production, the higher density, the improved handling or the uniform product shape and size [4].

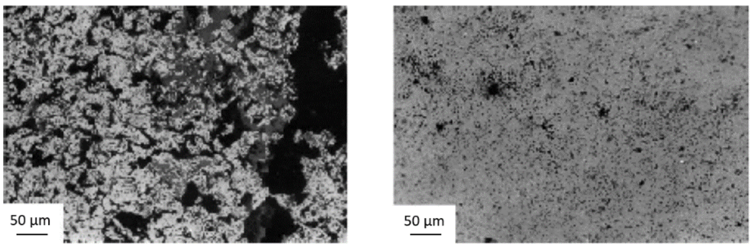


Figure 7: Comparison of the structure of DRI pellets (left) and HBI (right) [4]

Because of this reason, the advantages of HBI have become part of the International Maritime Organization (IMO) Shipping Regulation. There is a distinction between DRI and “sponge iron”. Sponge iron has been briquetted at temperatures of ≥650 °C and has an apparent density of ≥5 g/cm³. Moreover, “in addition to considerably simplified shipping requirements, open storage prior to loading is acceptable” [4].

Due to a possible degradation over time it is important to handle, store and transport the DRI product properly. The two most important reactions are oxidation and corrosion. Oxidation is the formation of either magnetite (Fe_3O_4) or hematite (Fe_2O_3) of metallic iron with oxygen in the air. Oxidation takes place when the DRI is hot and there is sufficient oxygen present. Corrosion, on the other hand, occurs when the DRI product (CDRI or HBI) comes in contact with water and oxygen over a longer period of time following production. As long as water is present, corrosion can take place. Since briquetting lowers the surface area, one can actively prevent corrosion and oxidation. Moreover, the higher the density of the briquette, the lower the metallization loss. This is shown in Figure 8. Additionally, the particle size of the sample has an influence on the metallization loss. The loss of metallization is much bigger for chips and fines (typically particle size <12 mm), which have a much higher surface-area–to–volume ratio. This is shown in Figure 9.

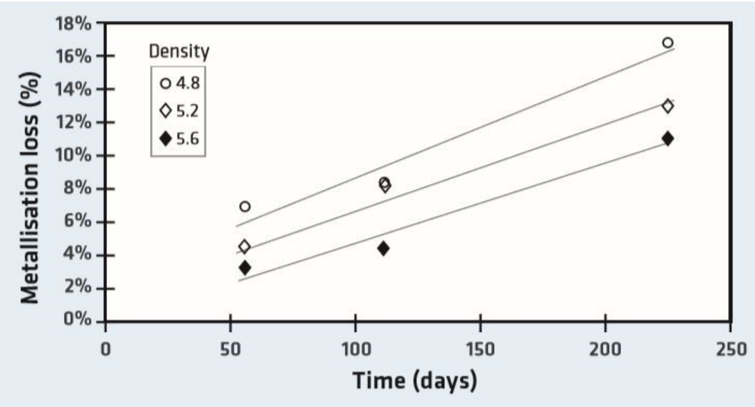


Figure 8: Metallization loss over time of various HBI densities [13]

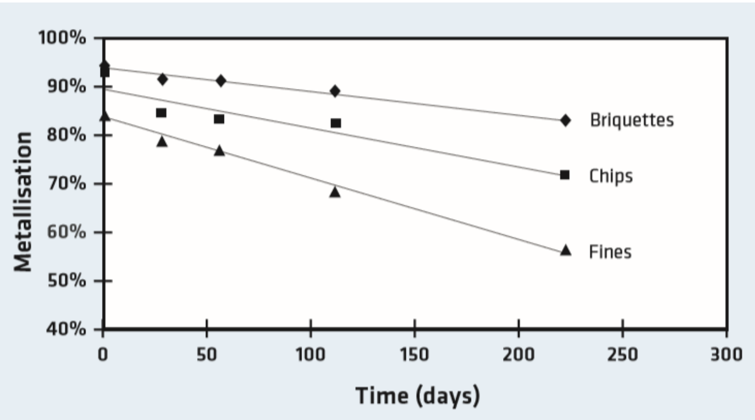


Figure 9: Metallization loss over time of HBI, chips and fines [13]

3.1.5.1 Material Properties of HBI

Some advantages of HBI have already been mentioned in this thesis. One of the most important specific characteristics of HBI is that there is only a minimal loss of metallization, even after long storage times or during shipping. Moreover, the open-air storage does not cause any problems. There is only a very small risk of overheating during storage and transport and only little production of fines during handling. Another big advantage is that the size of the pillow-shaped briquettes is uniform, which makes handling easier and the behavior in the BF predictable. Additionally, the chemical composition stays stable and is well known, which makes it a good product for the EAF. The bulk and apparent densities of HBI are relatively high [4].

In the HBI plant in Corpus Christi, the pillows have a nominal size of 33 x 48 x 106 mm and a density ≥5 g/cm³.

3.2 Briquetting – Agglomeration by Compression

Agglomeration describes the process of size enlargement in solid process engineering where smaller particles stick together to form relatively large assemblies, so called agglomerates. It is commonly used in many industries, e.g. food, chemical, or mining [17], [18], [19]. A prerequisite for agglomeration is the presence of binding mechanisms. There are 5 types of agglomeration bonding: solid-state bridges, capillary forces, adhesion / cohesion, attractive forces, and form closure. The strength and range of adhesive forces determine the strength of the agglomerate. There are different types of agglomeration processes e.g. build-up agglomeration, agglomeration in suspensions or press agglomeration [20].

Press agglomeration means that the agglomeration takes place under pressure. It can be achieved by various principles. These principles are shown in Figure 10. According to the pressing geometry (closed or open form) and the type of compaction limitation (geometrically- limited or force-limited) a classification can be made:

a) Press agglomeration in closed form with geometrically limited compaction like in stamping presses or tablet presses (Figure 10 a)
b) Press agglomeration in the open channel with force-limited compaction due to the resistance of the pressed strand in stamp presses (Figure 10 b)
c) Press agglomeration due to roller pressure in roller presses (Figure 10 c)

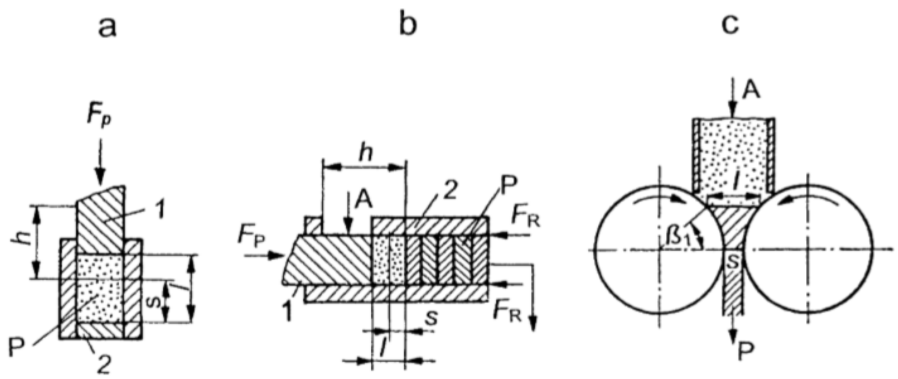


Figure 10: Operating principles of press agglomeration: a) closed form; b) open channel; c) roller pressure; 1- press plunger ; 2- press mold; A- feed material; P- agglomerate; F_P- pressing force; F_R- frictional resistance of wall; h- stamp hub; l- level before compaction; s- pellet size; β_1- half angle of entry [21]

In the case of roller presses, the compaction takes place in the gap of two opposing rotating rolls. The roll surfaces are either smooth or profiled, or formed with mold cavities. In the first case, the agglomeration product is a ribbon-like strand emerging from the nip of about 5 mm to 20 mm in thickness, which subsequently has to be crushed and classified. In the second case, briquettes are created [21]. The agglomeration in roller presses has advantages as well as disadvantages. As an advantage one can mention that this process is continuous and allows a high production capacity, which makes it suitable for heavy industries. Another advantage is that the compaction costs are relatively low. Agglomeration in roller presses makes a compaction of hot material (up to 1000 °C) possible, which is also a benefit. On the other hand, the produced briquettes aren't geometrically as uniform as those produced by a die press and therefore aren't suitable for certain areas of application, where the uniformity of the products is important [22].

The different types of briquetting are further described in section 3.2.2.

3.2.1 Briquetting Mechanisms

The goal of compaction is to enlarge the forces between small particles so that the product produced withstands subsequent handling. There are typically three mechanisms, when pressure is applied to a solid put in a die. They are shown in Figure 11.

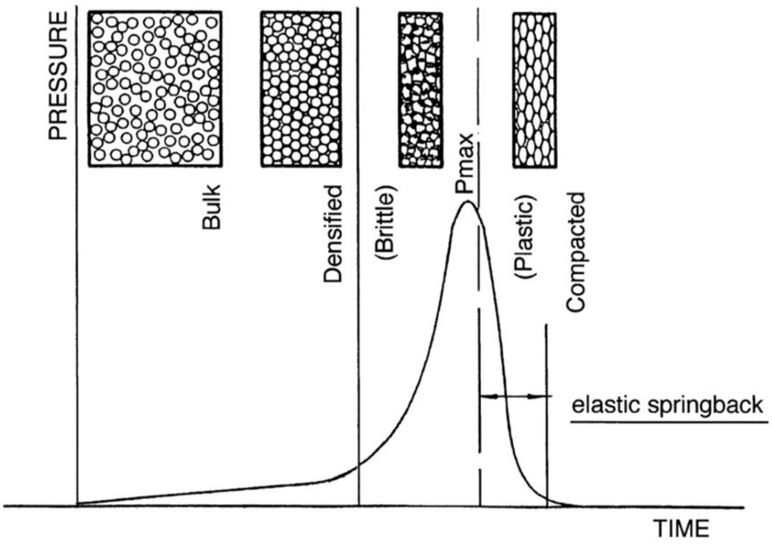


Figure 11: Mechanisms of compaction [23]

1. When the pressure is low, a rearrangement of the particles takes place. The result is a closer packing. The friction between the particles has to be overcome, which mainly dissipates the energy.
2. High pressures lead to elastic and plastic deformation and the area of interparticle contact is increased while the void spaces are reduced. Interlocking of particles is a possibility at this stage. For materials with low thermal conductivity and low melting points the energy released by the particle contact may be sufficient for increased

plasticity and even melting and facilitating particle deformation. For brittle materials, the pressure may lead to particle fracture and rearrangement of the fragments, resulting in a volume reduction.

3. Under continuous high pressure, the compact apparent density may get close to the true density of the material, also due to plastic deformation. At each stage of the compaction process, one can find elastic compression.

A simultaneous occurrence of all three mechanisms is possible. The properties of the particles and the speed of pressing determine the relative importance of the different mechanisms and the order of occurrence. In the bulk compression stage, broken or deformed particles can no longer rearrange since there are only few remaining cavities left. Therefore, a certain amount of interparticle conformity has been achieved. If the pressure is increased, the apparent density will further approach the theoretical density, depending on the yield point of the material [23].

3.2.1.1 Compaction in Smooth Roller Press

In a smooth roller press, the space between the working rollers of the press can be divided into two zones: the feed zone and the compaction zone (see Figure 12). In the feed zone ($\alpha'_E > \alpha > \alpha_E$), the feed material is drawn into the nip due to friction on the roll surface and is densified by a rearrangement of the particles. In this zone, the peripheral speed of the rollers is greater than the velocity of the material to be compacted. In the compaction zone ($\alpha_E \geq \alpha \geq 0$), the material moves with the roller and elastic and plastic deformation takes place.

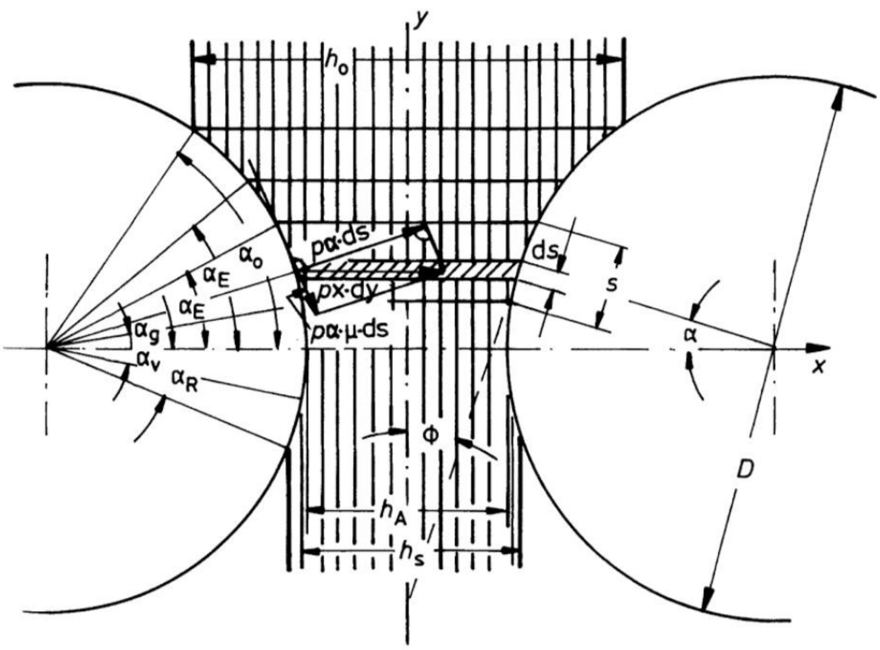


Figure 12: Compaction in the nip of a smooth roller press [23]

The so-called angle of delivery (α_0), is defined by the width h_0 of the feed opening, the material and the feeder characteristic. At the neutral angle (α_g), the sign of the friction force changes and the pressure in the material and the density are the highest. The thickness of the compacted material (h_S) is determined by the angle of elastic compression (α_V). If the elastic deformation of the rolls can be ignored, α_V becomes zero and the sheet thickness is shown by h_A. The compacted material, however, recovers elastically after the compaction and the actual sheet thickness is usually even bigger than h_S. The angle of release (α_R) corresponds to the actual outlet plane. The diameter of the rolls determines the overall dimension of the press and are therefore essential for the design of the press. With increasing diameter at the same circumferential speed, the time of compaction increases as well, which positively impacts the quality of the briquettes. For smooth roller presses, there is a close relationship between the width of the gap and the width of the final compacted material sheet. In some studies, it was assumed, that these two parameters are the same. However, the sheet width is always greater than the gap due to deflection of the roller shafts, bearings and the cage of the working rollers under the loads acting in the system and due to the expansion of the material after pressing. Parameters like the stiffness of the press structure, the diameter and surface character of the rollers and the physical material properties cause these different widths [23], [24].

3.2.1.2 Compaction in Roller Press with Molds

For briquetting, the gap between the rollers approaches zero (compared to the relatively large gap for smooth rollers) and the above described compaction process is changed significantly by the molds. Johanson has developed a theory of briquetting fine-grained materials, based on the rolling of bulk materials. This model is based on an empirical formula, which shows a relationship between the unit force exerted on the material and its density. Equation 3-6, also called “compaction equation”, refers to the compaction of bulk material in a closed mold.

$$\sigma_\theta = \sigma_\alpha \left(\frac{\gamma_\theta}{\gamma_\alpha}\right)^K$$

Equation 3-6

σ_θ, σ_α are the unit forces in different stages of compaction, γ_θ, γ_α the densities of the compacted material corresponding to the forces and K is the Johanson’s constant which includes the properties of the material compacted. Since the model is based on an empirical equation, it can only be called as partially analytical. The properties of the material briquetted are only included indirectly in this equation, which represents a disadvantage. Another point under critique is that the thickness of the rolled band equals the mean height of a briquette in this model which results in an omittance of the existence of the areas separating the pits in the working part of the rollers. This results in a crucial simplification of the real physical situation [24].

The briquetting process of fine grained material is shown in Figure 13. In this system, deep forming pits and shallow pits alternate and come in contact. Shallow pits of one roller get in contact with the deep forming pits of the other roller. This process can be compared to briquetting in a roll press and in a closed mold. Because of this, the process of briquette compaction as well as the phase of its expansion and the increasing compaction pressure can be shown in Figure 13. The expansion plays an important role in the quality of the briquette. Destructive stress appears and can cause destruction of bonds between the grains when it reaches a certain limit value [24].

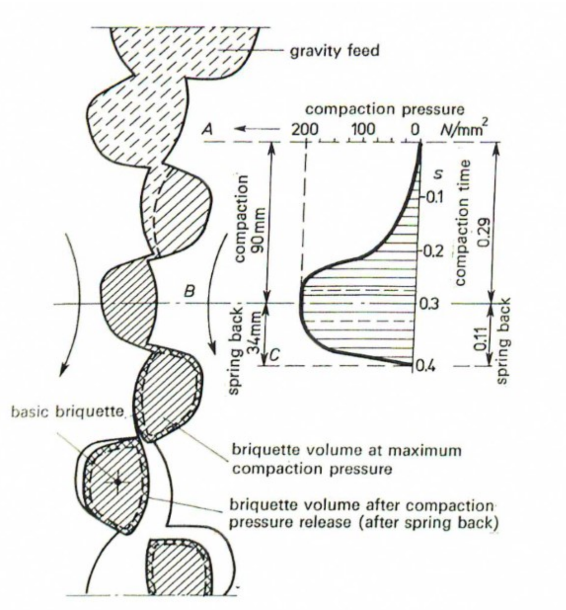


Figure 13: Compaction of material in a roll press [24]

Figure 14 shows the mechanisms of briquetting in a roller press. The most important phase is the final compaction phase in this case. When the lower axial land area passes through the line connecting the centers of the rollers, this phase starts. The pocket is closed at the lower edge, while feed can still get into the pocket through the upper edge. As a next step, the formerly closed lower edge opens, and the formerly opened upper edge closes. At this point, the compaction of the briquette is completed. The feed zone and the compaction zone are not as clearly defined for rollers with molds due to “interlocking” between material in the nip and the roller surface. They are only determined by interparticle friction. Since the lower edge opens up, the pressure in the upper edge increases, which “helps” to release the briquette out of the mold [24]. Another result of this pressure is a non-linear distribution of density within the briquette. The knowledge of the required density of the initially compacted material in the compaction feeder, the shape and volume of the forming pits as well as the circumferential speed of the rollers can help to mitigate this problem. All this knowledge is still largely based on experiments. There is not yet a comprehensive theory explaining the densification of particulate matter between counter rotating rollers [23], [24].

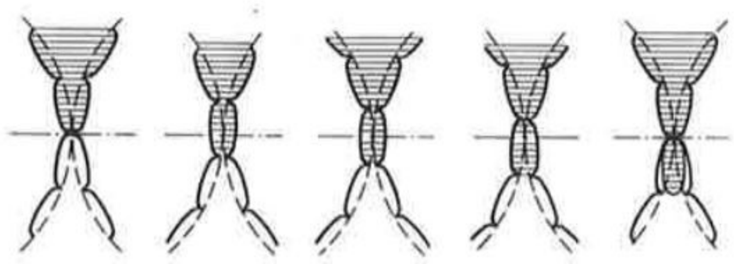


Figure 14: Formation of a briquette in a roll press [24]

3.2.2 Types of Briquetting

Depending on the temperature of the feed material, a distinction can be made between cold briquetting and hot briquetting. Cold briquetting takes place at up to 100 °C (212 °F) [25]. Depending on the feed material, it may be necessary to add binders to improve the product quality. In the case of sponge iron, the product quality is in most cases not satisfactory without binders if briquetted under cold conditions. An example for a binder is 6 % molasses, 3 % hydrated lime and 2 % water [26].

A feeder system introduces the feed material into the spaces above two counter-rotating rollers. The material is compacted and formed into briquettes of uniform size and shape. The briquettes are typically cushion shaped, but almond-shaped or stick-shaped are also possible. The pressing forces for cold briquetting range from 25 kN/cm for steel mill residues with binder to 140 kN/cm for aluminum. The necessary pressing force rises as a function of the roller diameter and the mold size [25].

The briquettes do not have the same fine detail and uniformity as tablets have. Moreover, the areas around a briquette pocket itself cannot be removed completely and reliably. Because of these characteristics, roller presses are applied where relatively low investment and operating costs are more important than absolute uniformity of the product. This agglomeration method is applied for a large number of materials in the pharmaceutical, chemical, food processing, mining, minerals and metallurgical industry [23].

3.2.3 Hot Briquetting

As mentioned in 3.2.2, hot briquetting takes place at high temperatures, usually between 250 °C and 750 °C (480 °F and 1380 °F). This means, that the use of highly heat-resistant roller presses is necessary. Hot briquetting is applicable for materials, when binding characteristics are activated at high temperatures. Hot briquetting is mainly used for the production of hot briquetted iron (HBI) from direct reduced iron (DRI) as already mentioned in 3.1.5 [27]. Figure 15 shows the flowsheet of a briquetting line for hot sponge iron. The equipment of a briquetting line will be further described in the following sections.

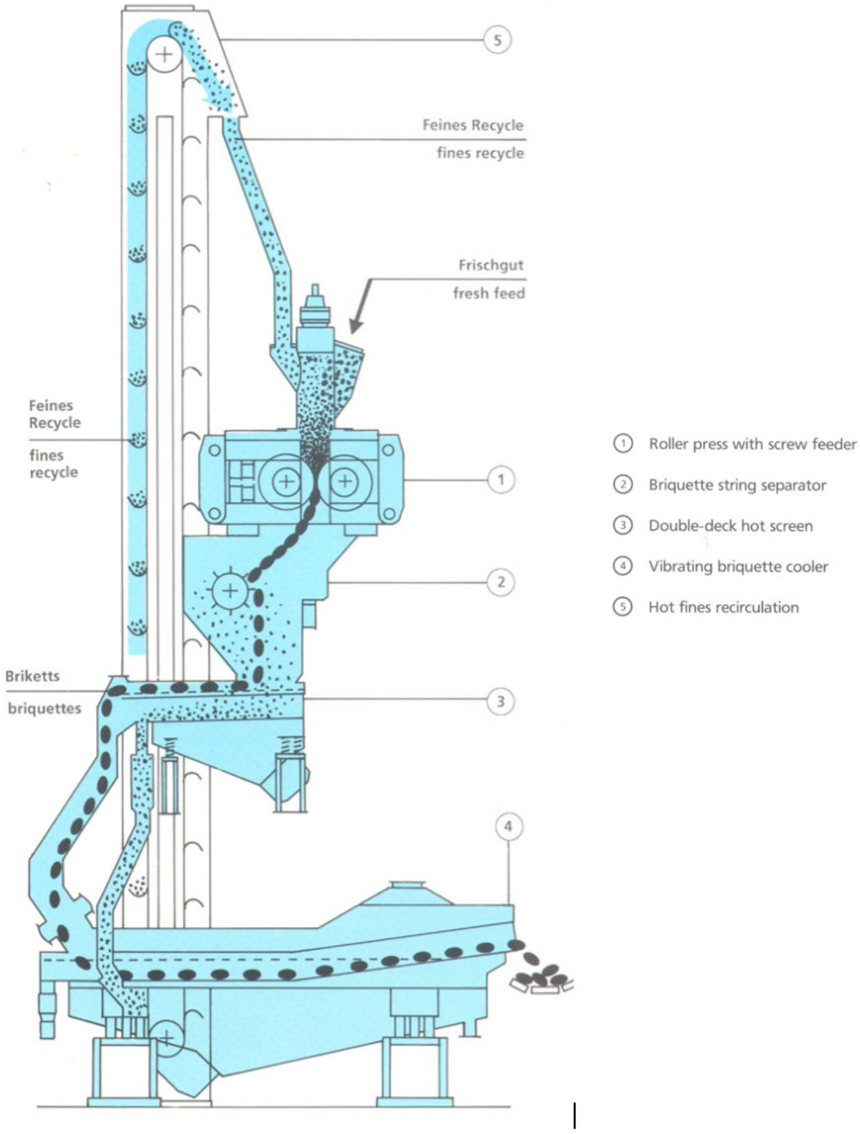


Figure 15: Flowsheet of a briquetting line for hot sponge iron [28]

3.2.3.1 Typical Equipment for Hot Briquetting

In this section, the various components necessary for hot briquetting are described. For hot briquetting of sponge iron, the typical components are the screw feeder, the briquetting press, the briquette string separator, the hot screen for the elimination of fines which occur during briquetting and separation, the product cooler, the bucket elevator for the recirculation of fines to the briquetting press, and the chutes and accessories [4].

3.2.3.1.1 Screw feeder

The material is fed into the press either through a gravity feeder or via a screw feeder. The feeding system is essential for a good compaction process and a uniform and continuous flow into the press. The speed of the screw feeder defines the amount of material which goes into the press [22]. In order to guarantee stable production, the speed of the screw feeder has to be high enough to make sure more material enters the roll nip than exits the press rollers [29]. Moreover, the screw feeder has the important role of pre-compacting the material before it enters the press and therefore creating an additional pressure on the feed material [29], [30]. Figure 16 shows some typical screw feeders.

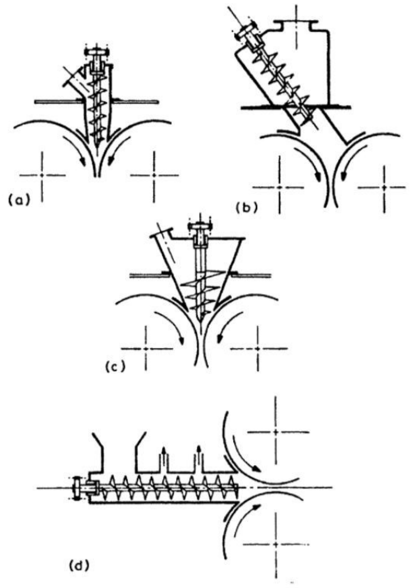


Figure 16: Some typical screw feeders: (a) vertical straight or slightly tapered screw feeder, (b) inclined straight screw feeder, (c) vertical tapered screw feeder, (d) horizontal straight screw feeder [23]

In Figure 17, a screw feeder, especially developed for operations with lump ore and pellets, is shown. A hydraulic motor drives the screw drive and can adjust the torque and speed to variable operating conditions. Through the larger opening, the hot material enters the hopper and is forced into the nip between the rollers. The second smaller opening is for the recycled material which gets mixed with the fresh feed [28]. Since gases enter the hopper and the roller press together with the feed material, a vent must be installed in order to allow the gases a way to escape. The gases are limiting compaction production throughput and compact quality and therefore should be removed in order to optimize the process [22].

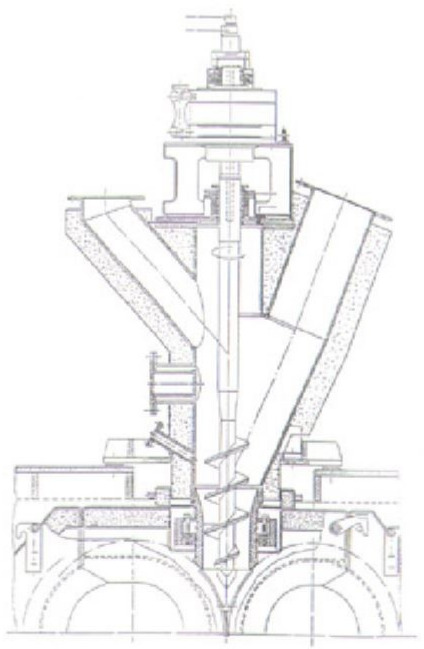


Figure 17: Schematic representation of a screw feeder for lump ore and pellets [28]

3.2.3.1.2 Briquetting Press

The briquetting press consists of two counter currently driven rotating rollers, where the material is squeezed between the rollers. Generally, one roller is fixed, while the other is movable (floating). The rollers are essential for briquetting: not only the geometrical characteristics but also the surface hardness has an impact on the briquette quality. The shape of the molds is optimized, so that there are no problems when ejecting the briquettes (sticking in molds or breaking). The molds are either individual segments, or a tyre type pressing tool. Depending on the feed material, the surface of the molds has to be processed in order to obtain a long lifetime and therefore keep costs as low as possible. The diameter of the rollers determines the maximum applicable stress on the briquettes, higher stresses can be used for bigger diameters. Not only the hardening of the molds can minimize wear, but also the operation of the rollers: both rollers must roll at the exact same speed and constant torque is essential. Typically, a hydraulic system is used to pressurize the rollers and a wide range of applied forces can be adjusted [22], [31].

Figure 18: Briquetting press for lump ore and pellets, roller diameter 1 m [4]

3.2.3.1.3 Briquetting String Separator

Usually, the briquettes leave the roller gap as a firm string. In order to obtain single briquettes, this string is guided via a chute to the string separator, where impact bars break the string first horizontally, then vertically. Due to the exerted forces, the string tries to lift-up after the breaking. To prevent this, the string is held in place by a down-holder [28]. Most of the plants nowadays produce two briquettes side-by-side. Through additional bending over a so-called nose piece located in the center of the chute, separation of the briquettes is achieved. In Figure 19, a representation of the process of a briquetting string separation is shown.

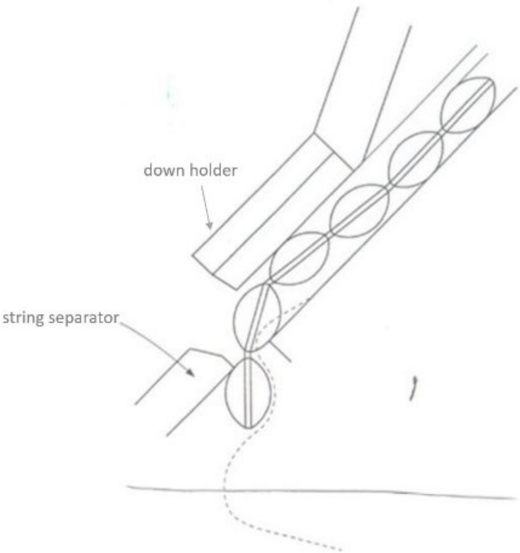


Figure 19: Schematic representation of the briquetting string separation [28]

3.2.3.1.4 Hot Screen

Through the process of briquetting and separation, a certain amount of chips and fines is generated. In order to keep the costs as low as possible, these fines are screened out and are recycled back into the briquetting press via a bucket elevator. This is done by a double deck hot screen. Typically, the particle size of the product is +12 mm, material smaller than that is separated. All chips and fines then enter a hot fines recirculation system. The recycling is realized with a bucket elevator and chute system which re-charges the undersized material into the smaller opening of the screw feeder hopper. There is minor heat loss due to the recirculation, however this can usually be neglected since the temperature of the fine material is at least 400 °C when reentering. Typically, the amount recycled is between 5 and 10 % [28].

3.2.3.1.5 Product Cooler

Product which passed the hot screen is transferred to a cooler. The hot briquettes have to be cooled down to about 80 °C. At this temperature the penetration of water into the pores can be prevented and the product surface can be dried-off. A possibility to cool down the product is by letting it fall into water which flows against the direction of the material transport. In order to cool down 50 t/h of product from 700 °C to 80 °C, about 250 m³/h water are necessary. The cooled product is then transferred to a belt conveyor. In order to regulate the appropriate amount of water, a temperature sensor is installed at the discharge point of the cooler [28].

Another solution for cooling down the HBI is via mist cooling. With this method, the hot DRI goes on to a cooling conveyor where it is sprayed with water. With this method, no sludge is built. Moreover, no cracks on the briquette occur, less fines are generated and there is no reoxidation [32]. Figure 20 shows a cooling conveyor for mist cooling of HBI.

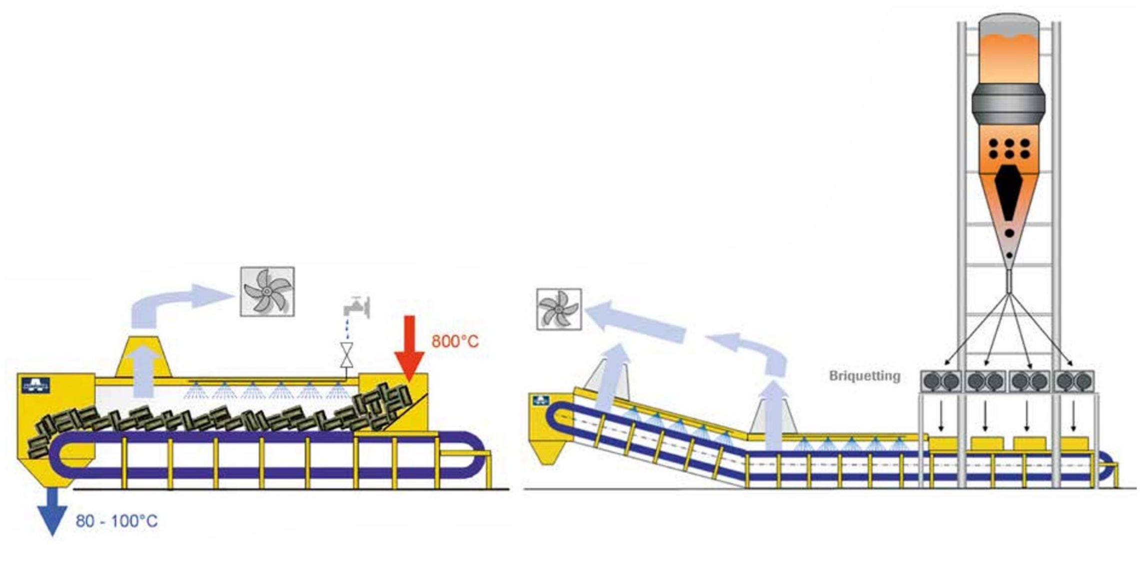


Figure 20: Scheme of mist cooling conveyor for HBI [32]

3.2.3.2 Influencing Factors for Briquetting Product Quality

The main influencing factors for the product quality (density and abrasion resistance) can be divided into three main categories: origin of the feed material, process conditions and operation of machinery.

3.2.3.2.1 Impact of Origin of Feed Material

As already mentioned in section 3.1.4.1.1, the Midrex process has either iron ore pellet or iron ore lump as a feed material. Table 8 gives an overview of the world's largest iron ore producing countries. As can be seen, most iron ore is produced in Australia, followed by Brazil and India.

Table 8: Overview of world's largest iron ore producing countries in 2016 [33]

Production of Iron Ore in 2016 in thousands of metric tons	
Australia	841,800
Brazil	431,400
India	184,500
China*	113,700
Russia	104,007
World	2,092,138

* converted to correspond with world average Fe content

The geographic location of the mine as well as the production process have a big impact on the chemical composition and the physical properties of the iron ore pellet or lump ore. Moreover, these factors influence the product quality of the HBI. The different pellets perform differently in the furnace. The influence of the source of the material is shown in Figure 21. As shown in this graph, in order to reach the required density of 5 g/cm³ for HBI, different pressures are necessary, depending on the source of the ore.

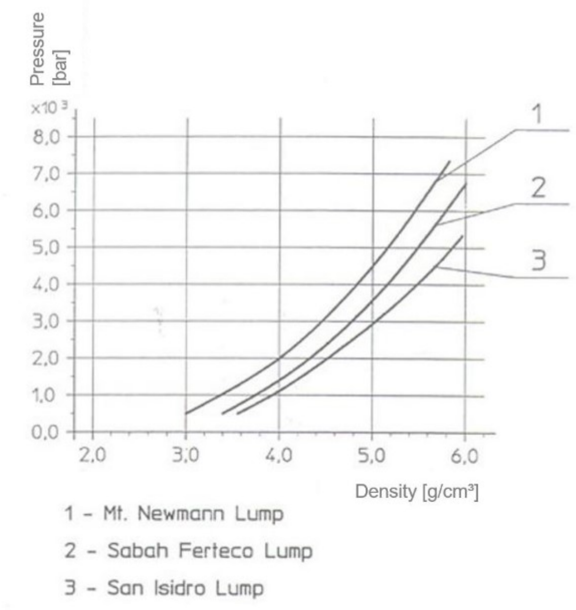


Figure 21: Densification curves for sponge iron from different ore sources at 700 °C [28]

3.2.3.2.2 Impact of Process Conditions on Product Quality

Briquetting is a very complex process and there are various factors which can influence the quality of the final product. The properties of the material briquetted are only one example of an influencing factor. Since the briquetting of the hot DRI takes place right after the reactor, no changes can be made to the feed of the roll presses. Therefore, the operating parameters have to be ideal in order to guarantee a high product quality. The different properties of the material and their possible impact on the product quality will be further described in the following section.

3.2.3.2.2.1 HDRI Temperature / Feed leg Temperature

At constant pressing force, the relationship between the temperature and the apparent density of different DRI products is proven. This is shown in Figure 22.

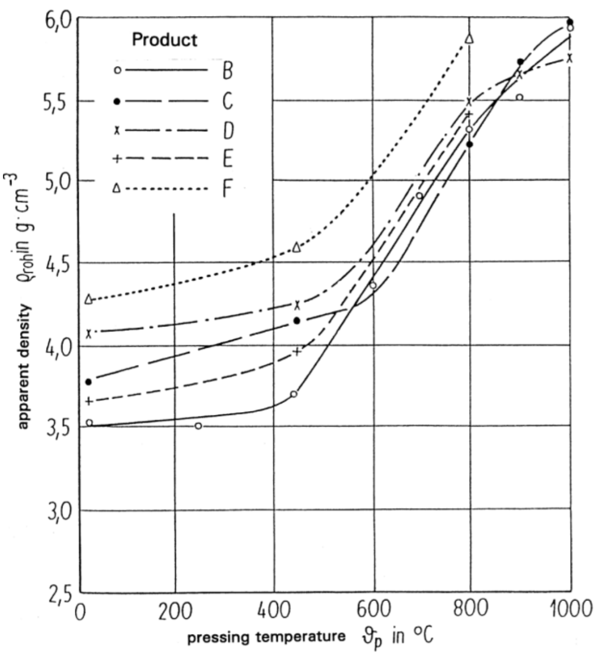


Figure 22: Influence of pressing temperature on apparent density of the compact at constant pressing force for different DRI products [34]

Between 450 °C to about 800 °C for most products there is a linear correlation between the apparent density and the pressing temperature. Table 9 gives an overview of the change in apparent density for different DRI products in the temperature range from 600 °C to 725 °C. One can see that a small increase in temperature (+25 °C) can already have a relatively large impact on the apparent density of the DRI product (+0.1 g/cm³).

Table 9: Change in apparent density for different DRI products at different pressing temperatures

DRI Product	$\rho_{600°C}$ [g/cm³]	$\rho_{625°C}$ [g/cm³]	$\rho_{650°C}$ [g/cm³]	$\rho_{675°C}$ [g/cm³]	$\rho_{700°C}$ [g/cm³]	$\rho_{725°C}$ [g/cm³]
B	4.4	4.5	4.6	4.7	4.9	5.0
C	4.3	4.4	4.5	4.6	4.7	4.9
D	4.6	4.7	4.8	4.9	5.0	5.1
E	4.5	4.6	4.7	4.8	4.9	5.1
F	5.0	5.1	5.2	5.3	5.4	5.5

Due to the high ductility of the metallic phase the composite material of metallic iron and iron oxides have a lower yield strength at elevated temperatures approaching the softening point compared to the yield strength of a pure mineral composite without metallic iron.

Moreover, as shown in Figure 23, the pressing temperature has an impact on the abrasion resistance of hot compacted DRI [34]. Tests were conducted with a tumble drum and it was shown that the higher the pressing temperatures, more particles with a size in excess of 30 mm after 200 revolutions (purple bars) remain. The red bars represent the amount of fines and chips produced after 300 revolutions of the tumble drum. With rising temperatures, less fines and chips are generated. This proves the positive impact of the pressing temperature on the abrasion resistance.

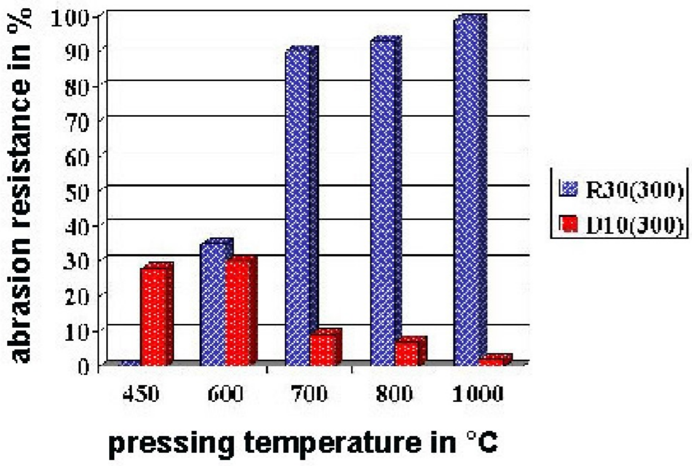


Figure 23: Influence of the pressing temperature on the abrasion resistance of hot compacted DRI; R30 (300): Amount retained on a 30 mm screen after 200 revolutions of the tumble drum; D10 (300): Amount passing a 10 mm screen after 300 revolutions of the tumble drum [34]

3.2.3.2.2.2 Carbon Content

There are studies for the compaction of DRI fines, however no study was found for the compaction of DRI pellets. A clear trend between the carbon content and the density has been reported [35]. The pressure required to reach a certain density increases proportionally with the carbon content. This can be seen in Figure 24. The dashed line represents the required density for HBI, 5000 kg/m³. As a result, increasing carbon content of compacted powders lowers the compressibility. Compressibility is defined as the relative volume change under a pressure change [36]. The presence of hard particles like iron carbides decreases the compressibility, since they hinder the plastic flow of individual particles.

It also has to be kept in mind that the density of iron with 7.87 g/cm³ is very high compared to the density of carbon with 2.25 g/cm³ [37]. Carbon can either be free in the briquette or bound as cementite (Fe_3C). The density of cementite is 7.69 g/cm³, which is also a high value [38]. A high free carbon content will decrease the density of the briquette significantly while the density of cementite is close to the one of pure iron.

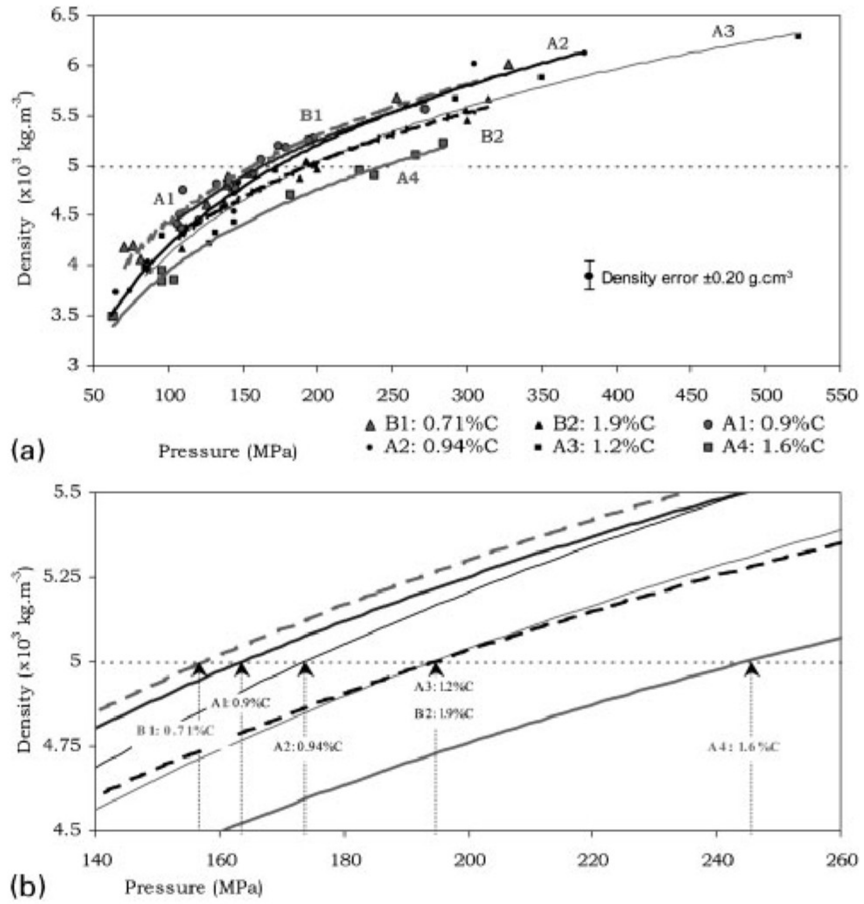
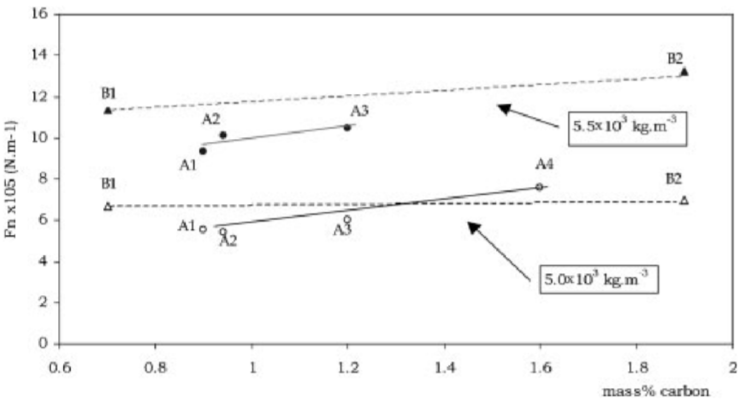


Figure 24: Compressibility curves for industrial DRI powders compressed at 650 °C [35]

Moreover, the carbon content has an impact on the fracture resistance, providing that the density is high enough. This can be seen in Figure 25. It can also be seen that the fracture resistance rises with higher densities. The influence of the density can be explained with the interactions of particles. With increased applied pressure, the contact areas and interlocking between particles increase, while at low densities, the contact areas are small and therefore the interlocking is poorly developed [35].



DRI source	Composition, wt-% Fe total*	Fe met.†	C	SiO_2	Al_2O_3
A1	NA	84·4	0·90	2·5	0·90
A2	91·8	83·0	0·94	2·8	0·89
A3	92·6	85·1	1·2	2·3	0·91
A4	91·8	82·5	1·6	2·1	0·84
B1	93·2	83·1	0·71	0·94	1·1
B2	92·8	84·3	1·9	0·95	0·80

*NA denotes not available.
†met. denotes metallic.

Figure 25: Influence of the carbon content on the fracture strength of DRI compacted samples at two different densities, compacting temperature 650 °C [35]

Even though this study was not done with DRI pellets, the impact of carbon content on the density and on the fracture resistance is expected to be similar for DRI pellets as for DRI powders.

3.2.3.2.2.3 HDRI Metallization

As already mentioned, Metallization is the percentage of iron present as Fe to total iron in a briquette. A test has been done where the effect of phase transition on compressive strength of iron oxide pellets has been tested. Table 10 shows the result of this test. The compression strength of pure iron is significantly lower than of iron oxides (Fe_2O_3, FeO, etc.) [39]. Therefore, a high metallic iron content (high metallization) is favored for the briquetting of HBI.

Table 10: Compressive strength of different iron phase transitions [39]

Phase transition	**Reduction time [min]**	**Temperature [°C]**	**Gas composition [%]**			**Compressive strength [N/p]**
			CO	**CO_2**	**N_2**	
1) Fe_2O_3	0	900	-	-	-	2973.3
2) $Fe_2O_3 \rightarrow Fe_2O_3/Fe_3O_4$	10	900	10	60	30	1168.0
3) $Fe_2O_3 \rightarrow Fe_3O_4$	28	900	10	60	30	718.0
4) $Fe_3O_4 \rightarrow Fe_3O_4/Fe_xO$	30	900	35	35	30	655.0
5) $Fe_3O_4 \rightarrow Fe_xO$	55	900	35	35	30	563.0
6) $Fe_xO \rightarrow Fe_xO/Fe$	43	900	68	2	30	735.2
7) $Fe_xO \rightarrow Fe$	78	900	68	2	30	930.0

3.2.3.2.2.4 Size Distribution of Material

Another influencing factor is the size distribution of the sponge iron. A test was conducted with different particle sizes of sponge iron from the same ore which were briquetted at the same temperatures, in order to keep the other possible influencing factors as small as possible. For bigger particles (5 - 25 mm), reaching the density of 5 g/cm³ requires less pressure than for small particles (≤3 mm). This can be seen in Figure 26.

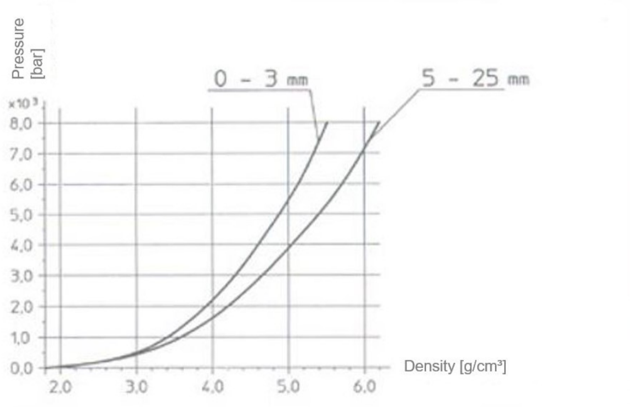


Figure 26: Densification curves for differently sized sponge iron at 700 °C [28]

3.2.3.2.3 Impact of Machinery on Product Quality

Not only the origin of the feed material and the process conditions have an impact on the product quality. The operation of the equipment has also a big influence on the final product. The influence of different parameters will be further discussed in the next section.

3.2.3.2.3.1 Velocity of Rollers

Temperature, compaction time and pressure are the main factors for forming a briquette successfully. A minimum time and pressure is essential to reach a good briquette quality (see Figure 27). An upper limit on the pressure that can be applied exists for friable material. Figure 27 shows the limits for pressures and compaction times [40]. Generally, the briquette quality improves with decreasing velocity, because the disintegrating forces due to the release of residual elastic deformation and compressed air trapped in the pores diminish [23], [41].

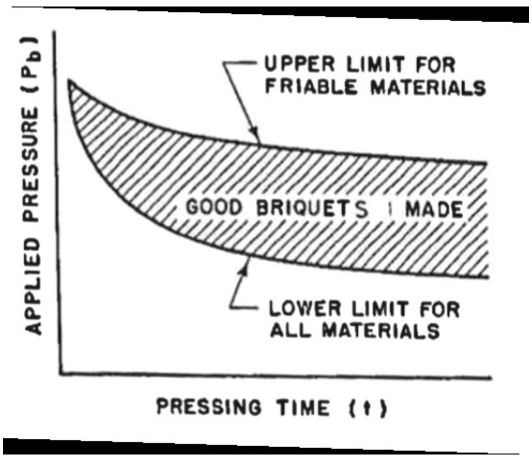


Figure 27: Time and pressure required to form a good briquette [40]

3.2.3.2.3.2 Velocity and Torque of Screw Feeder

The screw feeder plays an important role in briquetting. It does not only feed the briquetting press with material, but also applies pressure on the material. Therefore, pre-compaction takes place [30]. If the screw feeder is not aligned with the roller speed, it does not deliver material to the press fast enough, which hinders optimal production. Therefore it is important that the screw feeder is well adjusted to the process in order to guarantee stable operating conditions [40]. Due to factors like wear and usage of different pellet types in the DRI process, the briquetting conditions change. In order to compensate for these changes, increasing feed pressure can be applied by increasing the screw torque [40], [23].

3.2.3.2.3.3 Roll Pressure and Torque

The higher the roller torque the higher the densification of the material. The necessary torque for reaching the desired 5000 kg/m³ for HBI is highly dependent on many different factors, e.g. feed temperature, carbon content, metallization, wear, origin of ore, as well as particle size distribution [28].

If the temperature is kept at a constant value, the density of the briquette is directly linked to the applied pressure. The higher the applied pressure, the higher the density. The impact of temperature has already been discussed in further detail in paragraph 3.2.3.2.2.1. Temperature has a positive effect on the compaction of the material. The relation between density and applied pressure is shown in Figure 28. Moreover it is essential that the pressure between the rollers is kept constant in order to assure a constant density product [42].

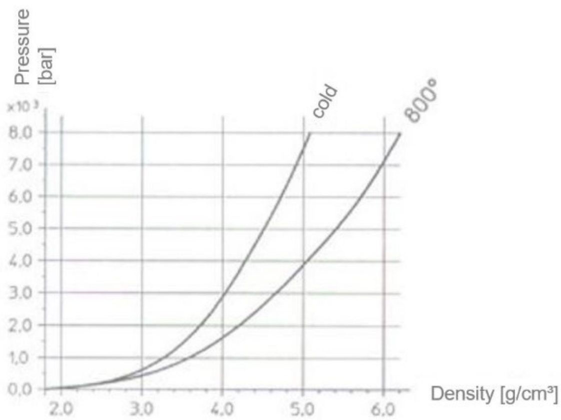


Figure 28: Densification curves for sponge pellets as a function of briquetting temperature [28]

3.2.3.2.3.4 Initial Gap

The initial gap approaches zero for a roller press without molds. If the rollers have molds, there is always an initial gap to make sure no damage happens to the segments [43]. During the briquetting operation, material properties change, and the press becomes worn out. One possibility to counteract the latter is to change the roll gap via a floating roll arrangement. In

Figure 29 the effect of a changing roll gap S can have on the maximum pressure P_M when other variables are held constant is shown. The greater the gap between the two rollers, the lower the maximum pressure P_M. In paragraph 3.2.3.2.3.3 the influence of the pressure on the density was shown. The higher the pressure, the higher the density, the better the briquette quality. Therefore a big initial gap and a small resulting maximum pressure negatively impact the HBI product quality [40]. Furthermore, the bigger the gap, the thicker the webbing around and between the briquettes. This leads likely to a higher generation of chips and fines during separation, which is not desired.

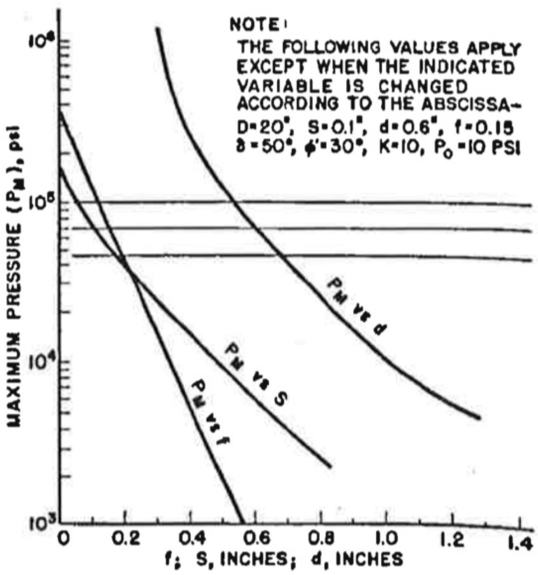


Figure 29: Effect of material loss and briquette size on maximum pressure P_M; f – ratio of rate of material lost from the roll bite to the feed rate; S – roll gap; d – average briquette thickness for zero roll gap; δ – effective angle of friction; ϕ – roll surface; *K* – compressibility factor; P_0 – feed pressure [40]

3.2.3.2.3.5 Segment Wear

Wear of the segments has a negative impact on the briquette quality. The shapes of the molds change, they deepen and their surface changes. Moreover, the webbing gets thicker. Figure 30 shows a new segment for briquetting of HBI. A thicker web is more difficult to break and therefore the separation of the briquetting string gets more complex. In general, one can say that the web is denser and therefore stronger than the briquette itself. Tests have been conducted and as a result it was shown that the strength of the web is five times bigger than the strength of the briquette itself. When the separator hits the briquette string, the briquettes break apart. However, due to thicker webbing resulting from wear, the breakage happens through the briquette, rather than the web. As a result, more half briquettes as well as more chips and fines are generated [44].

Figure 30: New segments for briquetting of HBI [45]

Due to wear, it gets more difficult to produce satisfactory briquette quality with a constant pressing force and torque. It is assumed, that higher pressing forces are necessary in order to keep a satisfactory product density and to mitigate chips and fines generation.

3.2.3.2.3.6 Separator Speed

The separator speed has to be aligned with the roller velocity. If it is not, the separator would either not be able to separate the briquette string or it would produce many chips and fines by breaking the string unevenly. A production of fines and chips is not economically desirable and should therefore be avoided.

3.2.3.2.3.7 Methods of Machine Control

There are different ways of machine control. One method is to control the gap between two rollers. This means that one briquetting roll is positioned relative to a second roll and the gap between the two rolls is kept constant. This enables a constant thickness of the formed product and therefore increased product quality. Not only the gap but also the energy of the roll positioning in order to be able to change the feed rate and therefore controlling the screw feeder is affected. A second possibility is to control the speed of the screw feeder linked to the roller speed. This should guarantee continuous material flow and therefore uniform product thickness [42].

Another method to control the machine is to constantly measure the temperature of the incoming material and adjust the pressure on the rolls hydraulically according to the temperature. The higher the temperature, the less pressure is necessary for briquetting. Another possibility is to adjust the temperature of the rolls, by controlling a heating apparatus. Depending on the temperature of the incoming material this apparatus heats the rolls in order to keep a certain constant temperature value. The pressure on the rollers is also kept constant [46].

3.2.4 Tests to Evaluate Physical Quality of Briquettes

In this section, two different tests to evaluate the physical quality of briquettes are further discussed.

3.2.4.1 Apparent Density and Water Absorption

The apparent density is defined as “the mass per volume (or the weight per unit volume) of a material, including the voids which are inherent in the material” [47]. To determine the apparent density and the water absorption of HBI, the standardized method ISO 15968:2000(E) is used.

In order to obtain the apparent density of a briquette, a dry briquette has to be weighed in air. Afterwards, the briquette is soaked in water for up to 60 minutes. The surface of the briquette is dried with a paper towel and the wet weight as well as the submerged weight are measured. With the masses obtained, the apparent density and the water absorption can be calculated.

The apparent density ρ_a is calculated with Equation 3-7,

$$\rho_a = \frac{m_1}{m_4} \qquad [g/cm^3 \ or \ kg/m^3]$$

Equation 3-7

where m_1 is the mass of the dried briquette in air, m_4 is the apparent mass in water of the soaked briquette, which is equivalent to the apparent volume of the briquette.

The water absorption *a* is the mass of water absorbed into the open pores of the dry material. It is expressed as percentage of the dry mass, shown by Equation 3-8,

$$a = \left(\frac{m_2 - m_1}{m_1}\right) * 100 \qquad [\%]$$

Equation 3-8

where m_2 is the mass in air of the soaked briquette and m_1 is the mass in air of the dried briquette [48].

Figure 31 shows an apparatus for measuring the apparent density of the HBI with a thin wire.

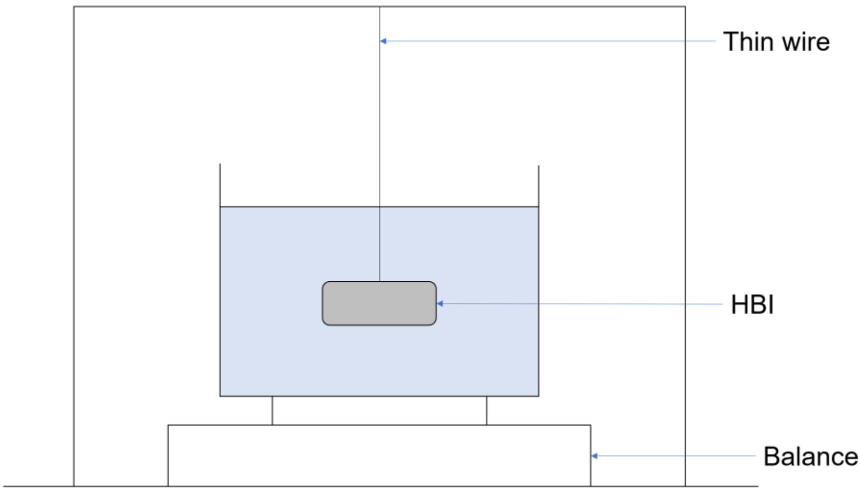


Figure 31: Apparatus for measuring the apparent density and water absorption

3.2.4.2 Tumble and Abrasion Index

To evaluate the abrasion resistance of direct reduced iron the standardized method ISO 15967:2007(E) is used. In this test, 15 kg (dry basis) of HBI is tumbled in a circular drum for 200 revolutions at 25 r/min and afterwards sieved with 2 test sieves (square openings of 6.30 mm and 500 µm).

The tumble index (TI) is defined as mass percentage of material greater than 6.30 mm and is shown by Equation 3-9,

$$TI = \frac{m_1}{m_0} * 100 \qquad [\%]$$

Equation 3-9

where m_1 is the mass of material greater than 6.30 mm and m_0 is the total mass placed in the tumble drum.

The abrasion index (AI) is the mass percentage of material less than 500 µm and is shown by Equation 3-10,

$$AI = \frac{m_0 - (m_1 + m_2)}{m_0} * 100 \qquad [\%]$$

Equation 3-10

where m_0 is the total mass placed in the tumble drum, m_1 is the mass of material greater than 6.30 mm and m_2 is the mass of the -6.30 mm +500 µm fraction [49].

4 Practical Part – Design of Experiment

In the next sections the production plant in Corpus Christi will be further described. Restrictions due to several factors like running production will be further discussed. Moreover, the design of a testing plan, tests on DRI and HBI as well as numeration of tests will be explained.

4.1 voestalpine Texas LLC in Corpus Christi

voestalpine Texas LLC started their direct reduction plant in October 2016 after about a two-and-a-half-year construction period. It is the world’s largest and most state-of-the-art plant with a production volume of two million tonnes of high-quality HBI. The plant is operated, as already mentioned, according to the MIDREX process and provides about 220 permanent jobs [50].

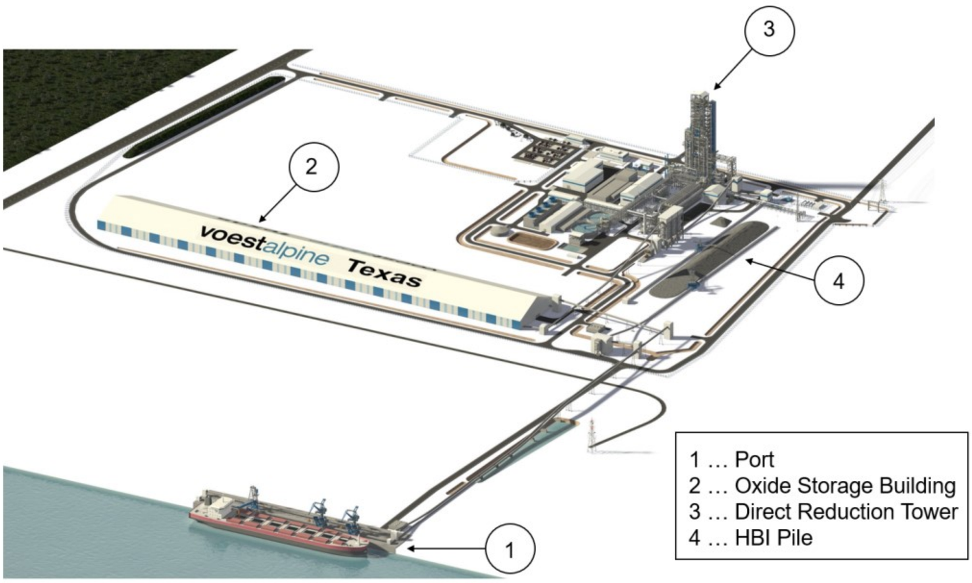


Figure 32: Overview of the voestalpine Texas LLC area in Corpus Christi [50]

Figure 32 gives an overview of the voestalpine Texas LLC plant. The iron oxide arrives at the sea port and is stored in an oxide storage building. This building is covered in order to keep the dust emissions as low as possible. Afterwards, the iron oxide is transported and fed into the top of the direct reduction furnace. While traveling through the furnace the oxide is reduced with cracked natural gas, discharged at the bottom and directly briquetted. Figure 33 shows a briquetting machine on the briquetting deck in Corpus Christi.

Figure 33: Briquetting deck at voestalpine Texas LLC [51]

After the separation of the briquette string, the briquettes are cooled off and are transported via belt conveyors to the HBI pile where they wait for shipping. Figure 34 shows an HBI pile and the reduction tower in Corpus Christi.

Figure 34: HBI pile and reduction tower in Corpus Christi [51]

4.2 Restrictions

Before the tests were planned, several restrictions had to be kept in mind. Testing is done during full production. Due to several reasons (price of iron oxide, quality, availability,) there are different types of iron oxide pellets fed into the furnace. Most of the time a mix of pellets is used. The tests for this thesis have no impact on the feed material mix. Therefore, the changing feed material and possible influences of this material (metallization, compressibility, reduction degree etc.) are not taken into account for this testing.

During full production, it is very difficult to have perfect operating conditions for testing. Testing is often done when it is possible and not when every aspect is perfect. The key parameters according to the literature review are roller torque, roller speed, feed leg temperature and segment wear. The feed leg temperature, for example, is given from the process and cannot be kept stable throughout testing. Therefore, a briquetting machine should be picked which had stable feed leg temperatures in the previous operating hours. Another restriction is the lifetime of the segments. From an economic point of view, it is important to run the segments as long as possible, provided that the product quality is satisfactory. In order to keep the influence of segment wear small, new segments should be used for testing. However, for testing new segments are not installed.

The roller speed determines the production rate of HBI in t/h. If the production rate is increased in the furnace or if another briquetting machine has an unexpected shutdown, then the roller speed of the other operating pressing machines has to be increased in order to make up for the loss. In order to be able to increase the roller speed, the screw feeder has to be in a good condition (no wear, no deposits, …), though. Too high torque on the screw might damage it and should be avoided.

One important economic factor for the production of HBI briquettes is to keep the generation of chips as low as possible - at the briquetting press itself as well as throughout material handling. As already described in section 3.2.3.1.4, the briquettes are screened after being broken by a separator. The generated chips and fines are recycled and brought back into the briquetting machine by a bucket elevator. This elevator does not have a scale, so the exact amount of chips generated due to changing briquetting parameters cannot be determined.

Those factors have to be kept in mind when planning and conducting the tests.

4.3 Development of Testing Plan

Together with the industry partner a testing plan is developed. There are seven different tests planned, which will be further described in the following sections.

4.3.1 Impact of Cooling Method (Air / Water Quench)

For this test the determination of the impact of two different cooling methods on the physical properties of the briquette is the main goal. The cooling methods to be evaluated are water quench and air cooling.

For this test, 40 briquettes of two different briquetting machines with different number of processed tons, which are operating under normal conditions should be selected. 20 briquettes will be water quenched while the other 20 will be cooled by air. The briquettes should then be analyzed in the laboratory.

Depending on the results of this test, the other tests will use the milder cooling method in order to assure that the cooling method does not impact the results of the tests.

4.3.2 Impact of Feed Leg Temperature

The impact of the feed leg temperature on the briquette quality (density and abrasion resistance) should be determined.

This test should be done at least 3 times throughout the time on site. In the beginning, a DRI sample should be taken. Two machines with large feed leg temperature difference should be selected and the other parameters (roller torque, production rate, segment wear, …) should be equalized. 20 briquettes per machine should be selected, cooled according to agreed method and analyzed in the laboratory.

4.3.3 Impact of Roller Speed

Goal of this test is to determine whether the roller speed has an impact on the quality of the HBI (density and abrasion resistance).

A machine which is operating in steady state should be selected. Again, a DRI sample will be taken. The production should be reduced to the lowest target rate, while the other machines are adjusted to pick up the extra capacity. After 30 minutes of steady operation 20 briquette samples should be taken and cooled by the agreed method. The speed should be increased, and the other running machines balanced. This should be repeated until all tests have been done. At the end of the test, again a DRI sample should be taken and the briquettes should be analyzed in the laboratory.

4.3.4 Impact of Press Torque

Main goal of this test is to determine the impact of the press torque on the briquette quality, especially on the density and the abrasion resistance (tumble and abrasion index). As a secondary goal, the relationship between press parameters should be established. Especially the relationship between press torque and screw feeder torque, gap, and pressure change is of importance.

Therefore, a machine operating under more or less normal conditions should be selected. At the begin of the test, a DRI sample is taken. The machine torque set point is lowered to the lowest value and run for 30 minutes. 20 briquette samples are taken and cooled by the agreed method. Afterwards, the torque is increased to the next increment and the machine is run for 30 minutes again. This should be repeated for 6 different press torque set points until all tests have been done. At the end of the test, again a DRI sample should be taken. The briquettes should then be analyzed in the laboratory.

4.3.5 Impact of Segment Wear

The impact of the segment wear on the briquette quality (density and abrasion resistance) should be determined.

A DRI sample should be taken in the beginning of the test. Two briquetting machines should be selected which have a large life span difference. The operating parameters should be kept as close as possible (feed leg temperature, roller torque, production rate). 20 briquettes from each machine should be selected, cooling according to agreed method and analyzed in the laboratory. This test should be done several times throughout the time on site.

4.4 Tests in the Laboratory

For every test conducted on the briquetting presses, the DRI as well as the briquettes are tested in the laboratory on the plant site. These tests will be further described in the following sections.

4.4.1 DRI Pellets Tests

In order to get a better understanding of the incoming material different tests with the DRI pellets are done. Following tests are done:

- Bulk density
- Particle size distribution
- Compression Strength
- Chemistry

The bulk density as well as the particle size distribution is determined. For the particle size distribution sieving with eight different sieve bottoms is done with a sieve shaker. The compression strength of the DRI pellets is also determined. Last step is to determine the chemistry of the DRI pellets. This was done with X-ray diffraction (XRD) and X-ray fluorescence (XRF). The XRF provides information about the elemental composition of materials. It is a non-destructive analytical technique. It does not give any information about the combination of the elements, though. This information is provided by the XRD. Therefore, a combination of the two methods allows for a more complete characterization [52]. More information about the XRF and XRD methods can be found in [53] and [54]. Figure 35 shows an apparatus which uses the XRF and XRD method combined.

Figure 35: ARL™ 9900 X-Ray WorkStation™ for XRD and XRF analysis [55]

4.4.2 HBI Briquettes Tests

For each test, 20 full briquettes per testing machine were taken to make sure a representative average is gained. Following tests should be done in the laboratory on the HBI briquettes collected:

- Simple visual classification:
  - 1 – excellent briquette
  - 2 – minor breakages in webbing
  - 3 – minor breakages of briquette
  - 4 – large piece missing
  - 5 – webbing and large piece missing
- 13 thickness measurements on briquette and webbing (see Figure 36)
- Apparent density
- Tumble test (abrasion index, tumble index)
- Weighing to determine loss of mass after tumble test of each briquette
- Chemistry

The visual classification is important to make sure only full briquettes are taken for the tests. The thickness measurements as well as the marking of each briquette will be the next step. Figure 36 shows the location of the 13 thickness measurements for each briquette. The measurement of the apparent density as well as the tumble test should be done according to the ISO standards described in sections 3.2.4.1 and 3.2.4.2. The briquettes are soaked in water after the determination of the apparent density. In order to be able to go on with the other tests, they have to be dried in the oven over night. This is done at 105 °C for at least 8 hours. After the tumble test, each briquette is weighed individually. With the information gained the loss of mass per briquette can be determined. The last step is to do the chemical analysis with the XRD and XRF methods, which are described in paragraph 4.4.1.

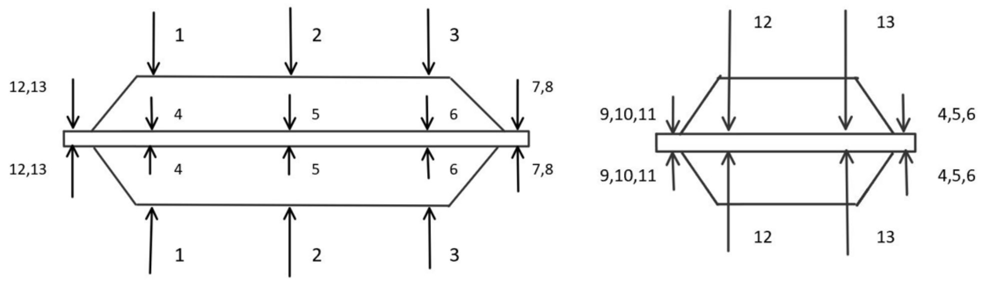


Figure 36: Overview of thickness Measurements of briquette and webbing

4.4.2.1 Adaptation of HBI Tests

The apparent density is measured slightly different compared to the ISO standard test described in section 3.2.4.1. The dry weight of the briquette is taken (m_1). Afterwards, the briquettes are put into water for up to one hour. When they are fully soaked (no more bubbles rising), the submerged weight (m_3) of the briquettes is measured. Afterwards, the briquette is dried with a paper towel and the dry weight (m_2) is taken. The apparent density is calculated with Equation 4-1.

$$\rho_{apparent} = \frac{m_1}{m_2 - m_3} \qquad [\frac{kg}{m^3}]$$

Equation 4-1

Figure 37 shows the schematic representation of the apparatus used for measuring the apparent density in the laboratory. It shows the weighing of the submerged weight.

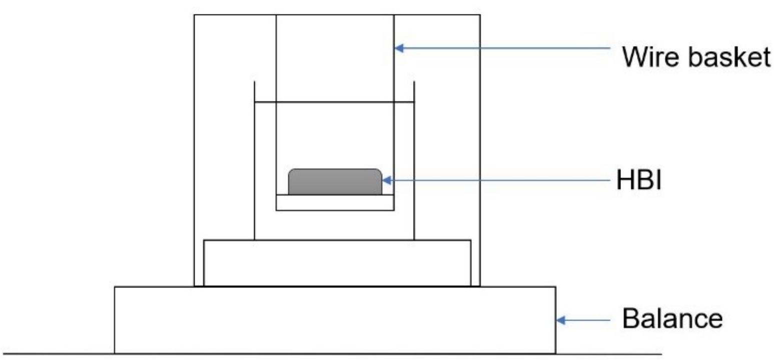


Figure 37: Apparatus for measuring apparent density in laboratory in Corpus Christi

4.5 Numeration of Test

A system for the numeration of each individual test was developed. Each test was marked with four different numbers. The first number would indicate which type of test is done. The second number tells us of which briquetting machine the samples are taken. The third number represents the cooling method and the fourth number indicates how often the test was done.

Table 11: Overview of numeration system for tests

1st number - Type of Test		2nd number - Briquetting Machine		3rd number - Cooling Method		4th number - Test Number	
1	Impact of Cooling Method	1	machine A	1	air cooling	1	first time
2	Impact of Press Torque	2	machine B	2	water quench	2	second time
3	Impact of Feed Leg Temperature	3	machine C			3	third time
4	Impact of Briquetting Speed	4	machine D				
5	Impact of Initial Gap	5	machine E				
6	Impact of Machine Wear	6	machine F				
7	Impact of Separator Speed	7	machine G				

As an example, the test name “1201” indicates that the impact of the cooling method is tested. The briquettes are taken from machine B, they are air cooled and it’s the first time this test is done.

Not only the tests are numbered but also each briquette is clearly marked on both sides. This makes sure that for each briquette the loss of mass after the tumble test can be identified and a better understanding can be gained. Figure 38 shows one briquette which is marked on its front and back side for identification after the tumble test.

Figure 38: Front and back side of briquette

5 Execution of Testing Plan and Results

After a planning phase, the tests have been conducted from January to April 2018 on the site of voestalpine Texas LLC in Corpus Christi. In the following section the execution and the results will be presented.

5.1 Impact of Cooling Method (Air / Water Quench)

The impact of the cooling method is tested once. The test is done according to the testing plan, which is described in 4.3.1. The sampling of the briquettes is done after the hot screen with a special type of shovel, which is shown in Figure 39.

Figure 39: Shovel for briquette sampling

For this test, it is important to keep the feed leg temperature, the roller torque, and the roller speed as similar as possible in order to suppress other possible influencing factors. This is done successfully. 40 briquettes are taken from two different machines. One has almost no wear (machine F, 2.0 % of segment life) while the other one is already worn out (machine G, 79.8 % of segment life). Only full briquettes are taken for this test. The sampling for the machine with new segments was easy, while the sampling for the worn-out segments was more difficult. Lots of fines, chips and half briquettes were sampled. It took significantly longer to get 40 full briquettes.

Table 12: Results of impact of cooling method

Relative average loss of mass, without broken briquettes			
F, air	F, water	G, air	G, water
0.9	1.5	1.0	1.6

The results of this test are shown in Table 12 and Figure 40. In Figure 40 the triangles represent the air-cooled briquettes while the rectangles represents the water-quenched briquettes. The red shapes represent machine F (no wear) and green stands for machine G (lots of wear).

Briquettes from machine G are thicker than those of machine F. With wear, the molds get deeper and therefore, briquettes get thicker with rising wear.

Briquettes from machine F (2.0 % of segment life) which are air cooled have a relative chips generation of 0.9 % in average, while water cooled briquettes of machine F have 1.5 % in average. For machine G (79.8 % of segment life), the air-cooled briquettes show a result of 1.0 % of relative chips generation and the water-quenched 1.6 %. Briquettes which break in half during the tumble test are not included in these results, because they would affect the results greatly.

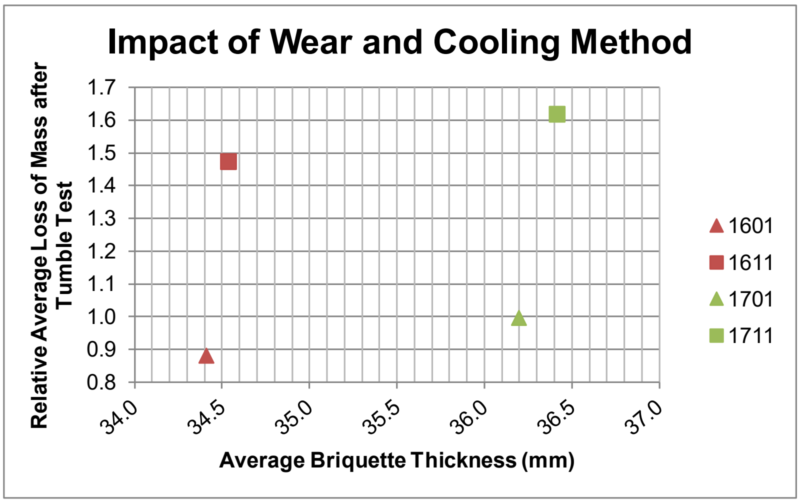


Figure 40: Impact of wear and cooling method on chips generation

5.2 Impact of Feed Leg Temperature

This test is done three times as described in section 4.3.2. The sampling for these tests is easier for machines with hotter feed legs. The machines with cold feed legs have tendentially more chips and fines. Therefore, sampling full briquettes takes longer for cooler feed leg temperatures.

It is important for this test that the compared machines are running with the same operating parameters (press torque, press speed, and segment wear). Table 13 shows the operating conditions for the three tests. As can be seen, they are kept similar in order to be able to compare the three tests.

Table 13: Overview set points and operating conditions for all tests

	Unit	Test 1		Test 2		Test 3	
		machine C	machine D	machine G	machine F	machine C	machine F
Average feed leg temperature	[Deg. F]	1271	1301	1315	1281	1310	1242
Relative press torque set point	[-]	1.03	1.03	1.00	1.00	1.00	1.00
Relative press speed set point	[-]	1.7	1.6	1.7	1.7	1.7	1.7
Relative segment lifetime	[%]	11.5	11.6	10.7	14.6	18.4	17.4

Despite the fact that there is always different feed material coming into the briquetting machines and that the total production varies greatly between the tests, there are clear correlations visible.

It has to be mentioned, that the distribution of the densities for the 20 briquette samples taken is rather big. This is shown in the boxplot below (see Figure 41). A boxplot consists of the upper whisker, the upper quartile, the median, the lower quartile and the lower whisker (from top to bottom). The line which divides the box into two parts is called the median. It represents the midpoint of the data, which means half of the data is greater than or equal to and half of the data is smaller than this value. The two boxes combined represent 50 % of the data. Outside of the boxes, the highest 25 % as well as the lowest 25 % are represented by the so-called whiskers. The top of the upper whisker marks the maximum value and the bottom of the lower whisker the minimum value [56].

Big boxes mean, that the apparent density varies greatly within the 20 briquette samples taken. Only two boxes are small (1314.5 °F and 1241.6 °F), which means that 50 % of the briquette densities are very close together (within 100 kg/m³). It also shows that for most tests, the medians are very different. 1270.7 °F and 1241.6 °F as well as 1300.6 °F and 1314.5 °F have similar median values, though. Despite the fact that for these tests the operating conditions are kept very similar, the median values vary greatly as well as the distribution of the apparent density. This has to be kept in mind when reading the results of the tests.

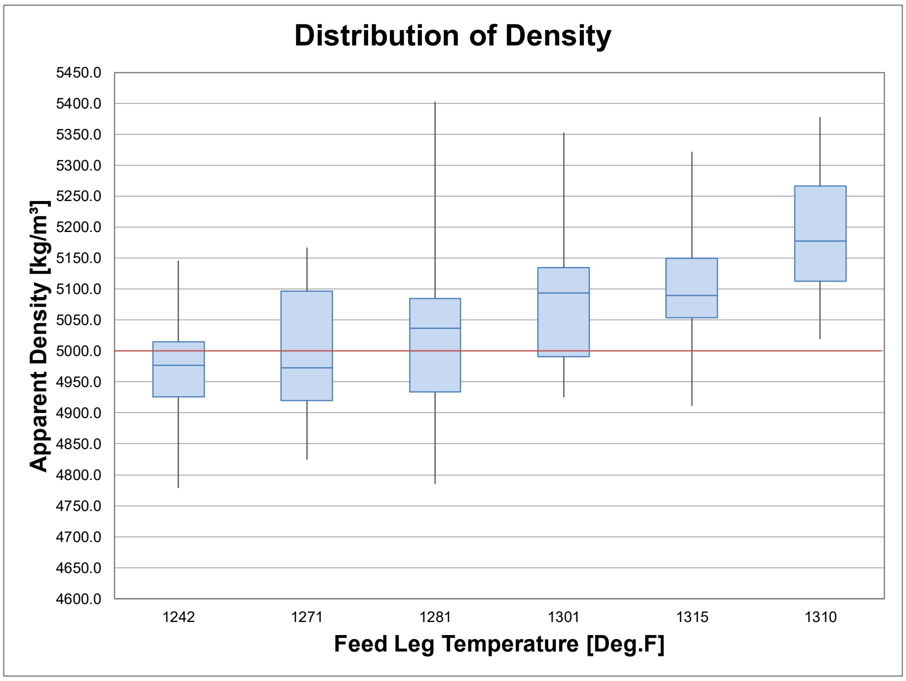


Figure 41: Boxplot - distribution of apparent density for feed leg temperature tests

The results of these tests show a clear correlation between feed leg temperature and average apparent density of the briquettes (see Figure 42). With rising feed leg temperature, the average apparent density of the briquettes increases. Figure 43 shows $\Delta_{Temperature}$ vs. $\Delta_{Density}$. The linear correlation between temperature and density is shown even better with this figure.

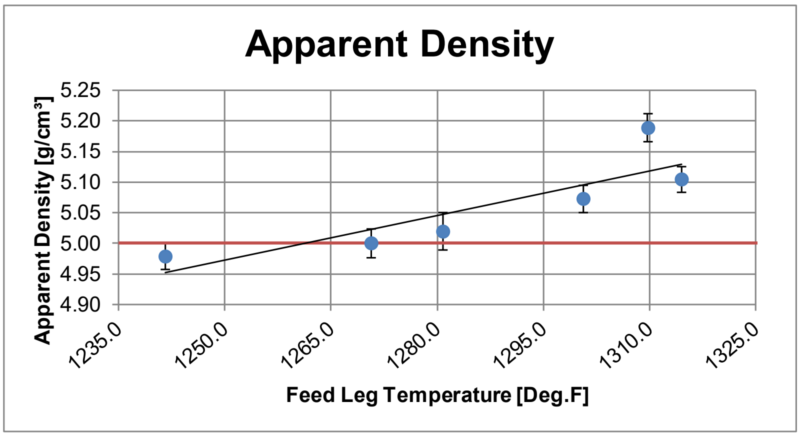


Figure 42: Impact of feed leg temperature on the apparent density of HBI

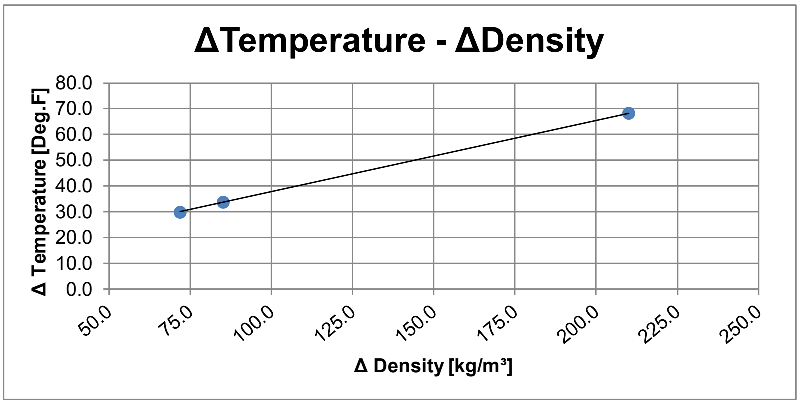


Figure 43: Impact of feed leg temperature on the apparent density of HBI

Moreover, more briquettes reach a density above 5.0 g/cm³ with increasing feed leg temperature (see Figure 44). This is, as already mentioned, very important for shipping regulations.

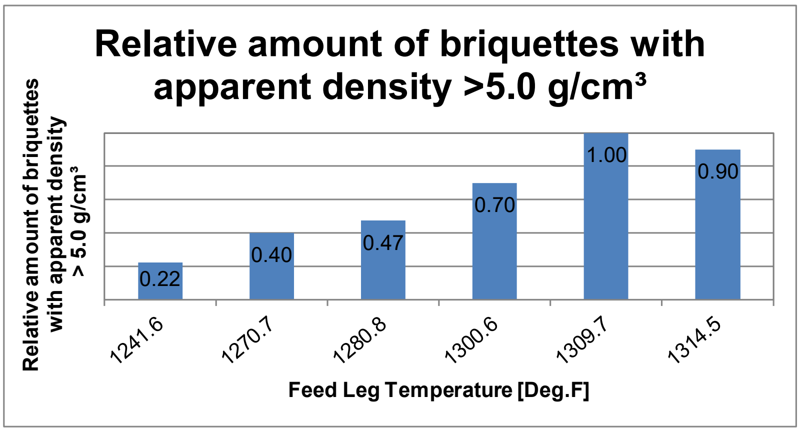


Figure 44: Relative amount of briquettes reaching apparent density >5 g/cm³

The briquettes tend to get more resistant to abrasion. The tumble index increases with rising feed leg temperature and the abrasion index decreases (see Figure 45). This means, less fines are generated, and more particles have a size of +6.3 mm with increasing feed leg temperature.

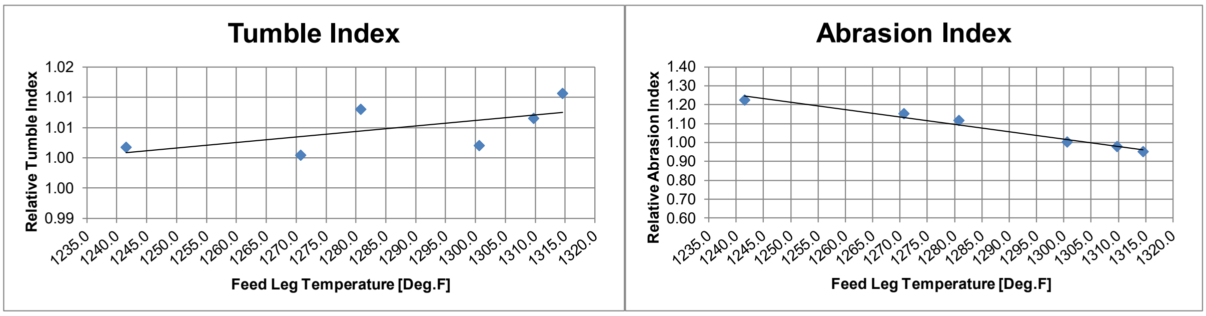


Figure 45: Results of tumble and abrasion index

The feed leg temperature also impacts the strength of the briquettes. After the tumble test, less briquettes break apart the higher the feed leg temperature is. Figure 46 shows a briquette before and after the tumble test. Briquetting took place at a feed leg temperature of 1271 °F. As can be seen, large pieces of the briquette are missing on the right side. The individual pellet shape is visible under the surface of the briquette. Moreover, the corners are broken off.

Figure 46: Briquette before and after tumble test; feed leg temperature of 1271 °F

The results for the relative amount of briquettes broken apart during the tumble test are shown in Figure 47. At a temperature of 1280.8 °F, 50 % more of the briquettes break in half compared to 1241.6 °F. At a temperature of 1314.5 °F only 40 % break apart compared to 1241.6 °F. That is important, considering the relatively rough material handling of the briquettes until they reach the EAF, BOF, etc. It is crucial for the customers, that they have as many full briquettes as possible.

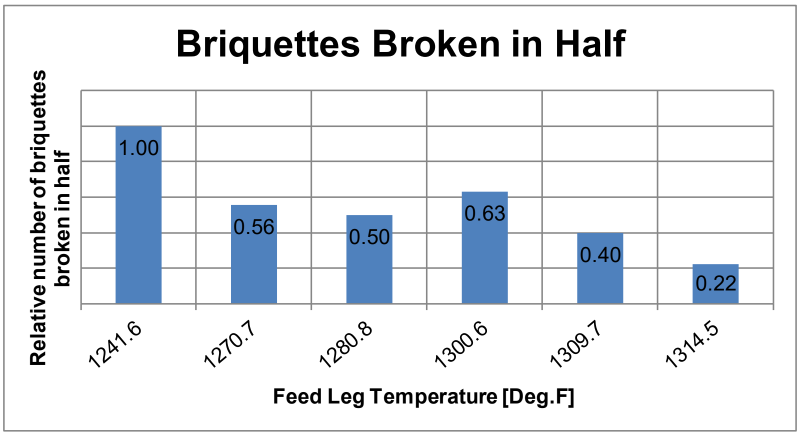


Figure 47: Relative amount of briquettes broken in half during tumble test

For the physical properties of the briquettes, no conclusions can be drawn. Neither the briquette volume, nor the mass of the briquettes show a correlation with the feed leg temperature. Figure 48 shows the results for the briquette volume. No clear trend can be seen.

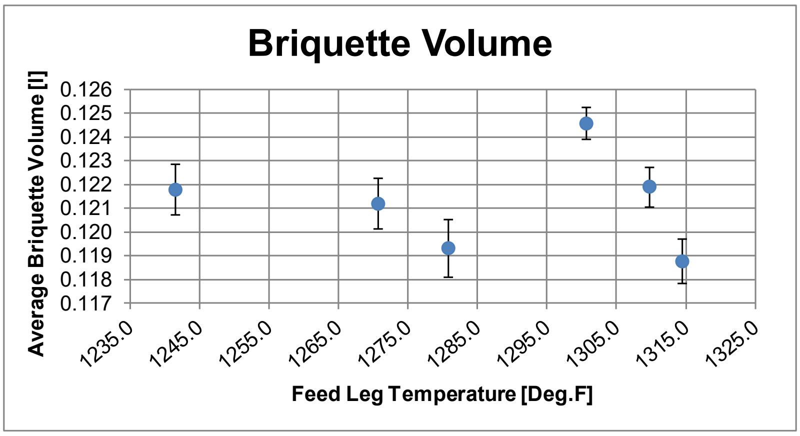


Figure 48: Results of briquette volume

5.3 Impact of Roller Speed

This test is conducted as in section 4.3.3 described. This test is done twice to verify the data gained from Test 1. A total of five different roller speeds is tested.

For this test it is important that the roller torque is stable throughout the test. Moreover, a machine is chosen which operates more or less stable and has not much wear. It would be important that the feed leg temperature is stable, this, however, cannot be controlled and therefore a certain influence of the feed leg temperature is possible. Table 14 gives an overview of important set points and operating conditions for the tests done. Sampling for this test is easy and there is no significant increase or decrease in chips generation with increasing roller speed.

Table 14: Overview set points and operating conditions for Test 1 and Test 2

	Unit	Test 1					Test 2				
Average feed leg temperature	[Deg. F]	1255	1283	1284	1281	1296	1303	1307	1307	1311	1296
Relative press torque set point	[-]	1.03	1.03	1.03	1.03	1.03	1.00	1.00	1.00	1.00	1.00
Relative press speed set point	[-]	1.0	1.3	1.7	2.0	2.3	1.0	1.3	1.7	2.0	2.3
Relative segment lifetime	[%]	7.3	7.3	7.3	7.3	7.3	18.4	18.4	18.4	18.4	18.4

As can be seen in Table 14, the set points for press torque as well as for press speed are more or less the same. The impact of the wear can also be neglected because both times the segments are not worn out yet. However, the feed leg temperature differs. In Test 1, the feed leg temperature varies greatly and is on average a lot lower than for Test 2.

Figure 49 shows the boxplot for these tests. As can be seen, again, the distribution of the apparent densities within the 20 briquette samples taken is big. Also, the median values are very different. For Test 1, the median values are very close to 5000 kg/m³ while for Test 2 they are generally higher. What can also be seen is, that with increasing roller speed, the minimum values get smaller than for slow roller speed. For the maximum values no trend can be seen.

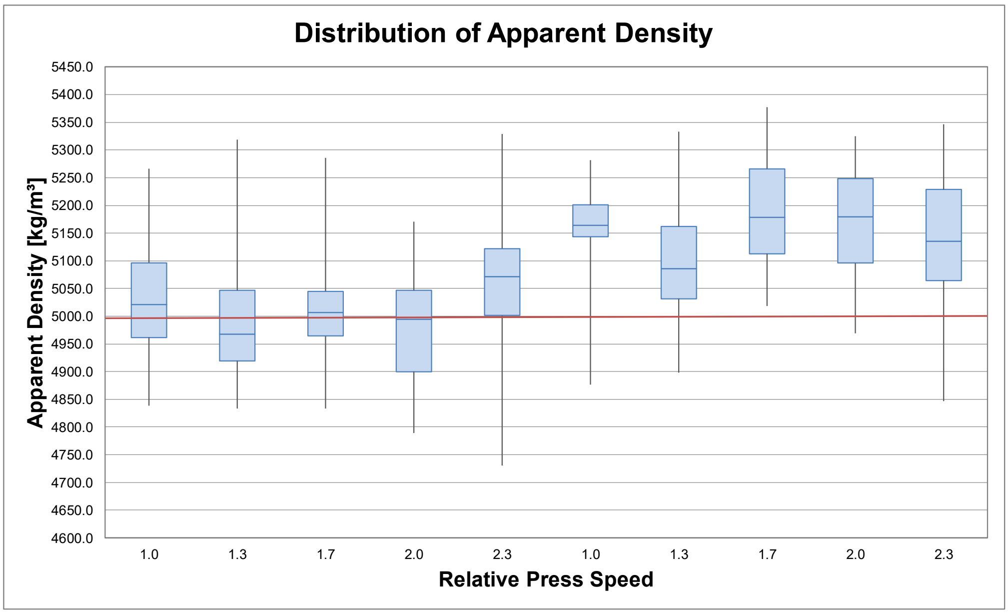


Figure 49: Boxplot - distribution of apparent density for roller speed tests

Figure 50 shows the results for the apparent density of both tests. As can be seen, no correlation between roller speed and apparent density can be drawn. In general, the densities for Test 2 are higher than for Test 1 despite the higher press torque set point for Test 1. One possible solution is, that the impact of the feed leg temperature is bigger than of torque or that the feed material for Test 1 is harder to briquette than the feed material for Test 2.

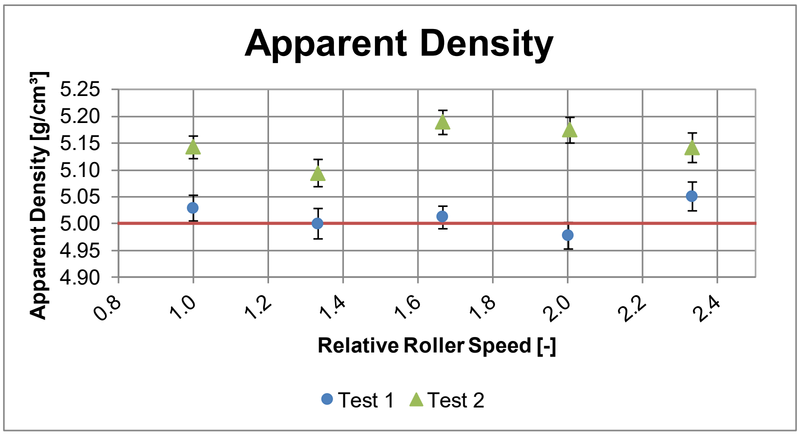


Figure 50: Results for apparent density of press speed tests

Figure 51 shows the relative results for the chips generation. Test 1 (blue circles) does not show a trend. Test 2, however, shows a slight trend: with increasing roller speed, more chips are generated (from 1.0 to 1.4). This graph again is not including the broken briquettes, because their loss of mass would falsify the results.

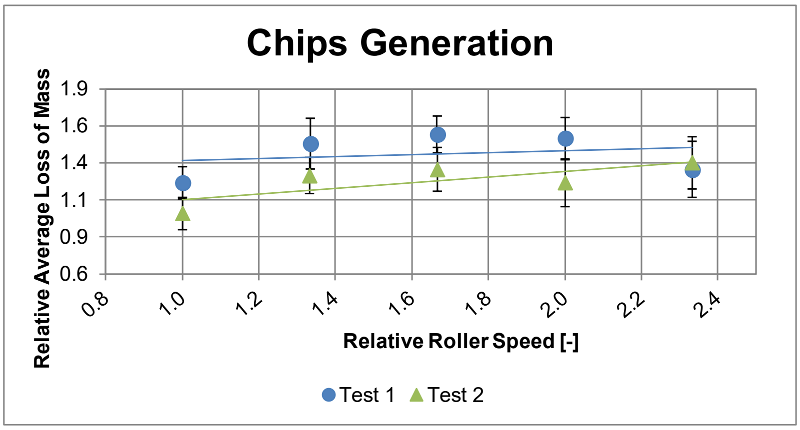


Figure 51: Results of relative chips generation for roller speed tests

Test 1 shows a clear trend: with increasing roller speed, the briquette strength decreases, and more briquettes break apart (see Figure 52). However, this trend cannot be verified by the second test. Moreover, neither abrasion index nor tumble index show a clear trend for the two tests.

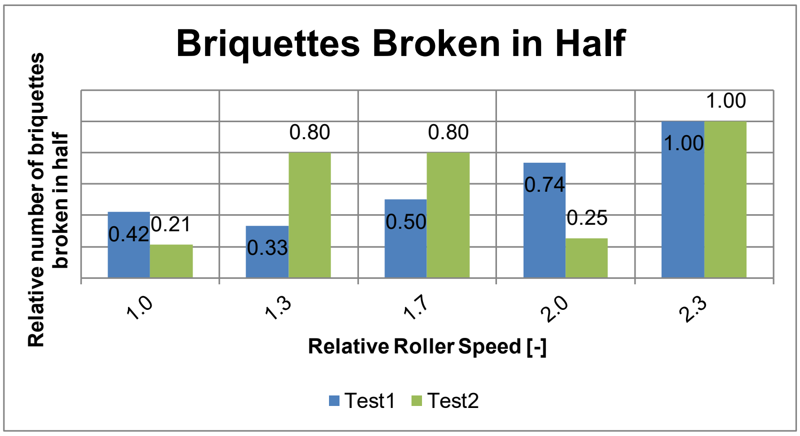


Figure 52: Relative amount of briquettes broken in half during tumble test

According to these results, the roller speed has neither an influence on the briquette density, nor on the briquette strength or abrasion resistance. Nevertheless, it is found, that the roller press has an influence on the physical properties of the briquettes. With increased roller speed, the volume and mass of the briquettes decrease significantly (see Figure 53 and Figure 54).

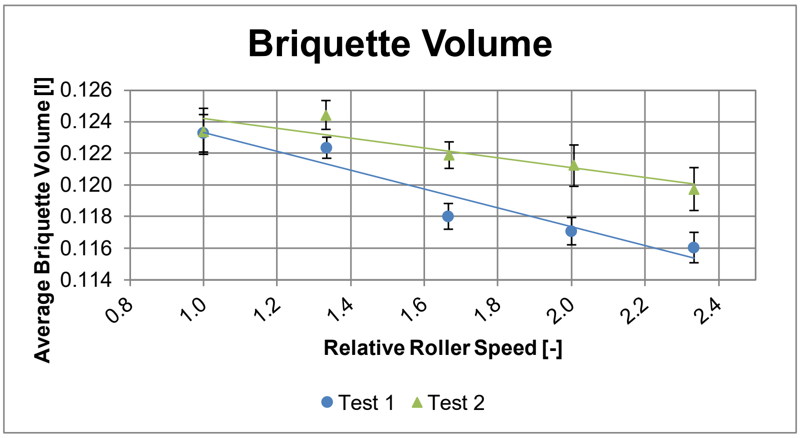


Figure 53: Results for briquette volume

The briquette volume decreases for Test 1 on average about 6.2 % and for Test 2 about 3.2 % with increasing roller speed. The average briquette mass decreases in Test 1 about 6.1 % and in the Test 2 about 2.7 %. This adds up to about 4.5 kg less material briquetted per rotation of the rollers for Test 1 and 2.1 kg for Test 2.

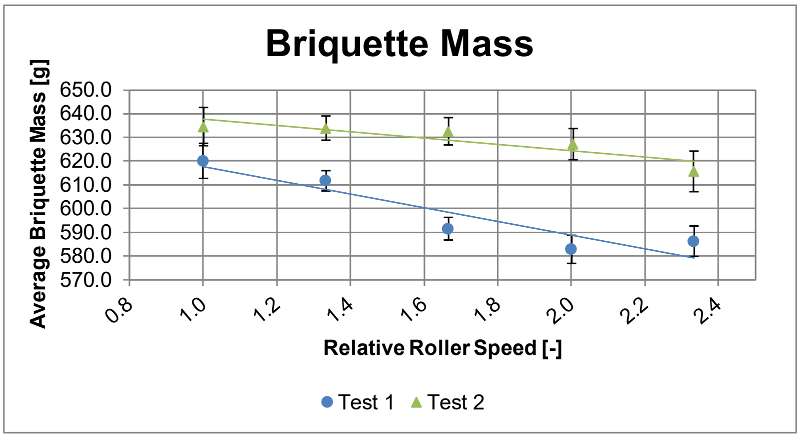


Figure 54: Results for briquette mass

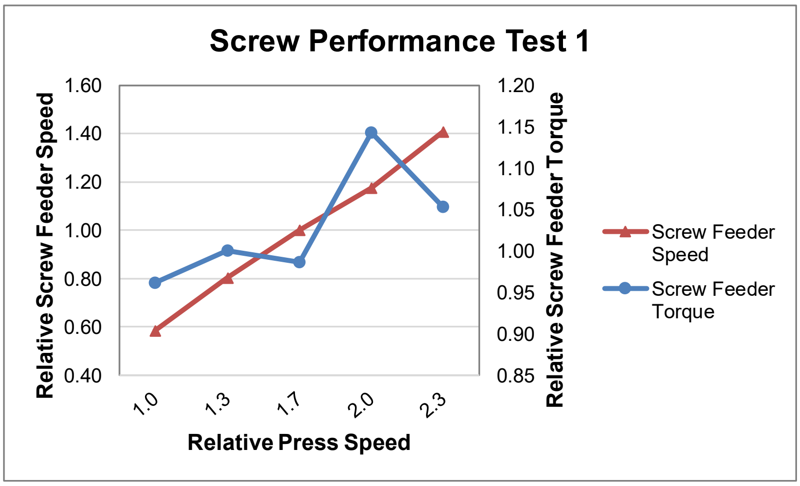


Figure 55: Screw performance of press speed Test 1

The screw performance of Test 1 is shown in Figure 55. One can see that with increasing press speed, the screw feeder speed also increases in order to keep up. The screw feeder torque does not show a nice trend though. In general, it tends to rise, reaches a peak at a relative press speed of 2.0 and falls again. A similar screw feeder torque trend can be seen for Test 2. Here also, the torque reaches a peak at a relative press speed of 2.0 (see Figure 56). The relative change of the screw feeder torque is very small for both tests and therefore can be considered as normal.

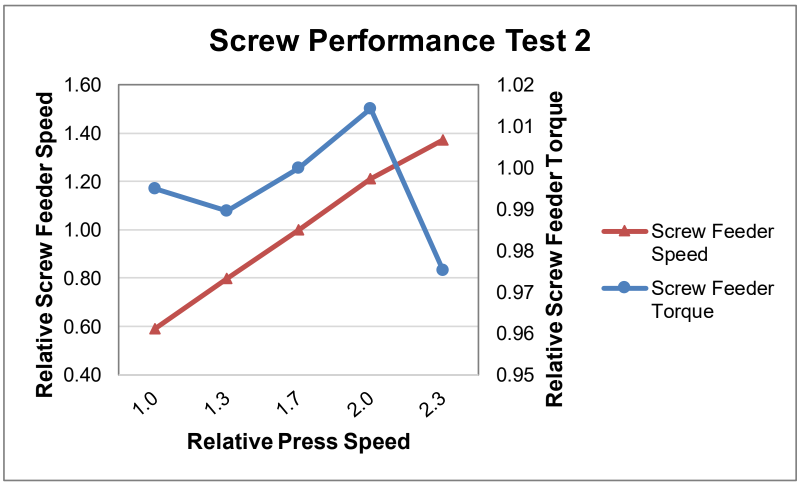


Figure 56: Screw performance of press speed Test 2

The hydraulic pressure as well as the average gap both decrease. Since the briquettes get lighter and smaller, less material seems to be fed into the press. As a result, there is a decreasing hydraulic pressure as well as a decreasing gap between the rollers. The changes are very small, especially for the pressure. They can be assumed as “normal measurement uncertainty”. The trend for Test 2 is very similar to Test 1. Figure 57 shows the trend for Test 1 of the relative hydraulic pressure and the relative gap.

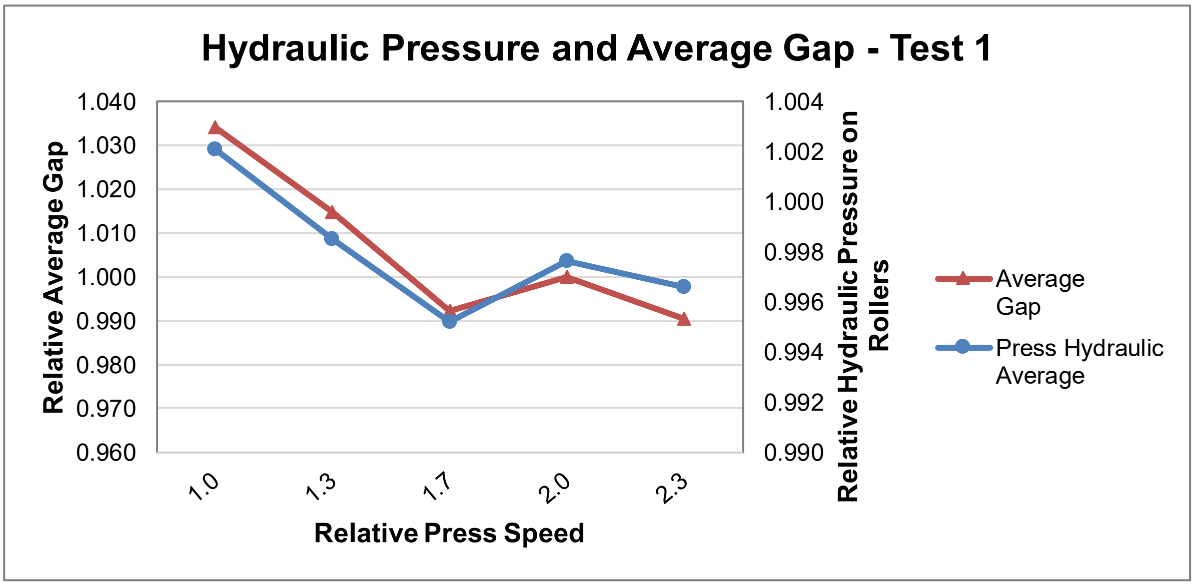


Figure 57: Hydraulic pressure and average gap for Test 1

5.4 Impact of Press Torque

This test is done twice to verify the results from the first test. Six different press torque set points are tested. The procedure is done according to the testing plan.

The sampling for this test gets easier the higher the torque set point is, which means it takes only a few minutes to collect 20 briquettes and there are less and less chips and half briquettes. For this test, machines with low wear are chosen. The operating set points can be seen in Table 15. The briquetting speed should be kept stable throughout the test and the feed leg temperature shouldn't change throughout the test, ideally. However, since tests are done during full production, the feed leg temperature cannot be controlled, and therefore it doesn't keep stable throughout this long test. Moreover, throughout the second test the roller speed had to be increased due to higher production.

Table 15: Overview of operating set points

	Unit	Test 1						Test 2					
Average feed leg temperature	[Deg. F]	1271	1303	1272	1270	1282	1298	1307	1316	1307	1296	1302	1287
Relative press torque set point	[-]	0.95	0.98	1.00	1.03	1.05	1.08	0.95	0.98	1.00	1.03	1.05	1.08
Relative press speed set point	[-]	1.9	1.9	1.9	1.9	1.9	1.9	1.5	1.5	1.5	1.6	1.6	1.6
Relative segment lifetime	[%]	0.83	0.83	0.83	0.83	0.83	0.83	11.6	11.6	11.6	11.6	11.6	11.6

In Figure 58 the boxplot for these tests is shown. As can be seen, again, the distribution is relatively big for most tests. Moreover, especially for the second test (last 6 boxes), the median values rise with increasing relative press torque, while in Test 1 almost all the median values are within a range of 50 kg/m³. Only the last value is significantly higher at about 5240 kg/m³. This boxplot confirms once more the importance of taking 20 briquettes for each test in order to get representative results.

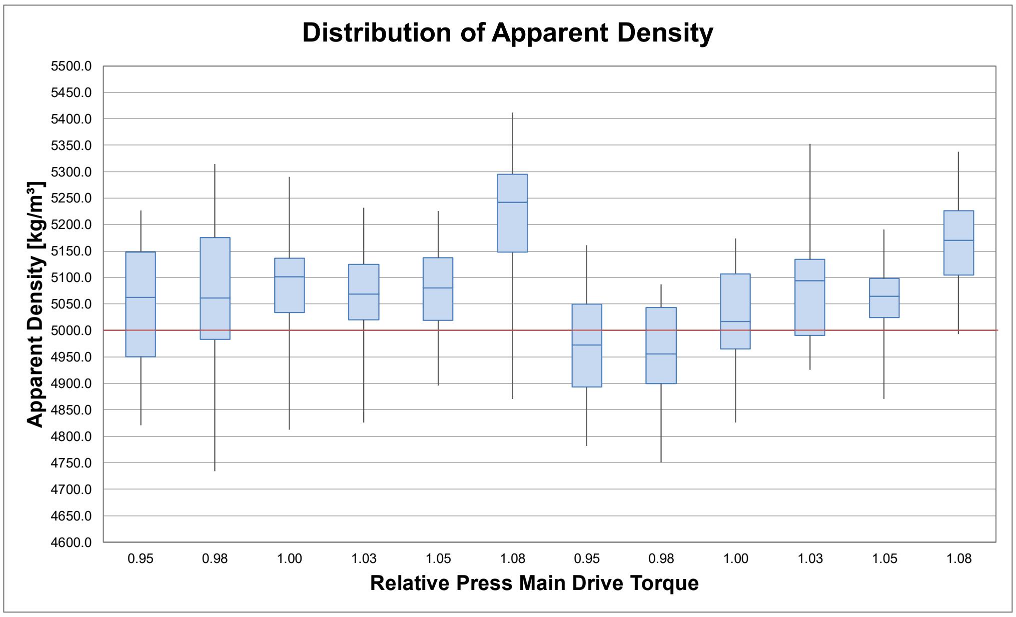


Figure 58: Boxplot - distribution of apparent density for press torque test

Despite the problems described above, there are trends visible. Figure 59 shows the change in apparent density with rising press main drive torque. Especially Test 2 (green rectangular) shows that with increasing press torque an increasing average apparent density can be achieved. Especially at a very high relative press main drive torque for both tests a high density (>5,15 g/cm³) is achieved.

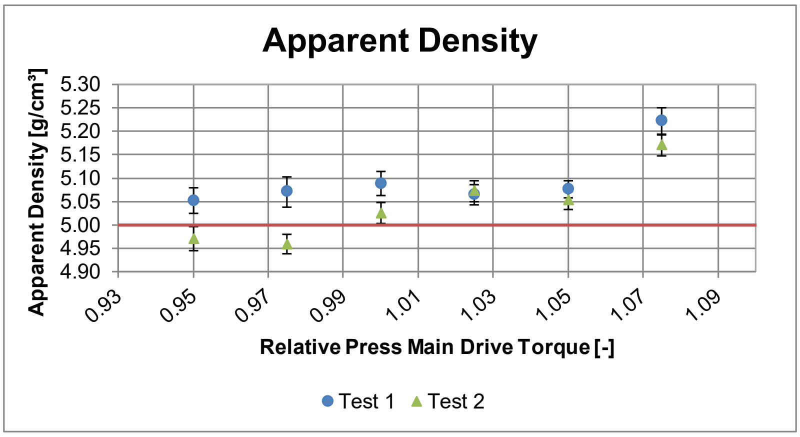


Figure 59: Impact of press main drive torque on apparent density

For shipping regulations, it is important that the apparent density of HBI is above 5 g/cm³. Test 2 shows that at low press torque this goal density cannot be reached. In Figure 60 it can be seen that with increasing torque, more briquettes reach a density of >5.0 g/cm³ and are therefore allowed for shipping.

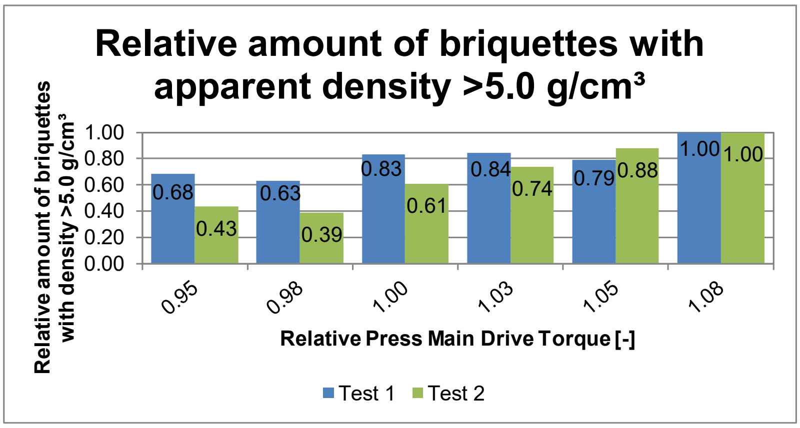


Figure 60: Relative amount of briquettes reaching apparent density >5 g/cm³

Not only the briquette density rises with increasing press torque but also the strength of the briquettes is increasing. The higher the press torque, the smaller the number of broken briquettes (see Figure 61). The breakage of briquettes usually leads to a high chips generation. Figure 62 shows that briquetting at higher press torque positively influences the chips generation and leads to less chips generation for both tests.

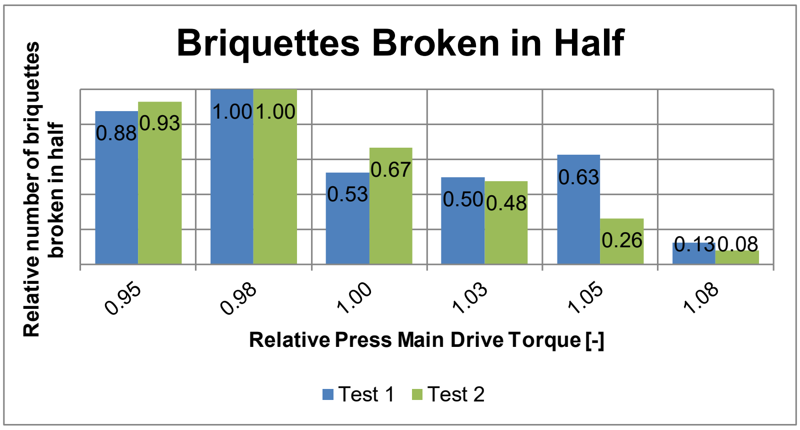


Figure 61: Relative amount of briquettes broken in half during tumble test

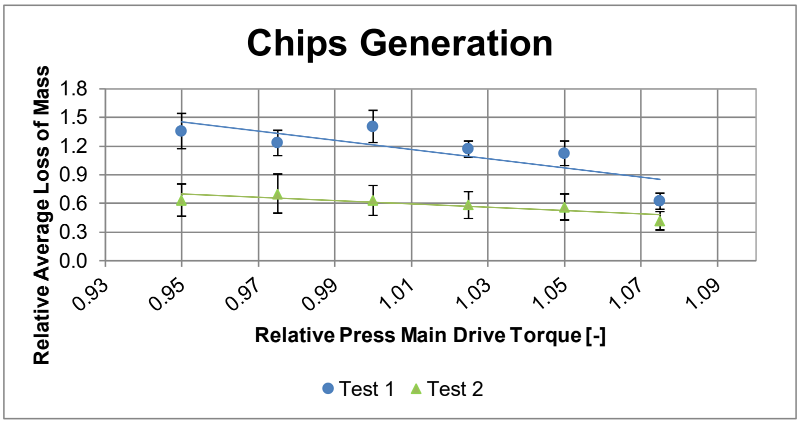


Figure 62: Results of relative chips generation for press torque tests

These results are also reflected in the tumble and abrasion indices. For both tests the tumble index increases with increasing press torque (see Figure 63) which means more particles have a size of +6.3 mm. Moreover, for both tests the abrasion index decreases with increasing press torque. This means less fines (-0.5 mm) are generated during the tumble test. Therefore, the abrasion resistance increases with increasing press torque.

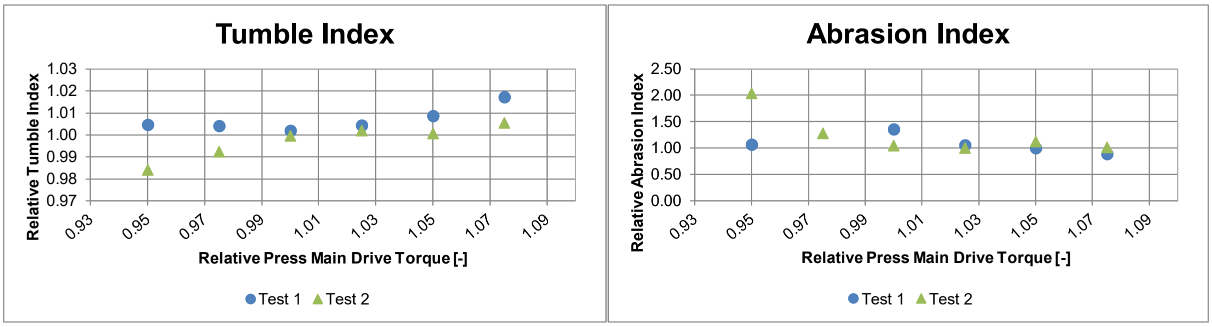


Figure 63: Tumble and Abrasion Index

Figure 64 shows the particle size distribution of Test 2 after the tumble test for six different relative press torque set points. One can see, that with rising torque set point, more particles with a particle size >40 mm are generated, while also less smaller particles are produced.

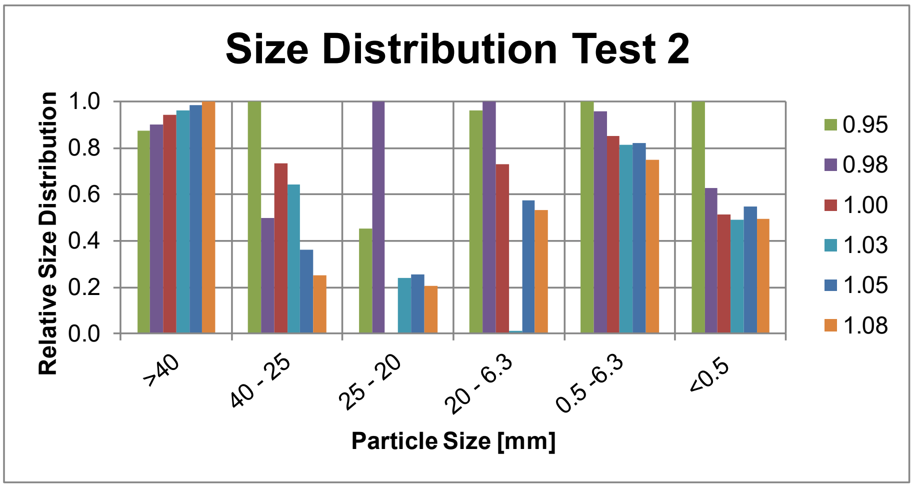


Figure 64: Size distribution of Test 2 after tumble test with relative press torque set points from 0.95 to 1.08

Another result of this test is that a change in press torque leads to a change in the physical properties of the briquettes. With rising torque, the briquette volume as well as the briquette mass increase (see Figure 65 and Figure 66). The average mass in Test 1 increases from 596 g to 637 g (+41 g) with increasing press torque and from 603 g to 653 g for Test 2 (+50 g). In Test 2 the segments used have already more tons processed than in Test 1 which means the form of the molds has probably already changed. As a result, on average, the briquettes from Test 2 are bigger and heavier than those from Test 1.

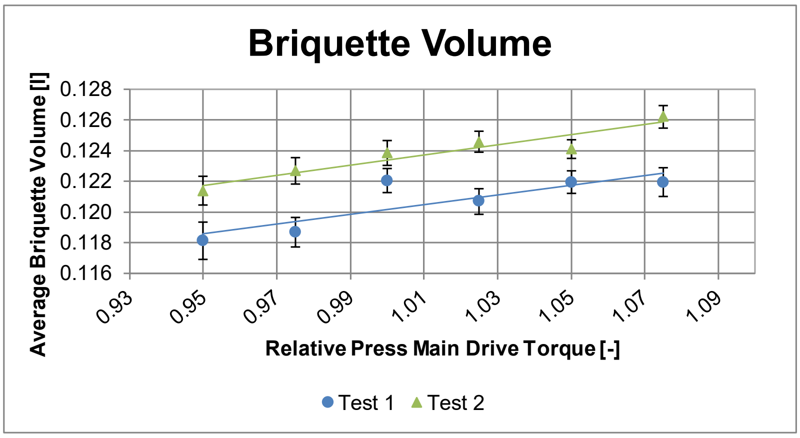


Figure 65: Change in briquette volume with increasing press torque

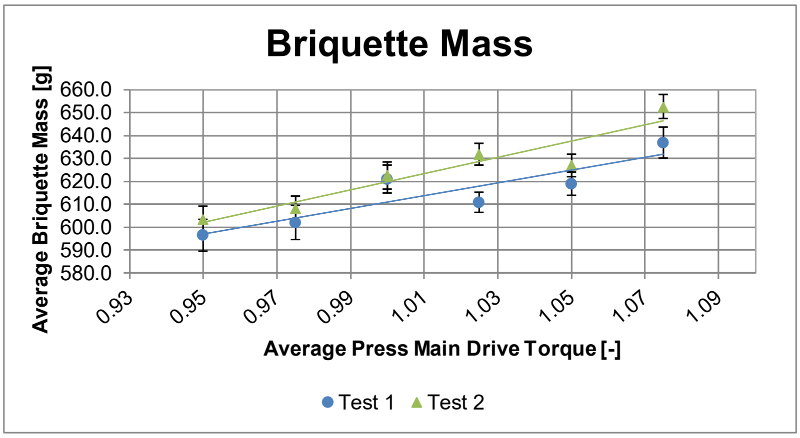


Figure 66: Change in briquette mass with increasing press torque

The secondary goal of this test is to determine the relationship between press parameters. For this test, the torque on the rollers is increased. It can only be increased by an increase in material fed into the press. If more material should be fed into the press, the screw feeder speed has to increase which also entails an increase in the screw feeder torque. This is represented in Figure 67 for Test 1. The screw performance looks similar for both tests.

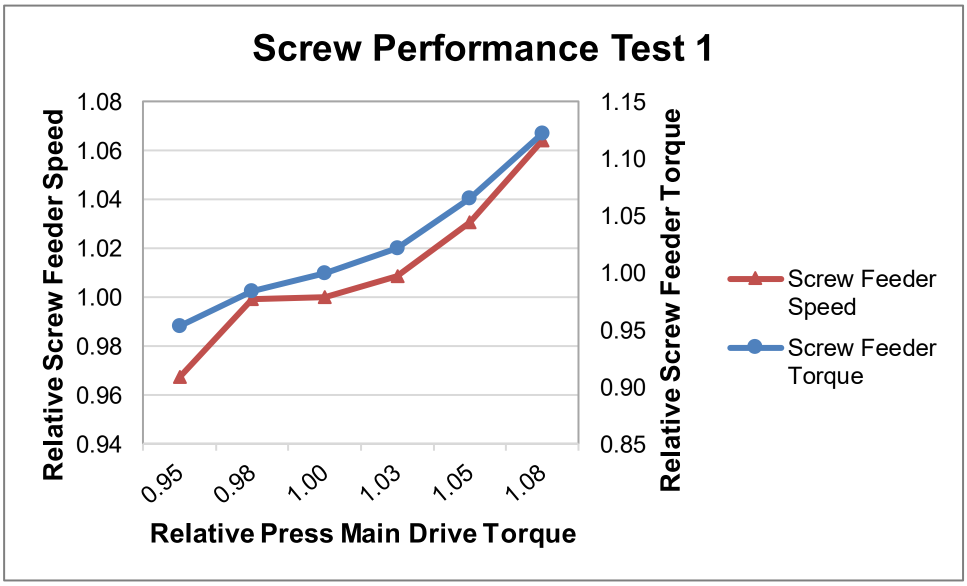


Figure 67: Screw performance Test 1

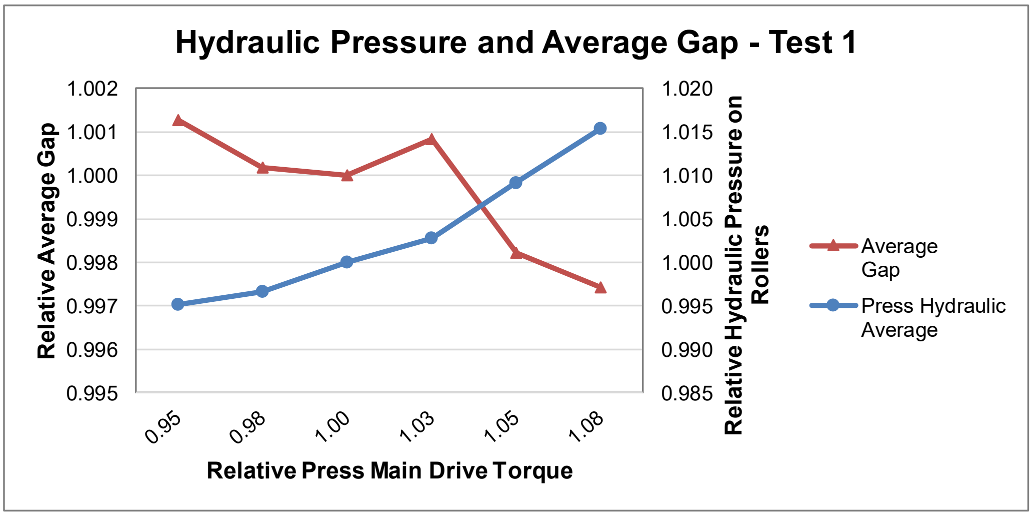


Figure 68: Hydraulic Pressure and Average Gap for Test 1

As already mentioned, an increase in press torque means that more material is fed into the press. As a result, the briquettes get bigger. Since more material is fed into the press, the pressure on the rollers rises. A rising pressure usually results in a closing gap. This can be seen in Figure 68. The relative changes in gap and pressure are very small though and can be neglected. Again, the results for both tests look very similar. For this reason, only one figure is shown in this work.

5.5 Impact of Segment Wear

The impact of wear on briquette quality is tested on four different days. The tests are done according to the plan describe in section 4.3.5. The sampling of these tests is very interesting and big differences can be seen. Sampling takes significantly longer when the roller segments are old. There are many briquettes broken apart or large pieces are broken. Moreover, the shovel with which the samples are taken, is filled with a big amount of chips and fines. While sampling usually takes about 3 minutes, for machines with wear it can take up to 10 minutes to get 20 full briquettes.

For this test, it is important to keep the process parameters as similar as possible. Especially the press torque, press speed and feed leg temperature should be as close as possible. The operating conditions for the four tests can be seen in Table 16.

Table 16: Overview set points and operating conditions for the four tests

	Unit	Test 1		Test 2		Test 3		Test 4	
		machine F	machine G	machine E	machine F	machine E	machine F	machine B	machine F
Average feed leg temperature	[Deg. F]	1296	1300	1295	1293	1285	1281	1304	1303
Relative press torque set point	[-]	1.05	1.05	1.00	1.00	1.00	1.00	1.00	1.00
Relative press speed set point	[-]	1.1	1.2	1.8	1.7	1.7	1.7	1.7	1.7
Relative segment lifetime	[%]	2.0	79.8	89.9	8.2	99.7	14.6	86.2	21.0

As can be seen in the table above, the operating conditions for each test individually are very close. However, for a comparison of the results of the different tests, like it is done in section 4.3.2 for the impact of feed leg temperature, some parameters differ greatly. Especially the feed leg temperature is in one test at 1280 °F while in another test it is above 1300 °F. The feed leg temperature cannot be controlled and is given from the process. Therefore, the tests have been done despite the great differences in temperature. In paragraph 4.3.2 it is shown that the impact of the feed leg temperature on the briquette quality is enormous, which makes it difficult to compare the results of this test.

Figure 69 shows the boxplot for the tests. As can be seen, the median values vary greatly for the tests. Moreover, there is also no clear trend concerning the maximum or minimum values visible. For some tests, the boxes are very large which means that they are greatly distributed.

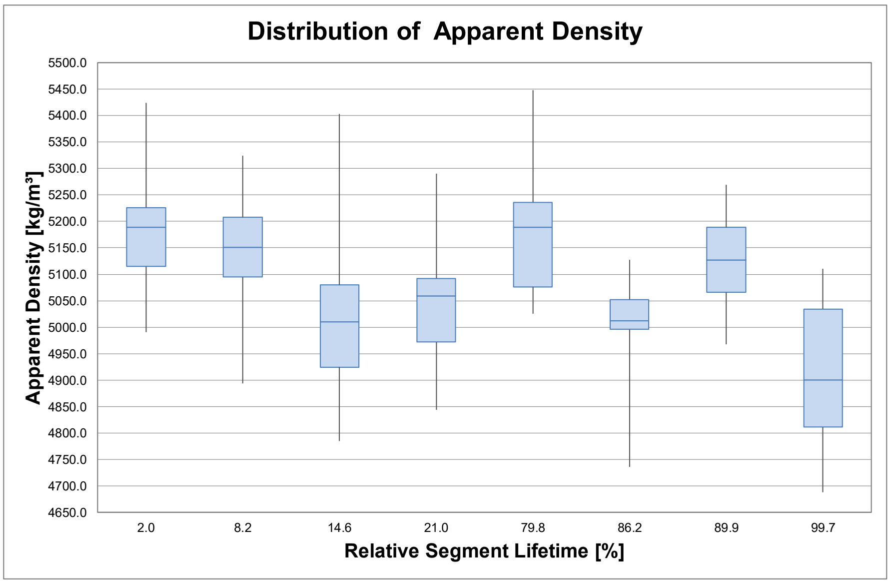


Figure 69: Boxplot - distribution of apparent density for segment wear tests

The results of the segment wear are shown in Table 17. As can be seen, if you compare the results of each test separately, the apparent densities tend to be higher of briquettes taken from machines with no wear. However, the difference is not significant. The impact of wear on the physical properties of the briquettes is clear, though. The shapes of the molds change, they get deeper. As a result, the briquettes are heavier, bigger and thicker. The biggest difference in mass can be seen for Test 3: In average, the briquettes from the worn-out machine have +113.5 g more than those from segments without wear.

Table 17: Results for impact of segment wear on briquette quality and physical properties

		Test 1		Test 2		Test 3		Test 4	
Relative Segment Lifetime	[%]	2.0	79.8	8.2	89.9	14.6	99.7	21.0	86.2
Apparent Density	[g/cm³]	5.18	5.18	5.14	5.13	5.01	4.92	5.05	5.01
Mass	[g]	649.7	709.9	614.2	632.1	593.4	706.9	616.5	660.0
Thickness	[mm]	34.4	36.2	34.1	34.7	33.9	37.8	34.3	35.4
Volume	[l]	0.125	0.137	0.119	0.123	0.118	0.144	0.122	0.132

As Figure 70 shows, there is no clear trend for the impact of the segment wear on the apparent density. A fraction of tests with no or low wear also results in very low product densities while contrary, some tests with lots of wear may result in high densities.

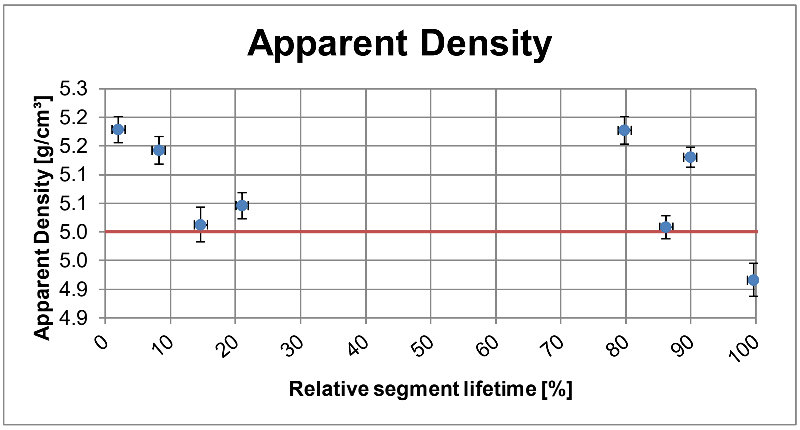


Figure 70: Results of impact of wear tests on apparent density

There are also no clear trends concerning chips generation and strength of briquettes. Figure 71 shows the results of the tumble test. There is no correlation between chips generation during the tumble test and segment wear. However, as already mentioned, there are significantly more chips generated directly at the briquetting machines.

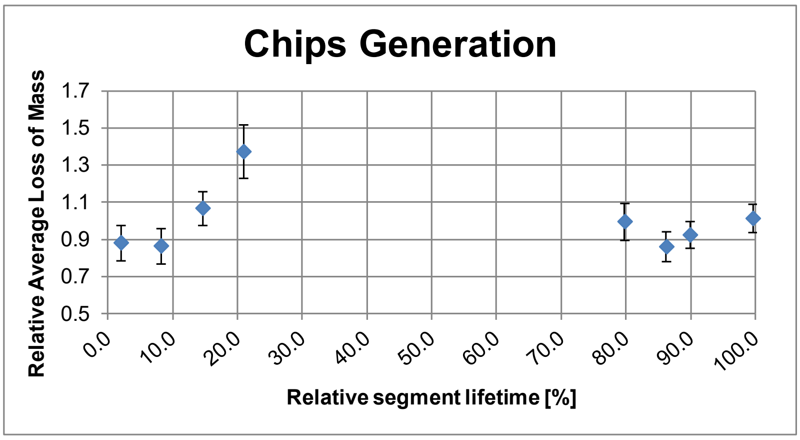


Figure 71: Results of relative chips generation for segment wear tests

The strength of the briquettes is also not linked to the wear of the segments. Neither the abrasion index, nor the tumble index show a clear trend. Moreover, Figure 72 shows the percentage of briquettes broken in half during the tumble test. Up to about 21.0 % of the lifetime, there is a nice trend: with increasing segment wear, more briquettes break apart during the tumble test. However, those briquettes briquetted with lots of segment wear did not break apart at all, which means, once the worn-out machine builds full briquettes, they are very strong and resistant.

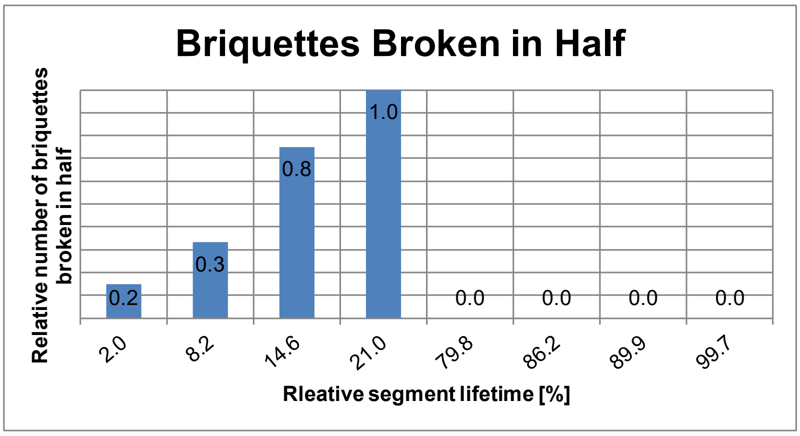


Figure 72: Relative amount of briquettes broken in half during tumble test

As already mentioned, the physical properties change greatly with increasing segment wear. The briquettes get thicker, bigger and heavier. The results for the briquette mass are shown in Figure 73. As can be seen, in average the briquettes have an increase in mass with increasing segment wear.

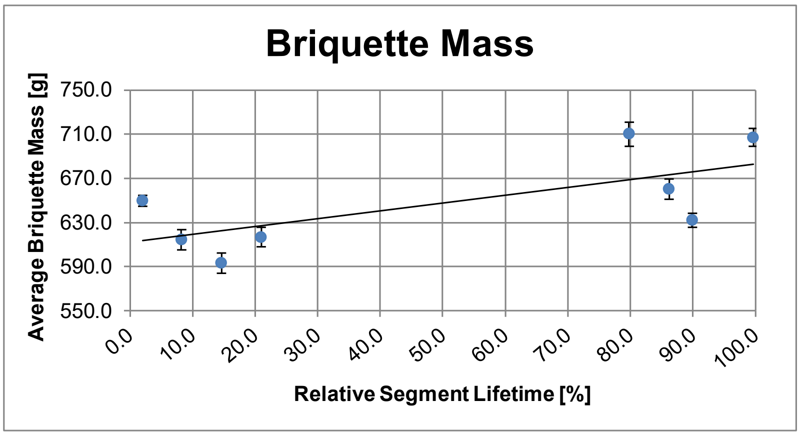


Figure 73: Results for briquette mass for increasing segment wear

The visual appearance of the briquette also changes with increasing wear. The briquettes get a different shape, the webbing is thicker, and the breakage goes through the briquettes, which means they are opened on one side (see Figure 74). The outline of the briquette is round, the surface gets rills. Moreover, the landing area around the briquette changes. From the wear, the molds get sharp, this is also reflected on the briquette.

Figure 74: Briquette showing typical signs of segment wear

Moreover, the briquette thickness changes over the three measurement points due to irregular segment wear (see Figure 75).

Figure 75: Changes of thickness of briquette due to segment wear

6 Discussion

The first test conducted for this thesis is to test the impact of the cooling method. As shown in section 5.1, the cooling method has a big impact on the chips generation of the briquettes after the tumble test. Air-cooling is gentler than water quenching and the briquettes are stronger, therefore significantly less chips are generated during the tumble test. A high chips generation should be avoided. Chips have a bigger surface area than full briquettes. As a result, reoxidation takes place faster and the product quality decreases. At the plant in Corpus Christi, the briquettes are cooled by water spraying. This method is described in paragraph 3.2.3.1.5. Cooling with water mist is not as harmful to the briquettes as water quench, but it is also not as gentle as air cooling. Air cooling however would need very long cooling conveyors, which are very hard to realize for a production volume of 2 million tonnes HBI per year.

According to the literature review, the feed leg temperature has a big impact on the apparent density of HBI briquettes. This is also proven by the tests conducted. The higher the feed leg temperature, the higher the average apparent densities when compressed at constant press torque. Especially Figure 43 shows the linear correlation between $\Delta_{\text{apparent density}}$ and $\Delta_{\text{feed leg temperature}}$. As a result of the tests it is shown, that below 1270 °F, the average apparent density of the briquettes is below 5.0 g/cm³, which states the lower limit requirement for shipping. The feed leg temperature cannot be controlled though. It is a result of the process parameters. Blockages inside the furnace and inside the feed legs can influence the feed leg temperature and should therefore be removed during maintenance work. It is also shown in the results, that the percentage of briquettes with an apparent density >5.0 g/cm³ increases with increasing feed leg temperature. In the literature review it is found that the abrasion resistance of HBI briquettes increases with increasing feed leg temperature. This information is verified by the tests conducted. The tumble index increases while the abrasion index decrease. Moreover, the percentage of briquettes breaking during the tumble test decreases with increasing feed leg temperature. As already mentioned, chips and fines negatively impact the economic feasibility of HBI briquettes and should therefore be avoided. With feed leg temperatures above 1280 °F, 50 % less briquettes break apart compared to a feed leg temperature of 1242 °F. Therefore, the higher the feed leg temperature, the better for briquetting. A temperature below 1270 °F is not recommended for two reasons: the median values for apparent density lie below the required 5.0 g/cm³ and the strength of the briquettes is getting low. As already mentioned, the material handling for HBI briquettes with several transshipping steps is rough and it is essential that the briquettes are strong enough and do not break apart.

In the literature review it is found, that a good quality briquette requires enough time for briquetting. A higher roller speed means less time for briquetting. As a result, the briquette quality should decrease with increasing roller speed. This is only partly proven by the tests conducted, though. There is no clear correlation between the roller speed and the average apparent density found. Two tests are done to find the impact of the roller speed. The results show that Test 1, which is done at a slightly higher relative press torque but lower feed leg temperatures than Test 2, has in average lower apparent densities. One possibility is, that the impact of the feed leg temperature is bigger than the one of the roller torque. This proves once more the importance of a sufficiently high leg temperature. As a result of this test it is shown that the roller speed can be high, therefore the production rate can be high and the target apparent density of 5 g/cm³ can still be achieved without problems. Nevertheless, it is also found that rising press speed negatively impacts the chips generation: with increasing press speed, the chips generation increases, and more briquettes break apart during the tumble test. An increase in roller speed has definitely an impact on the physical properties of the briquettes. Since the press should never run out of material, the screw speed has to increase in order to keep up with the rising roller speed. This trend is also shown in Figure 55 and Figure 56. However, the tests show that the screw does not deliver enough material into the roller press and the briquettes get lighter, smaller and thinner. The briquette mass decreases significantly with increasing roller speed. This means that the efficiency of the system decreases: more energy is needed to compress the same amount of material. As a result, it is recommended to improve the adjustment of the screw feeder in order to run more economically.

With increasing press torque, the density of the briquettes should increase, according to the literature review. The pressure on the rollers itself is set and cannot be adjusted easily. It can only be adjusted during total shutdown of the press. The impact of different pressures on the rollers is not tested during this work. However, the impact of the roller torque is tested. It is found that with increasing roller torque, higher apparent densities can be achieved. This test is done twice, while at Test 1 the feed leg temperature is in average lower and the relative press speed is in average higher than for Test 2. Nevertheless, in average, the densities in Test 1 are, even for very low press torques, already above 5.0 g/cm³. In Test 2, the target density is reached at a relative press torque of 1.0. Moreover, with increasing press torque, a higher percentage of briquettes reaches the target density of 5 g/cm³. A recommendation for the relative press torque is at least 1.0, because then for both tests more than 55 % of the briquettes reach the target density. The briquette strength is also positively impacted by a rising press torque: it decreases significantly. In Test 1 the chips generation without the broken briquettes decreases in general more than 55 % from a relative press torque of 0.95 to a relative press torque of 1.08. Test 2 shows similar results: A general reduction in chips generation with more than 65 % can be achieved by increasing the relative press torque from 0.95 to 1.08. The tumble index as well as the abrasion index support this statement. Tumble index increases with increasing press torque and abrasion index decreases. The higher the press torque, the higher the achieved densities. However, it has to be kept in mind that the customer does not pay more for denser products. High press torque means high energy consumption. For this reason, a density above 5.1 g/cm³ is not recommended, reached both times with a relative press torque of 1.08, though. It is recommended to run the machines, provided the feed leg temperature is high enough, at a relative press torque of 1.0 – 1.03. At these press torque setpoints, the average apparent density is high enough for both tests, and the strength of the briquettes is satisfactory too. The press torque not only has an impact on the apparent density and on the strength of the briquettes but also influences the physical properties. With increasing press torque, the volume, mass and thickness of the briquettes increases. A higher press torque can only be reached if the screw feeder speed increases too and more material is fed into the press. In this case, opposite to the roller speed test, the screw seems to feed too much material into the press and the briquettes get thicker. The increasing torque as well as the higher pressure on the rollers due to the increase in material leads to higher stresses on the gear (rollers as well as screw feeder) and should therefore be avoided.

The impact of the segment wear is also clearly described in the literature. The shape of the molds changes and the webbing gets thicker. The webbing, however, is the densest part of a briquette and therefore breakages through the briquette are more likely with higher segment wear, which results in an increase in chips generation. These changing forms of the briquettes, the changes in mass, volume and thickness are also seen in the tests conducted. There is no correlation found between apparent density and segment wear. The results show also no trend for a higher chips generation during the tumble test. It has to be kept in mind, though, that the literature talks about higher chips generation directly at the separator. During sampling, an increase of chips generation is found, and the sampling takes significantly longer. Since there is no scale at the screen or at the bucket elevator, it is hard to make any statement about the real chips generation within the press. Higher recycling rate negatively impacts the economic feasibility of the plant because a part of the material gets twice the energy. Moreover, as seen in the literature review, the size distribution of the particles also has an impact on the apparent density: with smaller particles it is harder to reach a certain density. For all tests, the fines recycling is turned on. Exact numbers about the amount of fines recycled are not available, though. In the tests it is found that those briquettes leaving the press as full briquettes, are very strong and do not break apart during the tumble test. As mentioned, during sampling, significantly more chips are found which means reoxidation of the chips and therefore a loss in quality will take place. New segments are costly and therefore the segments should be run as long as possible. However, predicting the ideal time to change the segments cannot be done from the tests conducted for this thesis.

Despite the fact that there are several factors that cannot be influenced for the tests and that are not ideal for the tests (feed mix, feed leg temperature, chemistry of briquettes with metallization and carbon content), there are some trends found. Nevertheless, the results are more or less like a “screenshot” of the plant, taken on a certain day, with a certain feed mix, at certain operating conditions. In order to get a full understanding of the correlations and therefore to find out the ideal operating set points, much more testing is necessary. The test for feed leg temperature for example is done at a certain roller torque set point and a certain roller speed set point. These parameters could be changed, and more tests should be done. Results of these tests might show the influence power of press torque vs feed leg temperature. A higher press torque could make up for low feed leg temperatures and the target density of 5 g/cm³ might still be achieved.

Other tests that would be interesting concern the product cooling. The amount of water for the mist cooling can be adjusted at the plant in Corpus Christi. Therefore, running a test with less water spraying in the first third of the cooling conveyor and intense spraying towards the end of the belt could be of high interest. This would give the briquettes more time to cool down gently.

According to the literature review, the initial gap also has an impact on the briquette quality, because the maximum applied pressure is dependent on the initial gap. There could also be a test done. One could take two machines with new segments and set different initial gaps. Not only the product quality of the briquettes could be analyzed but also the segment wear could be tracked. Requirements for the tests are that both machines have the same operating conditions (press torque, press speed and feed leg temperature). With these tests a better understanding of the correlation between briquette quality and initial gap/ segment wear could be gained.

To track the influence of the separator speed could also be of interest. The goal would be to determine the impact of the separator speed on the chips generation and on the breaking behavior of the briquette string. Therefore, a machine should run at steady process conditions and normal operating conditions. Different separator speed set points should be run. Videos should be taken of the separator itself to analyze the breaking of the string as well as of the screen, to count the number of double briquettes. With this, the optimal set point for the separator speed could be found and maybe a minimization of chips generation within the press can be achieved.

In these tests, the influence of the origin of the feed material is not considered. Nevertheless, it would be important to plan and conduct tests for this influencing factor as well. Besides reducibility and metallization, briquette strength is an important factor determining quality. Therefore, further plant tests should also focus on the different types of pellets and their briquetting quality.

Another factor that is not considered is the chemical composition of the briquette. Metallization and carbon content are the two most important ones. However, since these parameters are highly dependent on the process conditions run within the furnace, no testing is done within the framework of this thesis. Nevertheless, the literature review shows that there is a certain influence of metallization and carbon content on the briquetting quality.

The segment wear should also be further tested. Since this test should be a long-term test it was not possible to conduct this test during the stay at the plant in Texas. The segments are a high cost factor for the briquetting press and, as already mentioned several times, the higher the number of processed tonnes per segments, the better. One example for a test could be to keep two machines at different operating conditions for several months. This means that the press speed is the same on both machines while the press torque is different, for example. Then the wear could be regularly measured, and a profile could be made. With this test a better understanding could be gained about where the most wear occurs, at which tonnage and how the shapes of the briquettes change. However, it has to be kept in mind, that the feed material changes throughout the testing time as well as the feed leg temperature and therefore it will be difficult to determine the most important influencing factor.

Another result of these tests is that the sampling at the plant has to be rethought. The distribution of the apparent densities is extremely wide for the 20 briquette samples taken. Currently, about six briquettes are taken for the daily briquette analysis in the laboratory. This small amount can significantly influence the results of the measurements, as it is seen in the tests conducted.

7 Summary and Conclusion

The objective of this thesis is to relate briquetting machine parameters to their impact on briquetting quality. In order to achieve this goal, a testing plan was developed together with the voestalpine Texas LLC plant operations group. Five different types of tests were planned and successfully conducted.

As a first step, a literature research was done. The DRI process with its three main products HDRI, CDRI and HBI was described and the use of DRI in steelmaking was outlined. Moreover, the agglomeration by compression was explained. A difference was made between compaction in smooth roller presses and in roller presses with molds. The two different types of briquetting were described with a focus on hot briquetting. The typical equipment for hot briquetting was listed and the influencing factors for briquetting product quality were characterized. As a final step, tests to evaluate the physical quality of briquettes were presented.

With the results from the literature review as well as from the tests, the research questions can be sufficiently and adequately answered.

- Which factors affect the briquetting apparent density?

It was found that the origin of the feed material has an impact on the apparent density. Moreover, several process conditions have an impact. The feed leg temperature influences the apparent density due to decreasing yield strength of pure iron with rising temperature as well. Another influencing factor is the carbon content. The presence of hard particles like iron carbides negatively impacts the compressibility. The metallization also has an impact on the apparent density. With high metallization, a certain apparent density can be reached easier due to the low compression strength of pure iron compared to its oxides. The size distribution of the material also impacts the apparent density. Small particles ≤3 mm are harder to compress than bigger ones. Not only process conditions influence the product quality, but also the operating parameters of the machinery have an impact. A high velocity of the rollers negatively impacts the apparent density. The screw feeder plays an important role. It feeds the material into the press while pre-compacting it. A high roller torque is favorable for high apparent density while a high initial gap negatively impacts the product quality. Segment wear also impacts the product quality negatively due to a change in the geometry of the molds.

- How do different machine parameters influence the briquetting quality concerning chips generation?

The cooling method had a big impact on the chips generation. Water quenching led to about +6 % in chips generation compared to air cooling. The feed leg temperature influenced the chips generation too. With increasing feed leg temperature, the abrasion index decreased, and the tumble index increased. The roller speed also impacted the chips generation. With increasing roller speed, the amount of chips generated during the tumble test also increased. With increasing roller torque, the chips generation decreased. Moreover, the tumble index increased, and the abrasion index decreased. Another important influencing factor was the segment wear. During sampling, significantly more chips were seen, and it was difficult to get full briquettes. However, the full briquettes analyzed in the laboratory did not show any correlation between segment wear and chips generation.

- What are ideal operating conditions to achieve a high product quality?

According to the test results, one of the most important influencing factors is the feed leg temperature. However, the feed leg temperature cannot be directly controlled. Nevertheless, as a result of the tests conducted, it is recommended to briquette above 1280 °F in order to achieve a satisfactory product quality. A relative press torque of 1.0 – 1.03 is recommended, provided the feed leg temperature is high enough. At these press torque setpoints, the average apparent density was high enough and the strength of the briquettes was good. There was no correlation found between roller speed and apparent density. Therefore, no suggestions can be made for the roller speed setpoint.

- Do results from the literature research correlate with the results gained from testing on the plant?

According to the literature review, the feed leg temperature has a positive impact on the compressibility as well as on the abrasion resistance. This correlates with the results gained from the tests. Moreover, it says in the literature that high roller speed negatively impacts the product quality. The tests did not show any correlation between the roller speed and the apparent density. There was a correlation between chips generation and briquette strength, though. With rising roller speed, the briquette strength decreased, and more chips were generated. The literature review revealed that the press torque positively impacts the briquette quality. This was also found by the tests. Higher press torque resulted in higher apparent density as well as higher briquette strength. Moreover, the tumble index decreased, and the abrasion index increased. According to the literature review, segment wear results in changed mold forms and briquette forms. This could also be seen during testing. The webbing around the briquette got thicker due to wear. According to the literature, the webbing is the densest part of the briquette and therefore with an increase in webbing it is more likely that the breakage goes through the briquette and lots of chips are generated. During testing, this was clearly seen while sampling as well as on the full briquettes.

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8.2 Index of Abbreviations

HBI	Hot briquetted iron
DRI	Direct reduced iron
Mt	Million tons
CO_2	Carbon dioxide
GHG	Greenhouse gas
EAF	Electric arc furnace
BF	Blast furnace
CDRI	Cold DRI
HDRI	Hot DRI
Fe	Iron
P	Phosphor
S	Sulfur
Mn	Manganese
Cu	Copper
Ni	Nickel
Cr	Chromium
Mo	Molybdenum
Sn	Tin
Pb	Lead
Zn	Zink
FeO	Wüstite
wt%	Weight percent
CO	Carbon monoxide
RD	Reduction degree
O	Oxygen
BOF	Blast oxygen furnace
e.g.	Exempli gratia
H_2O	Water
H_2	Hydrogen
Fe_2O_3	Iron(III)oxide
ΔH	Standard enthalpy
SiO_2	Silicon dioxide
Al_2O_3	Aluminum oxide
COG	Coke oven gas
CH_4	Methane
N_2	Nitrogen
Fe_2O_3	Magnetite
etc.	Et cetera
vs.	Versus

Fe_3C	Cementite
ρ_a	Apparent density
TI	Tumble index
AI	Abrasion index
XRD	X-ray diffraction
XRF	X-ray fluorescence

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