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Chromite Ores Briquetting and H_2 Pre-Reduction for Sustainable Ferrochrome

Jana Elragal

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Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm

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Jana Elragal

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Supervisor: Joakim Mansfeld
External supervisor: Elsayed Mousa, Swerim AB
Examiner: Iain Pitcairn
Assessor:
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Abstract

Ferrochromium (FeCr) alloy is a critical material in stainless steel production and other specialty steels. As its production becomes increasingly important and scaled up, there is an urgent need to find sustainable methods that do not contribute to the growing carbon footprint. One potential solution is using biocarbon as a partial replacement for coke. Additionally, maximizing the recycling of iron-bearing materials, such as mill scale, and utilizing hydrogen (H_2) as a reducing agent for reducing iron oxides can help decrease carbon consumption and mitigate fossil CO_2 emissions. Furthermore, exploring the potential for the partial reduction of chromite ores may also contribute to these sustainability efforts.

In this study, a recipe was developed using chromite ore ($FeCr_2O_4$), mill scale (FeO), biocarbon (C), and binders. The composition of this recipe consisted of 39% chromite ore, 30% mill scale, 20% biocarbon, and 10% binder/additives. The reduction process was conducted on a representative sample using thermogravimetric analysis coupled with quadrupole mass spectroscopy (TGA-QMS) at a maximum temperature of 1100°C, with a gas mixture of 90% H_2 and 10% Ar. The results indicated that H_2 effectively reduces mill scale (mainly composed of FeO) at temperatures between 600°C and 750°C, while biocarbon facilitates the reduction of chromite ore ($FeCr_2O_4$) at temperatures above 850°C. Further research is, however, needed to investigate the reduction mechanisms and evaluate the potential of H_2 reduction and the developed phases.

Keywords

Ferrochromium, biocarbon, hydrogen, reduction, chromite ore, mill scale, CO_2 emissions, sustainability.

Sammanfattning

Ferrokrom (FeCr) legering är ett kritiskt material vid produktion av rostfritt stål och andra specialstål. När dess produktion blir allt viktigare och ökar i skala, finns det ett brådskande behov av att hitta hållbara metoder som inte bidrar till det växande koldioxidavtrycket. En potentiell lösning är användningen av biokol som en delvis ersättning för koks.

Dessutom kan maximering av återvinningen av järnhaltiga material, såsom kvarnskala, och användning av väte (H_2) som ett reduktionsmedel för att reducera järnoxider bidra till att minska kolförbrukningen och minska fossila CO_2-utsläpp. Att utforska potentialen för en partiell minskning av kromitmalmer kan också bidra till dessa hållbarhetsansträngningar.

I denna studie utvecklades ett recept med användning av kromitmalm ($FeCr_2O_4$), glödskal (FeO), biokol (C) och bindemedel. Sammansättningen av detta recept bestod av 39% kromitmalm, 30% glödskal, 20% biokol och 10% bindemedel/tillsatser. Reduktionsprocessen genomfördes på ett representativt prov med Termogravimetrisk Analys i kombination med Kvadrupol Masspektroskopi (TGA-QMS) vid en maximal temperatur på 1100°C, med en gasblandning av 90% H_2 och 10% Ar. Resultaten indikerade att H_2 effektivt reducerar glödskal (FeO) vid temperaturer mellan 600°C och 750°C, medan biokol underlättar reduktionen av kromitmalm ($FeCr_2O_4$) vid temperaturer över 850°C. Ytterligare forskning behövs dock för att undersöka reduktionsmekanismerna och utvärdera potentialen för H_2-reduktion och de utvecklade faserna.

Nyckelord

Ferrokrom, biokol, väte, reduktion, kromitmalm, glödskal, CO_2-utsläpp, hållbar.

Contents

Abbreviations

FEMOST	**Sustainable Ferroalloys for the Modern Steel Industry**
CAGR	Compound Annual Growth Rate
FeCr	Ferrochromium
SAF	Submerged Arc Furnace
TI	Tumbler Index
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
CCS	Cold Compression Strength
STS	Splitting Tensile Strength
PSD	Particle Size Distribution
TGA	Thermogravimetric Analysis
QMS	Quadrupole Mass Spectroscopy
RP	Roller Press
VP	Vibro Press
Wt. %	Weight Percentage
atm	Atmospheric Pressure

1 Introduction

1.1 Background

Ferroalloys are iron-based alloys that contain one or more elements in greater proportions than carbon (C), such as chromium (Cr), vanadium (V), nickel (Ni), titanium (Ti), and manganese (Mn). These elements play a crucial role in metallurgical processes. Among the various types of ferroalloys, this work specifically focuses on ferrochromium (FeCr) due to its significant impact on enhancing the properties of steel for various applications. FeCr is categorized based on the C content and is classified as high-carbon ferrochrome (HC FeCr), which contains 6-8% C; medium-carbon ferrochrome (MC FeCr), with 0.5-4% C; and low-carbon ferrochrome (LC FeCr), which has less than 0.5% C.

FeCr is essential for many modern industrial applications. The production of FeCr involves several intricate procedures, each affecting the final product's effectiveness, quality, and environmental impact. Chromite ore serves as a source of chromium. Since chromium and iron exist in their oxidized forms in chromite, adding a reducing agent is necessary; typically, coke is employed, leading to the emission of fossil CO_2 and posing a significant threat to the sustainability of this critical industry. Consequently, there is growing interest in alternative reduction agents that can mitigate these environmental effects while maintaining or enhancing production efficiency and product quality as global enterprises prioritize sustainability and strive to reduce their carbon footprints. Biocarbon and hydrogen (H_2) are promising substitutes for coke, as they could enable a potentially carbon-neutral process and reduce fossil CO_2 emissions. This study focuses on developing biocarbon-chromite briquettes and examines the potential of using H_2 as a reducing agent for the created briquettes. The objective is to contribute to the growing body of knowledge aimed at making FeCr manufacturing more environmentally friendly and aligned with the global trend towards increased production of FeCr. The study begins with a literature review to better understand the existing research. It also provides information about the various raw materials utilized, their compositions, the furnace, and the expected products. Next, the approach is explained, including the recipes' design, agglomeration process, evaluation of mechanical properties, and investigation of the reduction behavior with H_2. The findings are presented in the results section. After discussing potential arguments, the last section provides a summary and conclusion.

1.2 Literature Review

FeCr alloy is a vital component used in specialized steel production, which is widely used in advanced industries. Nearly 80% of the FeCr produced globally is used in stainless steel production, particularly stainless steel, with a Cr content of 10-20% (Erik, 2014). Stainless steel is widely used in nearly all end industries (Sommerfeld, Botinha, and Friedrich, 2024) and is also the largest consumer of FeCr. In 2023, approximately 58.4 million tons of stainless steel were produced (GMK Center, 2024). FeCr contributes to the hardness and luster of steel and enhances its wear resistance (Du Preez *et al.*, 2023). In 2022, around 35 million tons of stainless steel were produced in China alone, accounting for over 60% of the world's total production (Wu *et al.*, 2024).

In 2023, the worldwide market size of ferrochrome was valued at US$ 18.9 billion (Ferrochrome Market Outlook, 2023). Meanwhile, the global ferroalloys market

reached 53.4 billion USD (Ferroalloys Market Size, 2023). Furthermore, according to Wu et al. (2024), China imported 14.96 million tons of chromite in 2022. South Africa is China's primary exporter of chromite, creating a concentrated source of imports with unstable supply chains. It is estimated that 0.65% of total industrial CO_2 emissions result from the use of fossil-reducing agents in the ferroalloy industry (Sommerfeld, Botinha, and Friedrich, 2024). Consequently, enhancing industrial efficiency and reducing carbon emissions are now pressing problems that need to be addressed.

1.2.1 Production of FeCr using SAF

Producing FeCr primarily involves high-temperature carbothermic reduction. Coke converts chromite, an oxide of Cr and Fe, to form the iron-chromium alloy. A submerged arc furnace (SAF) is used to produce FeCr. SAFs are specialized heating systems that employ electrical power to create various ferroalloys. Electrodes are embedded in the furnace charge, which is fed from the top and consists of ores, fluxes, and coke.

The resistive heating of the furnace charge, which integrates into the electric circuit, provides the necessary energy (Lee, 2001). These are utilized in large-capacity furnaces. According to Lee (2001), transformers deliver the low secondary voltages and high secondary currents required for a SAF to produce ferroalloys. The electrical characteristics of the smelting furnace are essential to its construction and functionality. The operational resistance is a critical metric that relies on the charge's specific resistance. The ferroalloys industry refers to this as the K factor. The peripheral resistance, defined as $K=\pi DR$ where D represents the electrode diameter and R denotes the resistance, proves to be the same for smelting furnaces operating with similar raw materials (Lee, 2001).

Several benefits of the SAF include high process efficiency and safe maintenance. Given that the SAF's smelting process demands considerable energy, energy consumption constitutes a significant portion of the overall manufacturing cost. The SAF excels in producing ferroalloys, particularly in temperature control and its ability to adapt to varying reduction potentials. SAFs are utilized for pyrometallurgical smelting, which accounts for most ferroalloy production. They are categorized into closed, semi-closed, and open.

Typically, closed direct current (DC) arc furnaces and semi-closed or closed submerged arc furnaces (SAFs) are employed for chromite smelting. This process begins with an optional solid-state pre-reduction procedure (Sommerfeld, Botinha, and Friedrich, 2024). The energy consumption of a given furnace is influenced by various factors, including the applied technology, the grades of ores, the grades of coke, material preparations, ore pre-heating, and pre-reduction. A closed SAF that operates with hot-fed pre-reduced chromite can utilize as little as 2000 kWh per ton of FeCr produced, while a semi-closed SAF using unscreened feed materials can consume as much as 4500 kWh/t FeCr produced (Davies *et al.*, 2022). **Figure 1** illustrates the schematics of FeCr smelting in the SAF, detailing the necessary raw materials and temperatures.

Types of SAFs:

- **Closed SAF:** Strict control over chemical composition is essential due to the enclosed furnace design, which prevents contaminants from entering and disrupting the smelting process. To maintain the reducing environment within the furnace, closed SAFs generally operate at low temperatures, as this design minimizes heat loss and keeps outside oxygen at bay, which is necessary for sustaining the reactions. This

approach offers better control over the smelting process, resulting in reduced emissions and enhanced energy efficiency.

- **Semi-closed SAF**: Its design reduces the risk of overpressure by allowing some gas to escape while maintaining enough control to minimize contamination. The temperature during the charging process is typically slightly higher; this increased temperature provides more flexibility in the charging process, enabling adjustments to be made on demand based on the furnace's current conditions.
- **Open SAF**: Since it allows gases to escape and offers less stringent atmospheric control, these furnaces are more resilient to impurities found in raw materials. However, this tolerance leads to decreased process efficiency and more emissions. Even greater charging temperatures are necessary for open SAFs due to greater heat loss and exposure to atmospheric gases.

Materials used in SAFs:

- **Chromite Ores:** The main raw material used to make ferrochrome is chromite ore, a mixture of iron and chromium oxides It can be used as lumpy or fine material and is derived chiefly from the mineral chromite. It is mined straight from the Earth. The ore's high chromium concentration is crucial because a significant portion of metallic chromium is needed for the reduction process to provide high-quality ferrochrome (ICG, 2023). It must usually be agglomerated before charging into the SAF (Niemelä and Kauppi, 2007).
- **Reducing agents**: As chromium and iron are oxidized in chromite, a reducing agent must be added. Typically, a carbon source in the form of coke is used to reduce chromium oxide (Sommerfeld, Botinha, and Friedrich, 2024). However, using hydrogen as a reducing agent could be one of the options to partially reduce fossil carbon emissions in the metallurgical sector, which is what this study aims to examine. Another option is the utilization of biocarbon. According to Monsen et al. (2001), biocarbon is carbon derived from biological and renewable resources, such as wood chips and different biomass sources. It possesses stronger CO_2 reactivity, relatively low density, lower electrical conductivity, and lower mechanical strength than traditional coke (Han and Tangstad, 2024). One practical and promising strategy to lower CO_2 emissions is biocarbon usage in metallurgy. Future Eco is a partner in the FEMOST project to supply the biocarbon used in this study.
- **Fluxes:** Used to create slag, molten oxides floating atop the liquid metal, and aid in the impurity separation process; examples are silica, lime, and dolomite (Sommerfeld, Botinha, and Friedrich, 2024).

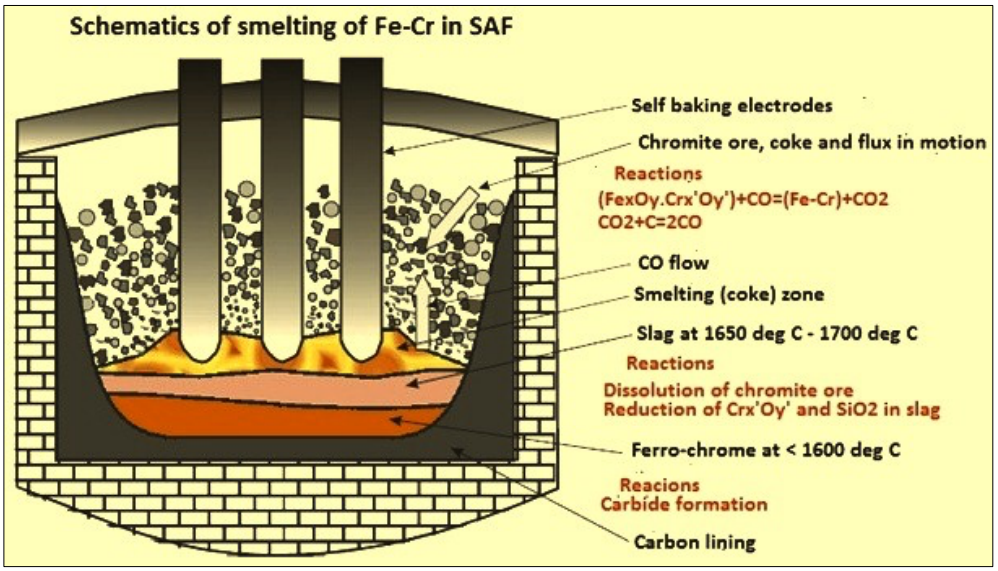

Fig. 1 Inside SAF with different raw materials. This scheme shows a production process with coke as a reducing agent.

1.2.2 Agglomeration Process

Using chromite ore directly in furnaces presents some challenges and drawbacks. By briquetting the ore into a compact form, dust production can be minimized, increasing efficiency and safety during smelting (Rao and Das, 1997). Significant dust is produced while handling and feeding chromite as is, posing risks to the workforce's health and possibly disrupting operations. Additionally, the varying size and form of loose ore can lead to uneven feeding, potentially undermining the stability and effectiveness of the furnace. Different sizes of loose ore might produce varying reduction rates. The slag can trap fine particles from loose ore, increasing impurities in the finished FeCr product. Further, uneven feeding and heat distribution from loose ore can also create localized hot spots and thermal stress, which could harm the furnace's lining.

Various agglomeration techniques exist, and they necessitate varying raw material sizes; the most common examples are the following:

- **Pelletizing:** The process involves agglomerating finer chromite fractions into pellets (10-20 mm). The raw materials are first milled to fine particles and then mixed; additional binders, usually bentonite, are added in this step. After that, the mixture is well mixed to ensure homogeneity. The combined mixture is placed into a drum or pelletizing disk, which rotates to roll it into green pellets. After that, the green pellets, pallets that have just been compacted, are heated (sintered) to make them stronger. **Figure 2** shows a schematic diagram for a typical FeCr plant, where the pelletizing process is shown.

  The ideal way to handle raw mixtures for sintering is through pelletizing. Sintering is a thermal cycle in which the compacted part is heated to a temperature below the melting point of the base metal for a predetermined amount of time.

- **Briquetting**: Briquetting, on the other hand, is the most basic agglomeration method. Briquettes are made by mixing raw materials, including the binder, adjusting moisture, adding water, if necessary, and then pressing the mixture into a mold. **Figure 3** shows the cold-bonded

briquette production process in the Roller Press. Another briquetting technique is using the Vibro Press presented in section 2.2.1.

Briquettes are simpler to handle, store, and feed into the furnace. They also increase worker safety and lower the dust usually produced while working with powdered loose materials. Briquettes' regular size and shape provide more reliable feeding, which promotes steady furnace operation and increased efficiency. Since briquettes have a larger bulk density, they maximize heat conductivity and furnace space utilization, improving energy efficiency.

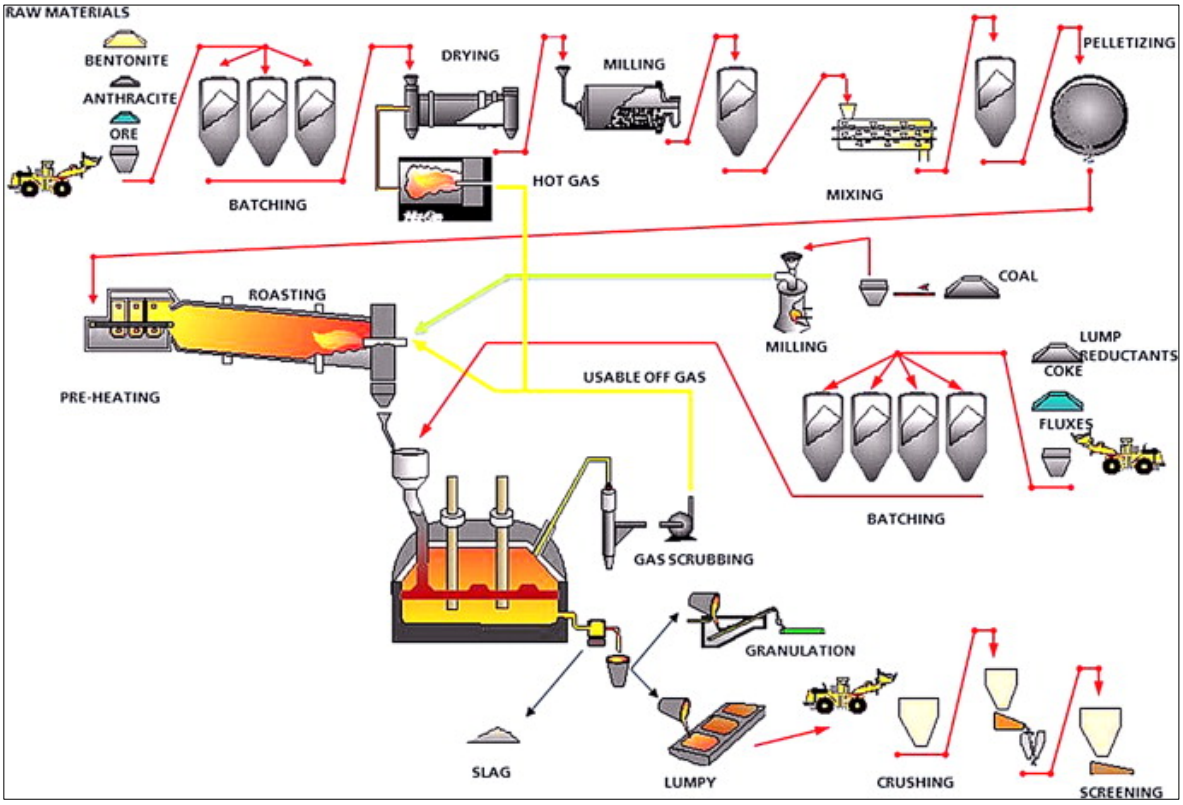

Fig. 2 Schematic diagram for FeCr production plant, showing the pelletizing process. The bentonite is used as a binder. (Basson and Daavittila, 2013)

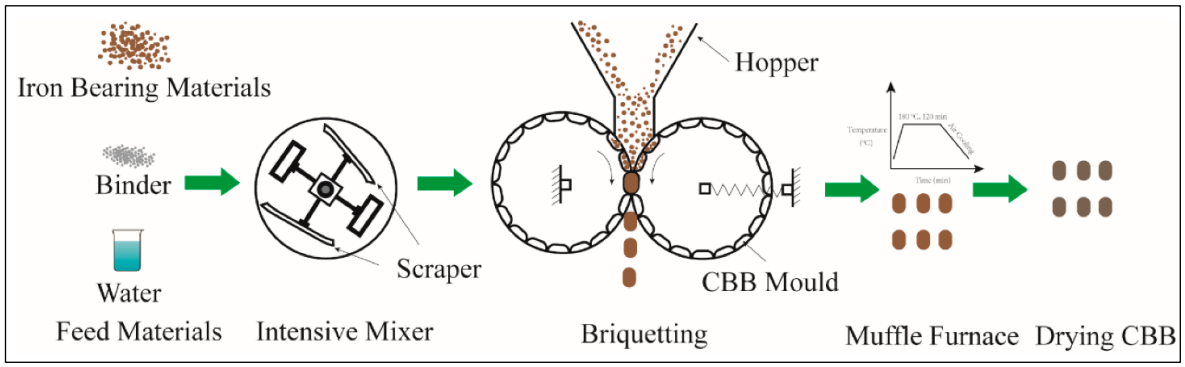

Fig. 3 Roller Press schematic diagram showing the cold-bonded briquetting process, with cement as a binder. (Li et al., 2021).

1.2.3 Smelting and Operation Conditions

The initial stage of the smelting process involves charging the burden materials into the SAF. The SAF is charged with the prepared chromite ore mixture, fluxes, and reducing agents. The subsequent melting and reduction reactions can occur

effectively with preheating. This successive charging is necessary to maintain the right temperature gradients and chemical reactions inside the furnace. Around 1,700°C is the temperature reached inside the furnace (Sommerfeld, Botinha, and Friedrich, 2024). Chromium oxide (Cr_2O_3) is reduced to chromium and CO_2 gas at these high temperatures. FeCr alloy is created when iron and chromium oxides are reduced. As a byproduct of the smelting process, the fluxes mix with the impurities in the ore to generate a slag. Because it is less dense than the FeCr, the slag can be periodically removed from the furnace and floats on top of the molten FeCr.

At regular intervals, the molten FeCr is tapped out of the furnace. To do this, a tap hole must be opened to let the alloy escape. The furnace can have one or more tapholes, for example: one is where both slag and FeCr flow together and are then separated using tapping, and two is where there is one for the low-density slag and one for the higher-density metal that lies below the slag. The material is periodically tapped out of the furnace; once the furnace hearth is full enough of melted FeCr, the tap hole is drilled, allowing a stream of molten metal and slag to pour into a sand bed or a ladle through a trough (Eric, 2014). There is a sequential usage of two ladles during tapping, the primary ladle accepts both metal and slag, whereas the secondary ladle collects slag that overflows from the primary ladle; it is also possible to cast directly into ingots without the use of ladles. Large castings of FeCr form after it solidifies and is prepared and crushed for different uses (Balasore Alloys: Production Process, nd).

One important byproduct produced during the FeCr production process is flue dust. The high-temperature FeCr production process releases several volatile substances and particulates. The off-gases carry these pollutants away, and air pollution control systems, including bag filters and electrostatic precipitators, then collect them as flue dust. Usually, a mixture of metals, oxides, and other chemicals is found in the flue dust. Common components are chromium oxides (Cr^{+6}, CrO_3), iron oxides (FeO, Fe_2O_3, Fe_3O_4), magnesium oxide (MgO), alumina (Al_2O_3), silica (SiO_2), and carbon. Sometimes, traces of hazardous elements are present. Flue dust comes in various particle sizes, but it usually consists of small particles that are easily inhaled and spread, which can harm one's health.

Since FeCr production is increasing, so is the amount of flue dust being generated. Due to the rich metals it contains, numerous research projects are underway globally to collect and recycle the waste produced. Chromium and other metals are extracted from the dust using technologies such as a high-power plasma DC reactor (Angadi *et al*., 2011). These results suggest that the plasma reactor has the potential to recover higher Cr values than any other method currently in use (Angadi *et al.,* 2011). Recycling flue dust improves resource efficiency and financial returns while lessening environmental impact.

1.2.4 Overview on using H_2 as a reductant

It is known that coke, which is primarily made from coal, is utilized as a reducing agent in the SAF at high-temperature settings used in the manufacturing of FeCr. Using coke can have certain disadvantages, though, mainly because it produces fossil CO_2 emissions, a greenhouse gas. H_2, on the other hand, does not have these disadvantages and is eco-friendly, as its by-product is H_2O. If using H_2 has worked as a reduction agent for FeCr, it will have significant benefits, such as zero carbon emissions, as the sole byproduct is water, making the process more environmentally friendly; absence of impurities: since H_2 is a clean reducing agent, the alloy's quality may be enhanced; renewable energy source, as H_2 can be generated by sustainable methods such as solar or wind-powered water electrolysis, which uses renewable energy. Hence, by switching

to H_2, FeCr production may have a much smaller carbon footprint, which would be consistent with international efforts to minimize hazardous gases and cut greenhouse gas emissions. Using H_2 is also consistent with the greater shift toward renewable energy and the circular economy concepts, as the industry is moving toward more sustainable practices. It can also partially help in decarbonizing the steel industry.

Davies et al. (2022) discuss the use of H_2 for the reduction of pre-oxidized chromite and how it can change the behavior of oxides. **Figure 4** shows how the tested samples were pre-oxidized at 1100°C for 60 minutes before being reduced under H_2 and how they compare to those reduced without pre-oxidation. The figure shows a significant enhancement in Fe metallization for the pre-oxidized samples; the Cr metallization, however, remains minimal, regardless of pre-oxidation. This shows that H_2 could pre-reduce FeO but not $FeCr_2O_4$ before use in a furnace.

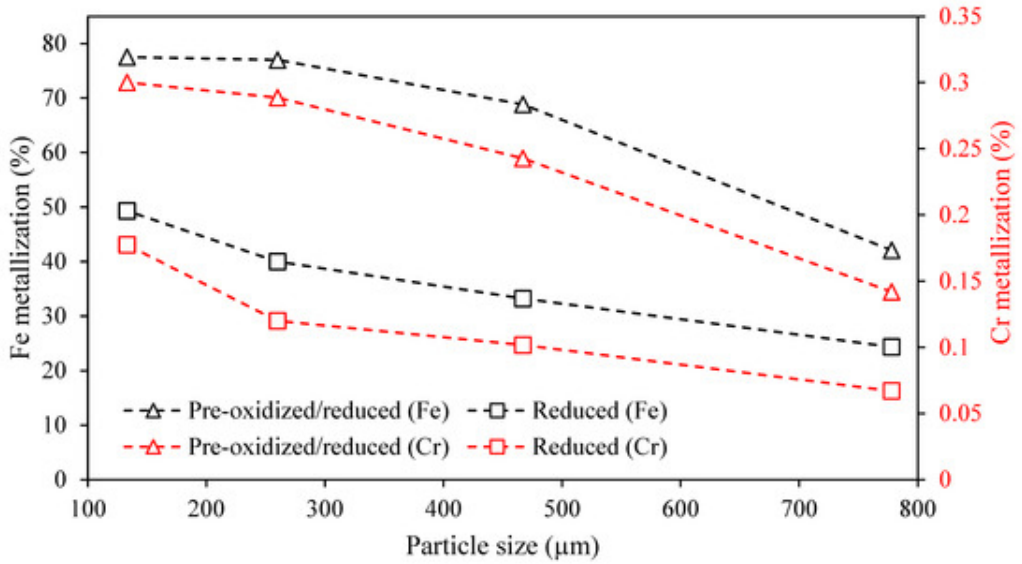

Fig. 4 Effects of pre-oxidation using H_2 on the metallization of Fe and Cr. (Davies et al., 2022).

1.2.5 Overview on thermodynamics

Thermodynamics examines the interactions and transformations between heat and other types of energy. It involves examining motion, transformation, and the impact of energy on matter.

It determines whether a reaction is endothermic (absorbs heat) or exothermic (releases heat), which is important for temperature control. In the case of chromite reduction with H_2, it is an endothermic reaction. Along with kinetic studies, it helps determine the reduction process's activation energy. Lower activation energy means a faster reaction rate at a given temperature. Thermodynamics can also help increase energy efficiency while optimizing temperature, pressure, and gas flow rate parameters.

Predicting the equilibrium states of chemical reactions in a system at high temperatures is the foundation of thermodynamic modeling. Thermodynamics models compute properties such as Gibbs free energy, entropy, and enthalpy to predict reaction behaviors, phase transformations, and material stability under conditions like pressure and temperature, aiding in understanding how the materials behave during the production of FeCr. One of the best programs in this field is FactSage 8.2, which integrates extensive thermodynamic databases and computation modules to simulate high-temperature processes. It has tools for

calculating equilibrium and phase diagrams as it integrates databases that contain thermodynamic data for chemical elements, compounds, and phases.

An Ellingham diagram, which shows the equilibrium states of different oxides, including $FeCr_2O_4$, as a function of temperature, was described by Davies, Paktunc, et al. (2022). The Gibbs free energy of $FeCr_2O_4$ with carbon reduction reaction is shown in **Figure 5**.

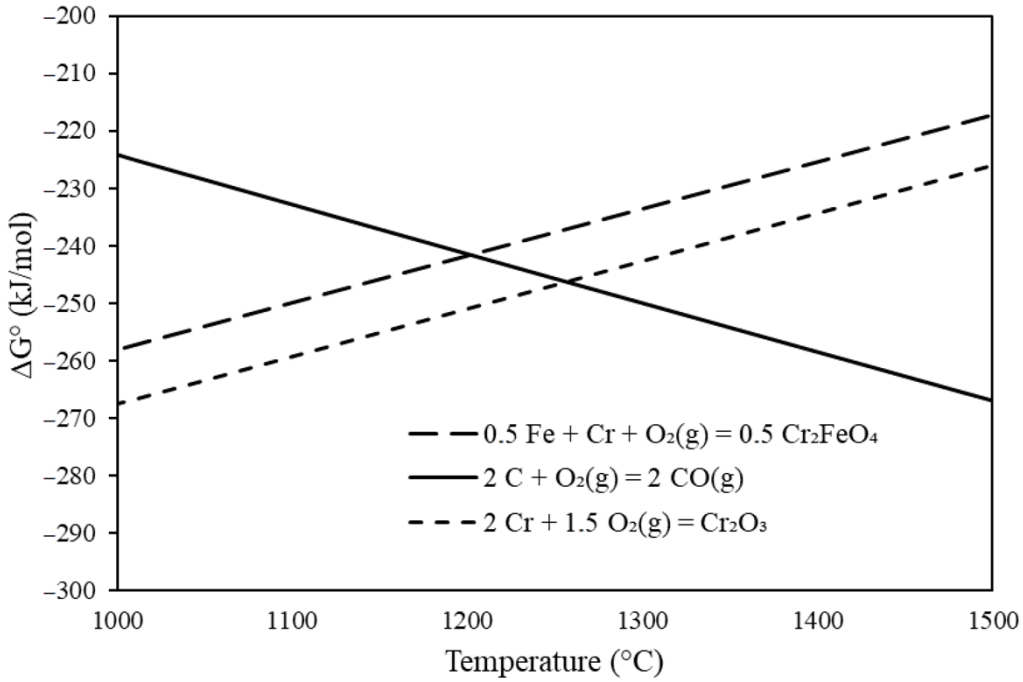

Fig. 5 Ellingham diagram indicating ΔG° of the reduction of Cr_2O_3 and $FeCr_2O_4$ with C. (Davies et al., 2022).

The study by Wu et al. (2024) states that $FeCr_2O_4$ can be reduced using methane (CH_4) as a hydrogen-carrier gas. The paper mentions that CH_4 helps with carburization during the reduction process. It emphasizes that, under the right conditions, specifically at high temperatures of about 1350°C and with a sufficient concentration of methane, CH_4-H_2 mixtures are effective reductants for chromite, capable of reducing both iron (Fe) and chromium (Cr) to their metallic forms. It was reported that 90% hydrogen and 10% methane made up the ideal mixture found for reaching a metallization rate of 36.3%, indicating the efficiency of this gas mixture in the reduction process of chromite ore (Wu *et al.*, 2024).

1.3 Aim

This thesis aims to ascertain if utilizing H_2 to reduce mill scale can conserve biocarbon for chromite ore reduction. Mill scale is the iron source in this project, serving as an iron carrier. This byproduct is generated during continuous steel casting when an iron oxide layer forms on the steel ingots' surface and detaches during cooling (Bugdayci *et al.*, 2018). When repurposed, mill scales can be a useful resource, and one objective of the project is to enhance resource efficiency by creating a closed-loop system between ferroalloy and steel makers. Around 13.5 million metric tons of mill scales are annually produced worldwide (Bugdayci *et al.*, 2018). Therefore, the project will investigate and confirm if using the steel industry's byproducts in the SAF's FeCr production is feasible.

Additionally, suitable recipes and agglomeration techniques were included in this research to produce briquettes that meet the requirements for FeCr production.

This effort is part of the FEMOST project, funded by VINNOVA, with project partners including Swerim, Vargön Alloys, RISE, Future Eco, Uddeholms, and Ovako. **Figure 6** depicts a comprehensive schematic concept for the FEMOST project. The FEMOST initiative aims to enhance the sustainability of ferroalloys and the steel industry. Cold-bonded briquettes are agglomerated with materials like biocarbon, mill scale, and chromite fines (<16mm). H_2 is then used for pre-reduction, followed by an analysis of the reduction behavior.

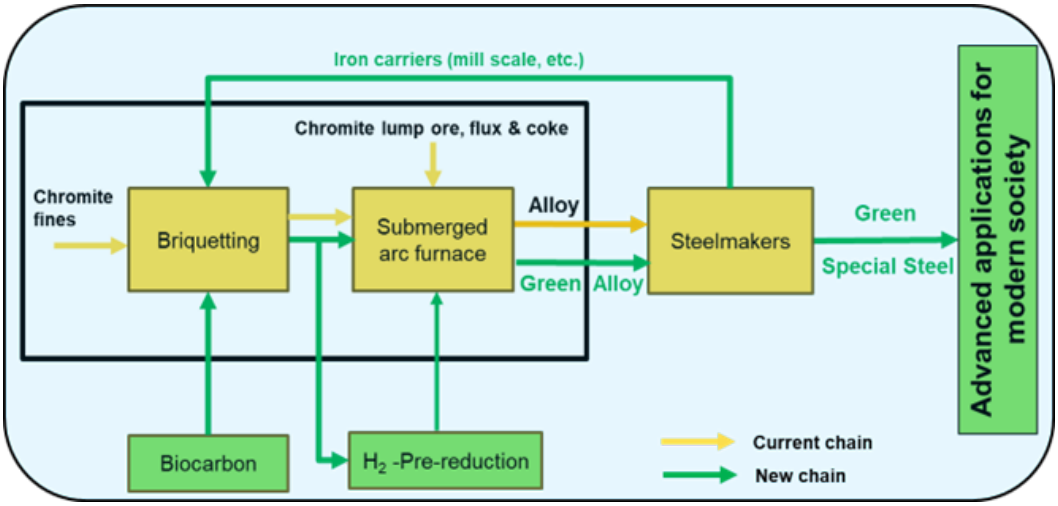

Fig. 6 FEMOST project concept.

2 Methodology

2.1 Material Preparation and Equipment

Briquetting, as previously indicated, is the best method for supplying raw materials into the furnace, yet it requires preparations. Vargön Alloys supplies the chromite ore for the process, Future Eco provides the biocarbon, and Ovako and Uddeholm supply the mill scales. In addition, some binders and additives were used in the briquettes' agglomeration. As previously mentioned, biocarbon presents some challenges, and one approach to addressing these challenges is to compact biocarbon using a roller press, as it increases the biocarbon's density while reducing reactivity due to the reduced surface area.

Some analyses were made for the different materials used in designing the recipes. As a starting point, a Mettler Toledo moisture analyzer was used to measure the moisture content of different materials to allow the optimization of recipes. It was measured by placing around 10 grams of each material inside the device; then, the percentage was measured using a halogen heating device and a balance to weigh the difference before and after drying, finally displaying the calculated difference as the moisture content. Following is a Retsch particle size distribution (PSD) determined using a vibratory sieve shaker and sieves ranging in size from 0.063 to 11.2 mm. The PSD shaker works by stacking the various mesh sizes in order, then weighing some of the material, approximately 500 grams, and loading it into the top. The sieve shaker was then activated for 5 minutes with a 60-oscillation amplitude. After 5 minutes, the material retained on each mesh was weighed and recorded.

To determine mechanical strength, cold compression strength (CCS) and splitting tensile strength (STS) were measured to determine mechanical strength. The TGA tests the pre-reduction of the developed recipes, while the QMS determines the off-gases. Lastly, the materials' mineralogical and chemical compositions were assessed using X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyzers to test the phase and chemical compositions, respectively. XRD is a non-destructive analytical technique that analyzes phase compositions, crystal structures, and physical properties. While XRF is an analytical method that determines the chemical composition of a sample through the interaction of X-rays. The briquettes were ground into a powder before a representative sample was placed in the device for testing. **Figures 7, 8, 9, 10, 11, 12, and 13** depict the devices used to perform the required measurements and analyses. **Tables 1, 2, and 3** show the moisture content and chemical composition of raw materials. **Figures 14 and 15** illustrate the individual and cumulative percentages of the different raw materials, respectively. Before reduction, XRD was performed on the best-performing formulations with 20% and 10% biocarbon, R3_RP and R9_VP, respectively. Their graphs are given in **Figures 16 and 17,** respectively. The developed recipes are described in the following section.

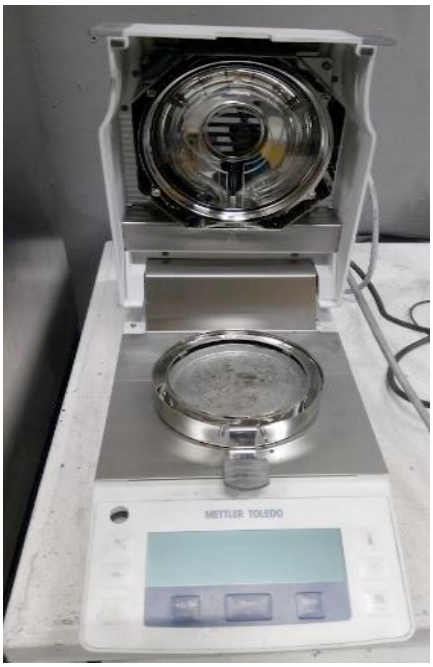

Fig. 7 Mettler Toledo moisture analyzer: measures the moisture percent in samples.

Fig. 8 Retsch Sieve Vibrator: measures the PSD.

Fig. 9 Compression device: measures briquettes' strength.

Fig. 10 STS: measures briquettes' splitting tensile strength.

Fig. 11 Netzsch STA 449F3 TGA used for the pre-reduction trials using H_2.

Fig. 12 Netzsch QMS 403: measures off-gases during reduction by determining the molecular weight.

Fig. 13 XRD: tests phase composition

Table 1. Moisture content of all applied materials (%)

Material	Chromite Ore	Ovako Mill Scales	Uddeholm Mill Scales	Biocarbon	Dust
H_2O (wt. %)	3.79	0.78	2.36	31.47	0.51

Table 2. Chemical analysis of 2 different mill scales and chromite ore (%)

Material	CaO	MgO	SiO_2	Al_2O_3	MnO	Cr_2O_3	NiO	MoO_3	FeO	Fe_2O_3
Ovako Mill Scales	0.3	1.1	3.0	2.0	0.6	1.1	0.4	0.1	57.8	29.4
Uddeholm Mill Scales	0.1	-	1.7	0.1	0.5	3.0	-	0.7	-	93.0
Chromite Ore	0.5	19.1	4.9	17.5	0.1	42.9	0.2	-	12.8	-

Table 3. Chemical analysis of the biocarbon (%)

Material	C	H	O	Volatiles	Ash	CaO	MgO	SiO_2	Al_2O_3	Na_2O	K_2O	P	Energy Content MJ/kg
Future Eco Biocarbon	88.7	1.5	0.7	5	0.6	0.32	0.1	0.08	0.02	0.01	0.07	0.02	29.4

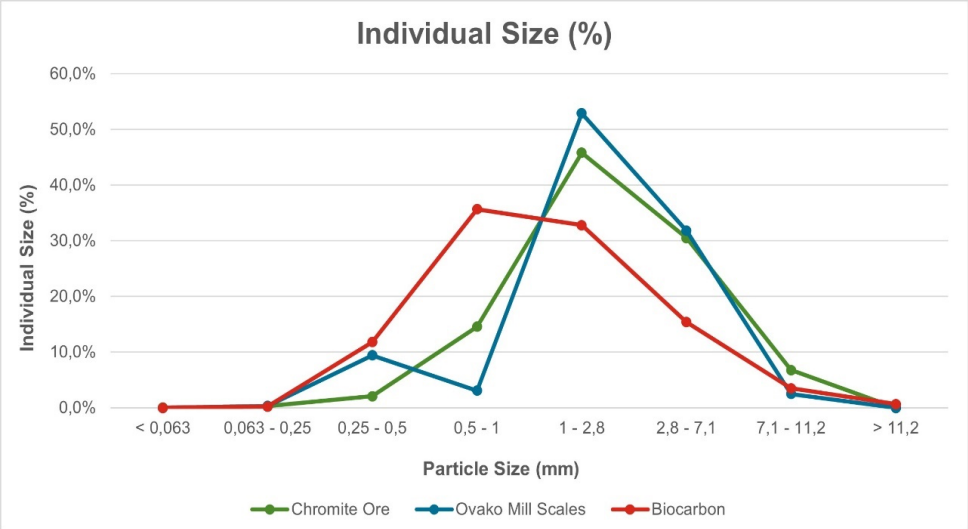

Fig. 14 Individual Size PSD of Chromite Ore, Ovako Mill Scales, and Biocarbon (%).

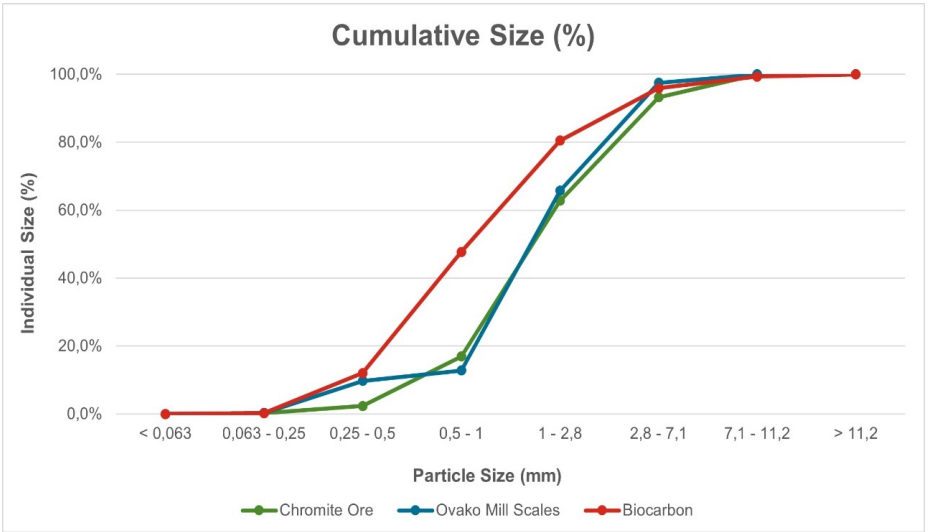

Fig. 15 Cumulative Size PSD of Chromite Ore, Ovako Mill Scales, and Biocarbon (%).

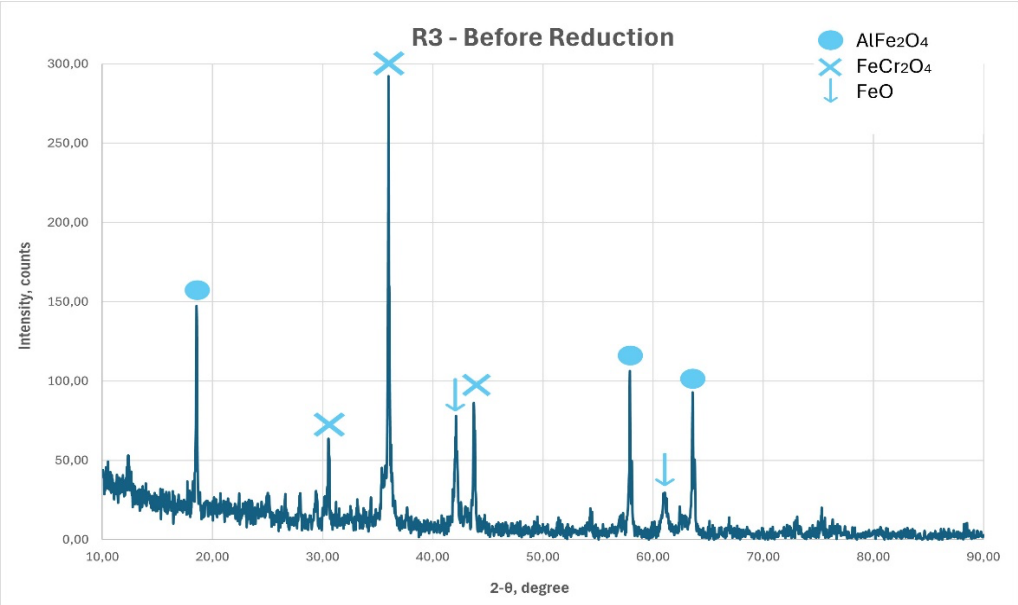

Fig. 16 R3_RP recipe's XRD analysis before reduction with 20% biocarbon. The highest peak is shown at $FeCr_2O_4$, and the lowest is shown at FeO.

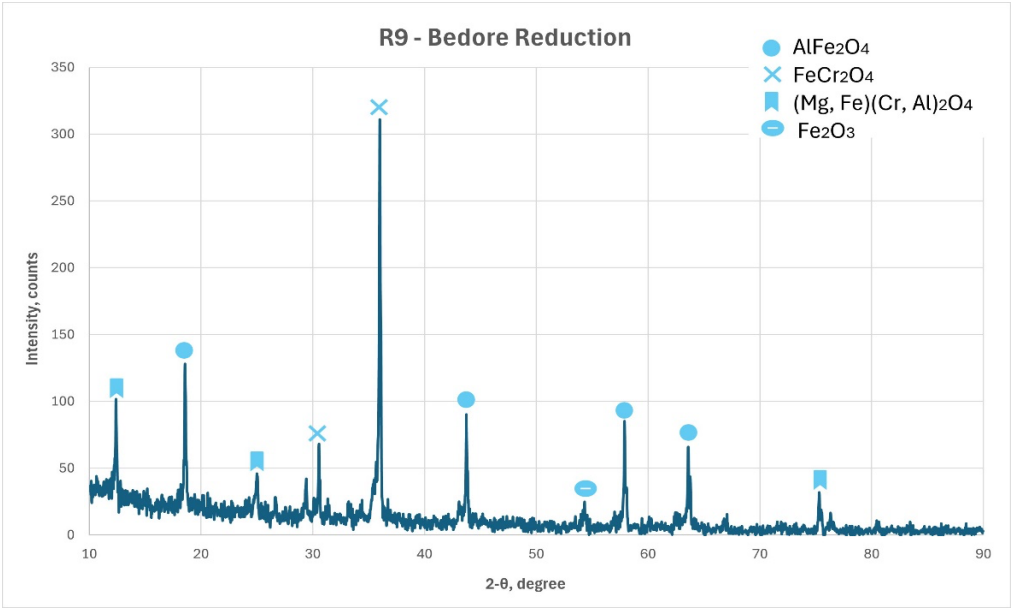

Fig. 17 R9_VP recipe's XRD analysis before reduction with 10% biocarbon. The highest peak is shown at $FeCr_2O_4$, and the lowest is shown at Fe_2O_3, which could be a small amount present in the mill scale.

2.2 Method

Two different briquetting devices have been used in this project: Vibro Press (VP) and Roller Press (RP). The VP creates hexagonal-shaped briquettes, and the RP creates pillow-shaped briquettes. Each technique requires a certain particle size, usually <11.2mm and sometimes smaller. Additionally, the moisture content should be adjusted for each briquetting technique. Depending on the technique, VP, and RP, the materials' PSD was adjusted for ideal mixing before compaction. After mixing the different materials to create a mixture, the mixer used for the RP had a capacity of 500kg, as shown in **Figure 18**. Each recipe was then put into both presses for the briquette production. Creating the various recipes for each of the two equipments comes next.

Fig. 18 A picture of the mixer with the dry materials, already added is the biocarbon, mill scales, chromite ore, cement, and dust, the binders are being added while mixing is taking place.

The main materials added to each recipe are mentioned below:

For the VP, the following recipes were tested (**Table 4**):

- Chromite Ore (reference)
- Chromite Ore + Mill Scales + 10% biocarbon (developed recipe)

For the RP, the following recipes were tested (**Table 5**):

- Chromite Ore + 30% mill scales + 20% biocarbon + binder(s) (developed recipe with higher carbon compared to VP)
- Chromite Ore + 30% mill scales + 30% biocarbon + binders(s) (developed recipe with extra carbon)

Table 4. Designed recipes for the Vibro Press (wt. %)

Recipe No.	Chromite Ore	Mill Scale	Dust	Binders	Biocarbon
R3_VP	93	-	3	4	-
R8_VP	59	20	2	9	10
R9_VP	60.5	20	2	7.5	10

Table 5. Designed recipes for the Roller Press (wt. %)

Recipe No.	Chromite Ore	Mill Scale	Binders	Dust	Biocarbon
R1_RP	37	30	12	1	20
R2_RP	27	30	12	1	30
R3_RP	39	30	10	1	20
R4_RP	32	30	17	1	20
R5_RP	29	30	10	1	30

After production, the CCS/STS of the briquettes were measured as an indicator of their mechanical strength. The green briquettes were immediately tested right after compaction, and some briquettes were oven-dried at 105°C for 2 hours, while others were left to air-dry at room temperature. The raw materials were subsequently charged into the furnace, and the chosen recipe was used to produce the briquettes.

2.2.1 Vibro Press

The VP trials were carried out at Vargön on an industrial scale. Three different recipes (previously shown in **Table 4**) were decided on as Pre-Trials and the best-performing recipe was chosen for large-scale production. During the mixing process, dry materials were first added and mixed. Then, gradually, wet-based materials were added and mixed further. The parameters measured for the briquettes were density, moisture content, and mechanical strength. After production, the moisture content and the strength of the briquettes were measured on a green basis right after production, after curing for 24 hours in a curing chamber, and after 1 week and 3 weeks of airdrying. The strength of the briquettes was measured by a drop test from a height of 2 meters; the drop test and tumbler index were not done on green briquettes. **Figure 19** shows some VP briquettes just after compaction on an industrial scale at Vargön.

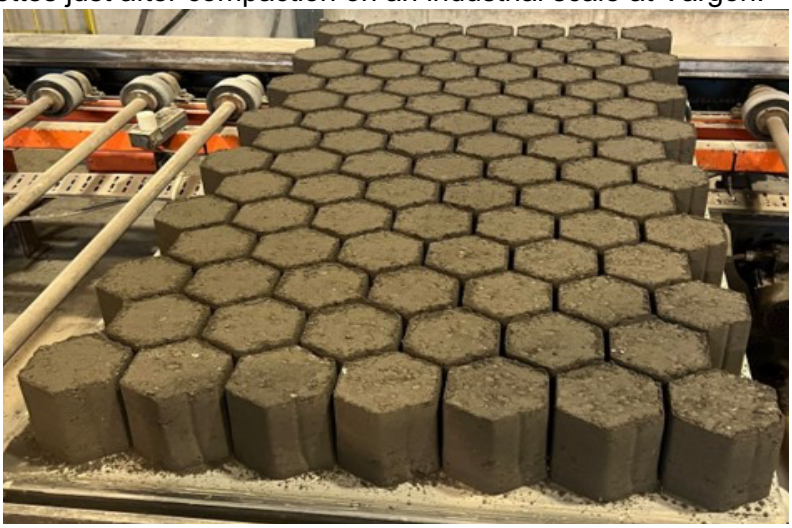

Fig. 19 A close-up picture of the VP-produced briquettes; notice their hexagon-shaped.

2.2.2 Roller Press

Five different recipes were designed (previously shown in **Table 5**) and produced using the RP. The briquettes produced were tested for their mechanical strength, moisture content, and density. The best-performing recipe was recommended for scaling and implementation in the SAF in future work.

The main objective was to compress the biocarbon along with other materials (chromite ores, mill scale) and binders to enhance its density and decrease its reactivity, bringing it closer to the properties of fossil coke.

Fig. 20 A close-up picture of some of the produced RP briquettes.

The first step required the different materials to be weighed, after which a predetermined amount of water was added to modify and adjust the suitable moisture content for compaction. Before feeding the finished mixture into the RP, the cement mixer was used to mix the materials, ensuring that binders and water were distributed evenly for a homogeneous mixture. The mix is then placed into the conveyor for roller press briquettes' production. **Figure 20** displays some RP briquettes right after compaction.

Produced briquettes were assessed regarding their moisture content, density, and mechanical strength. This was done by measuring the green strength of some briquettes, which were produced directly after compaction, then some others were placed in the oven at 105°C for 2 hours, and the others were air-dried at room temperature for 1 week.

All green, oven-dried, and air-dried briquettes were tested for their mechanical strength, using the CCS and STS, and moisture content with a moisture analyzer. For each recipe, 4 briquettes were tested as green, oven-dried, and air-dried for both CCS and STS, and the average was taken, and then a small sample from the core of the briquettes was placed inside the moisture analyzer. This was done to assess the different recipes and determine the best, which will then be chosen for large-scale SAF charging.

The densities of the 5 different recipes were measured and the results are given below in **Table 6**. The density of R3_RP also emphasizes that it is the densest, which could be attributed to the highest compaction and higher content of chromite ores. The mechanical strength is discussed in section 3.

Table 6. Briquettes' densities of different recipes in the RP (g/cm^3)

Recipe	R1	R2	R3_RP	R4	R5
Density (g/cm^3)	2.5	3.8	4.8	2.7	3.9

Large-scale production then took place. The different materials were prepared and then placed in a mixer with a capacity of around 500 kgs (shown previously in **Figure 18**), and then the dry materials were mixed to ensure a homogeneous mixture. Next, water was added gradually as the mixer rotated. Water was optimized according to the moisture content of the materials and ongoing conditions at the time of mixing. Afterward, the mixture was transferred into the RP, and production was preceded until all the mixture was used in briquettes. The briquettes were again tested for their mechanical strength by using CCS and STS as green briquettes, oven-dried at 105°C for 2 hours and air-dried for 1 week, as well as their moisture content in each state. After production of the upscaled briquettes in the RP, some briquettes were chosen for the reduction trials with H_2. The recipes decided on depended on the best-performing briquettes and the amount of water added.

2.2.3 Reduction with H_2

The Thermogravimetric Analysis coupled with quadrupole mass spectroscopy (TGA-QMS) was used to measure the briquettes' reduction behavior. TGA identifies the reduction behavior of briquettes with different biocarbon percentages by measuring weight loss over time during heating from room temperature until reaching the aimed reduction temperature. While the QMS works by identifying the mass spectra of evolved gases by m/*z* (mass-to-charge ratio).

Before combining chromite, mill scales, and biocarbon in the SAF, the purpose of pre-reduction was to enable the H_2 to help pre-reduce mill scales. Subsequently, when all raw materials are fed into the SAF, the biocarbon will focus on chromite ore reduction.

The aim was to do four trials while testing two recipes, one produced by the RP containing 20% biocarbon and the other produced by the VP containing 10% biocarbon. Trials were done with 90% H_2 mixed with 10% Ar with a flow rate of 150 mL/min and then cooling down with 100% Ar with a flow rate of 250 mL/min. Two trials were done with an isothermal step, one for each of the two recipes, by heating from room temperature to 650°C and stabilizing for 1 hour, then heating again until reaching 1100°C and stabilizing for 1 hour. The aim of these two trials is to test the effect of the low temperature on the reduction of the mill scale before the gasification and the reaction of the biocarbon start. Next, two trials were heated linearly until the temperature reached 1100°C, then stabilized for 1 hour. The aim of these two trials is to investigate the reduction at a higher temperature and the interaction of biocarbon in the presence of H_2. The heating rate used for all four trials was 10°C/min. The QMS was connected to measure the off-gases in the trials, testing for gases such as H_2, H_2O, CO, CO_2, and CH_4. The two recipes used in the reduction trials from both presses are shown below in **Table 7**. XRD was performed on both recipes, R3_RP and R9_VP, to test the phase compositions before reduction.

Table 7. Recipes used for the H_2 reduction trials (wt. %)

Recipe No.	Chromite Ore	Mill Scale	Dust	Binders	Biocarbon
R3_RP	39	30	1	10	20
R9_VP	60.5	20	2	7.5	10

2.2.4 Thermodynamic Analysis

FactSage 8.2 was used to test the materials' theoretical behavior during reduction trials and the smelting process in the SAF. The databases relevant to the material were FactPS, FToxid, and FSstel. The pressure was standard as in 1 atm, and the temperature was set for 1100°C during reduction reactions starting at room temperature. The theoretical insights produced were then compared with the experimental results.

The solid-gas reaction involving chromite ore and H_2 uses the general mineral composition of chromite ore, $FeCr_2O_4$, and H_2 as the reducing gas. This was compared to biocarbon C, a reducing agent, to test the difference between reducing agents and their ability to reduce $FeCr_2O_4$. The following reactions were carried out, and the temperature was set to 1100°C, the maximum temperature reached during the reduction done in the TGA. **Figures 21 and 22** show the ΔG° of the two following reactions calculated in FactSage. **Figure 21** shows the reaction between $FeCr_2O_4$ and H_2, where no reduction reaction occurred as all the ΔG° values were positive, while in **Figure 22,** the reduction reaction shown is between $FeCr_2O_4$ and C and the reaction occurred starting at 1100°C, where ΔG° is negative, indicating ongoing reaction.

- $FeCr_2O_4$ (s) + H_2 (g) = Cr_2O_3 (s) + Fe (s) + H_2O (g) (1)
- $FeCr_2O_4$ (s) + C (s) = Cr_2O_3 (s) + Fe (s) + CO (g) (2)

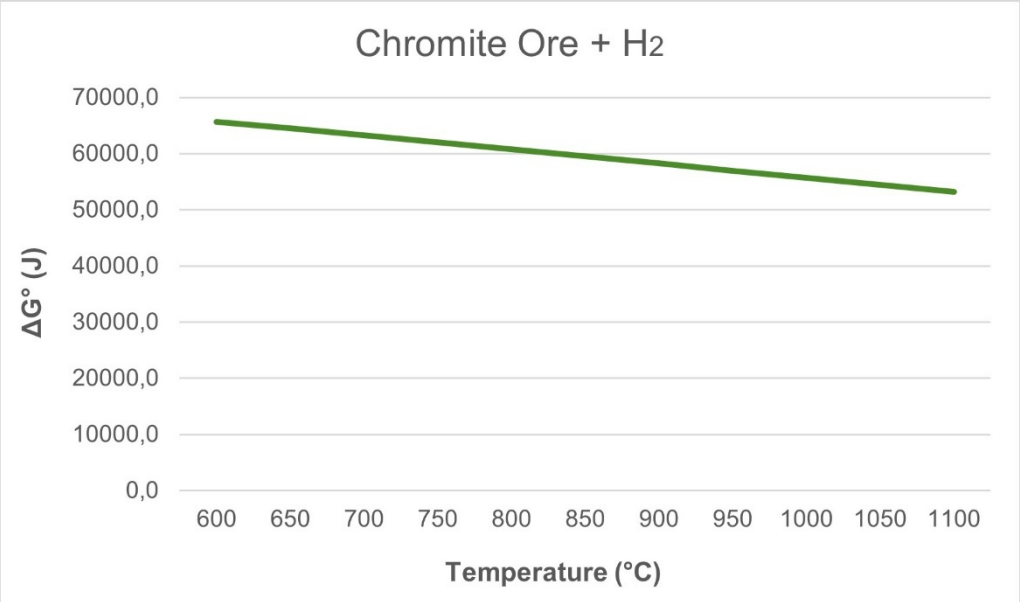

Fig. 21 Gibbs free energy of Chromite Ore + H_2, where all ΔG° values are positive showing no reaction occurred.

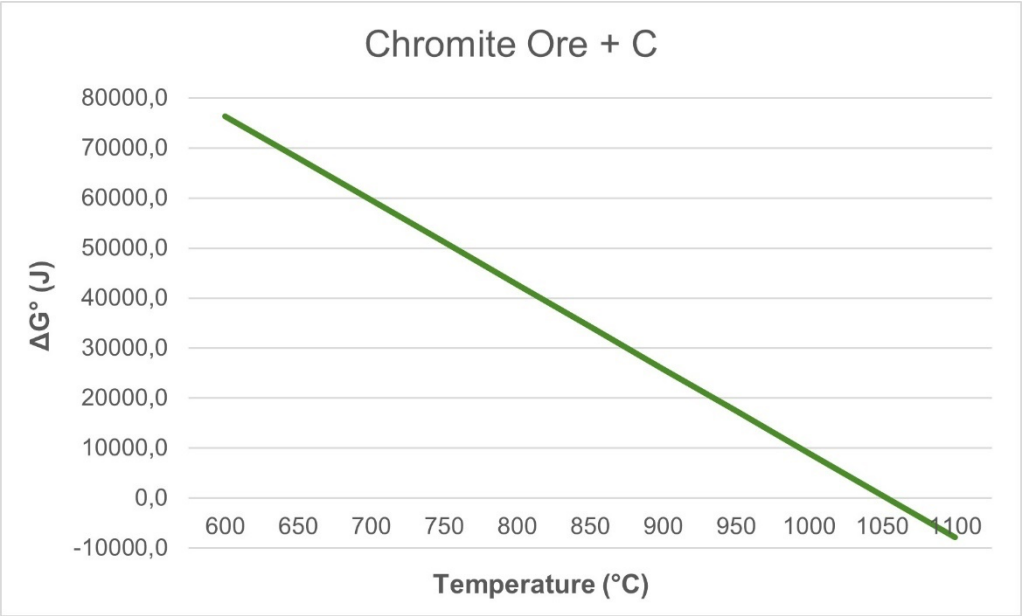

Fig. 22 Gibbs free energy of Chromite Ore + C, where negative ΔG° appeared at the intended reduction temperature 1100°C.

Below, shown in **Figures 23, 24, and 25,** are the reduction reactions done using FactSage to calculate the theoretical reduction behavior. The reactions shown in the below figures are the following:

- $FeCr_2O_4 + C + H_2$; Figure 23 shows all pure states produced
- $FeCr_2O_4 + C + H_2 + FeO$; Figure 24 shows only the off-gases produced during the reaction
- $FeCr_2O_4 + C + H_2 + FeO$; Figure 25 shows only pure states without the gases produced during the reaction

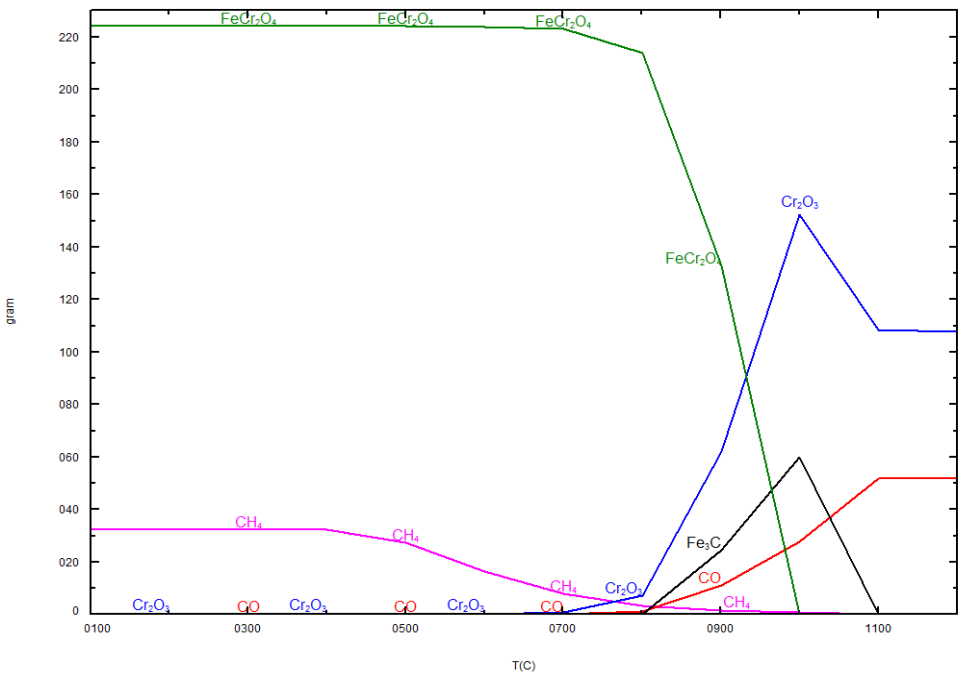

Fig. 23 Reduction reaction $FeCr_2O_4 + C + H_2$ under 1 atm until reaching a temperature of 1100°C.

The reduction process between $FeCr_2O_4$ + C + H_2 is seen in **Figure 23**. As the figure illustrates, the chromite could be reduced to create chromium oxide and iron carbide, with the $FeCr_2O_4$ beginning reduction at 800°C - 850°C and sharply decreasing around 900°C where Cr_2O_3 and Fe_3C peaks appear. The off-gas present between 900°C and 1100°C, the same temperature the Cr_2O_3 and Fe_3C peaks appeared, is CO, which means that C was the reducing agent, not H_2, and it reduced the $FeCr_2O_4$. However, CH_4 is present, and further investigation is required to determine whether it participates in the reduction process.

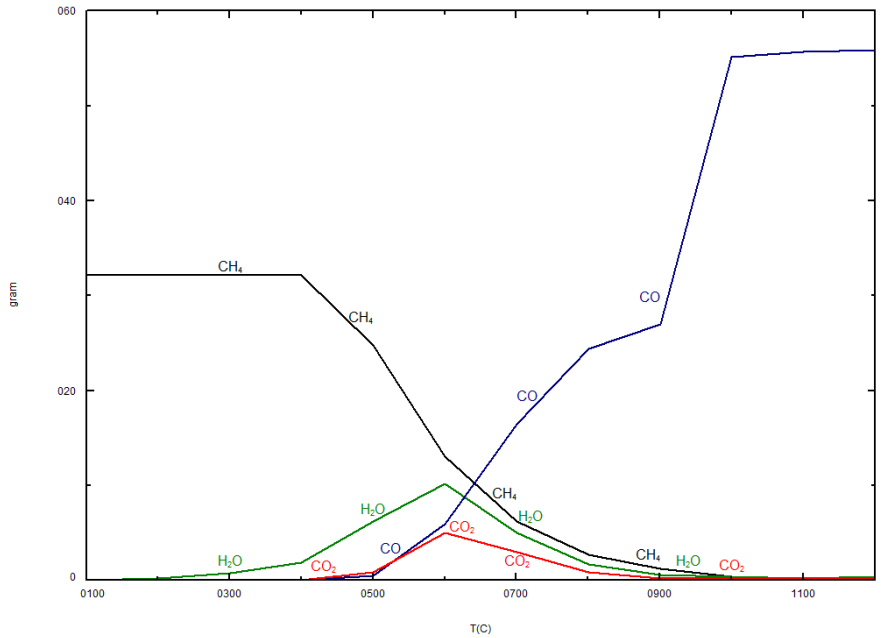

Fig. 24 Off-gases during the reduction reaction FeCr2O4 + C + H2 + FeO under 1 atm until reaching a temperature of 1100°C.

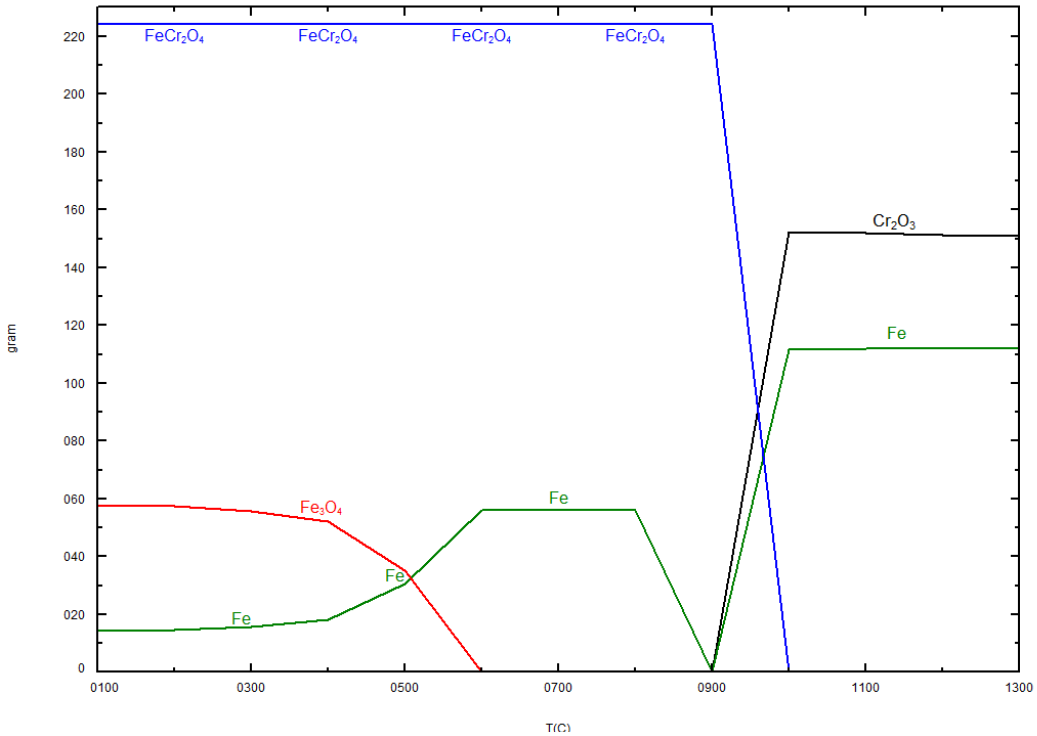

Fig. 25 Solids and liquids during the reduction reaction FeCr2O4 + C + H2 + FeO under 1 atm until reaching a temperature of 1100°C.

Figures 24 and 25 show the off-gases evolved and the other phases without the gases during the reduction reaction $FeCr_2O_4 + C + H_2 + FeO$, reaching the maximum temperature of 1100°C, respectively. The reduction of $FeCr_2O_4$ began around 900°C, the temperature at which CO started to rise and peaked at 1000°C, simultaneously marking the end of the reduction of $FeCr_2O_4$. The reduction of $FeCr_2O_4$ resulted in the production of Cr_2O_3 and Fe. CH_4 was also present in the reaction, and further investigation is required to determine whether it participates in the reduction process.

The difference between the two reactions is that in **Figure 23,** the reduction of $FeCr_2O_4$ produced Cr_2O_3 and Fe_3C, yet in **Figure 25,** the reduction of $FeCr_2O_4$ produced Cr_2O_3 and Fe.

3 Results and Discussion

3.1 Recipes and Briquettes' Evaluation

The five pre-trial recipes of the Roller Press (previously shown in Table 5) were conducted and evaluated for mechanical strength, density, and moisture content. Based on the best-performing recipe, it was further upscaled to the SAF charging. **Figures 26, 27, and 28** illustrate the measurements taken for the five different recipes immediately after production on a green basis, after oven drying at 105°C for 2 hours, and following air drying at room temperature for 72 hours. According to the density, CCS, and STS variations, the best-performing recipe was R3_RP. Among all five recipes, R3_RP produced the highest green, oven-dried, and air-dried briquettes. In **Figure 26**, regarding moisture content variation, R3_RP displayed the second lowest moisture content in both green and air-dried briquettes; however, the overall moisture percentage was average compared to the other recipes p

After producing and assessing all five different recipes, the best-performing recipe was determined to be R3_RP due to its high mechanical strength, uniform physical appearance, and low moisture content compared to the other recipes. Additionally, the briquettes emerged from the roller press intact, without any broken parts or briquettes, unlike the other four recipes. With that in mind, recipe R3_RP is chosen for upscaling for charging in the SAF.

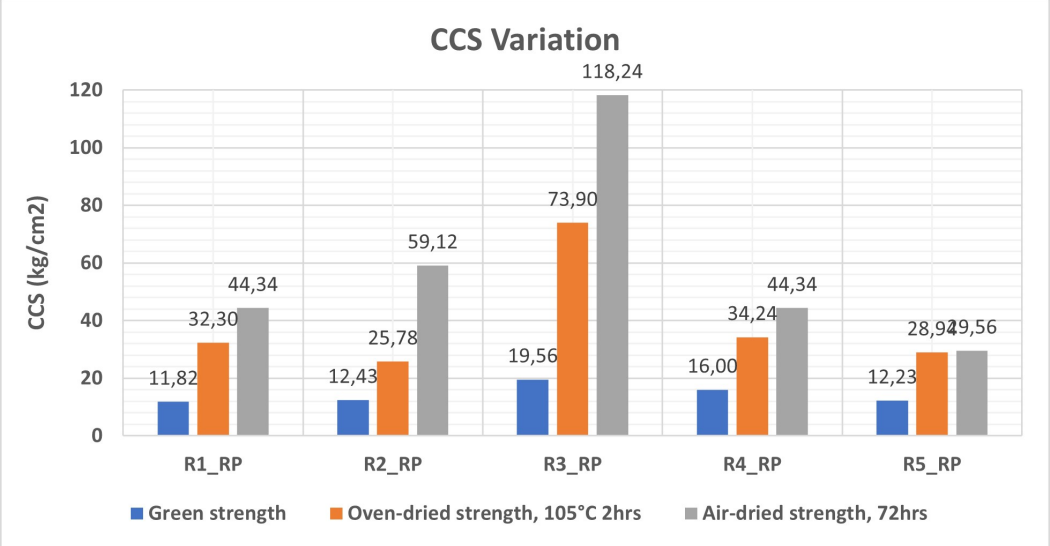

Fig. 26 CCS variation of the 5 different recipes carried in the roller press.

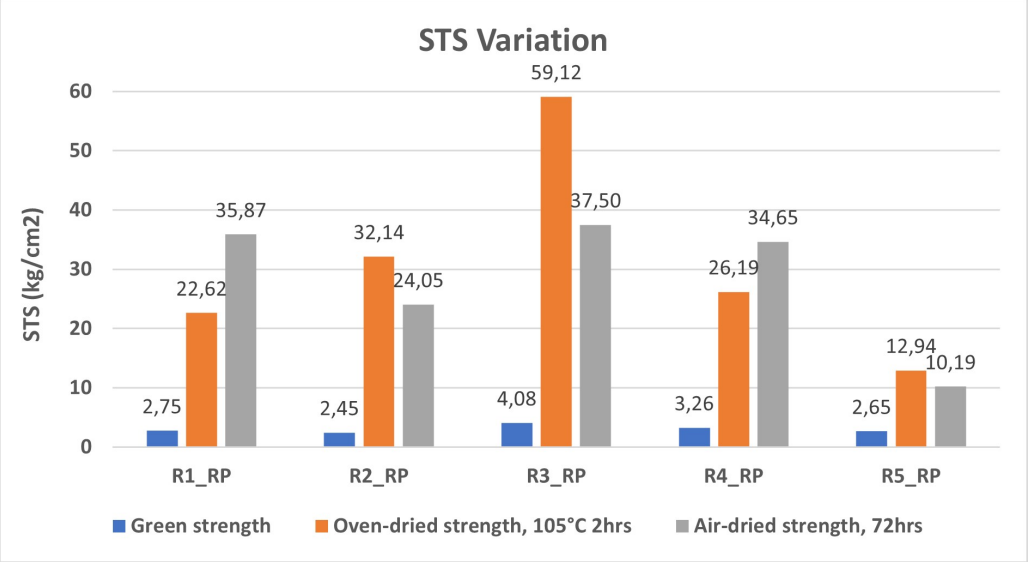

Fig. 27 STS variation of the 5 different recipes carried in the Roller Press.

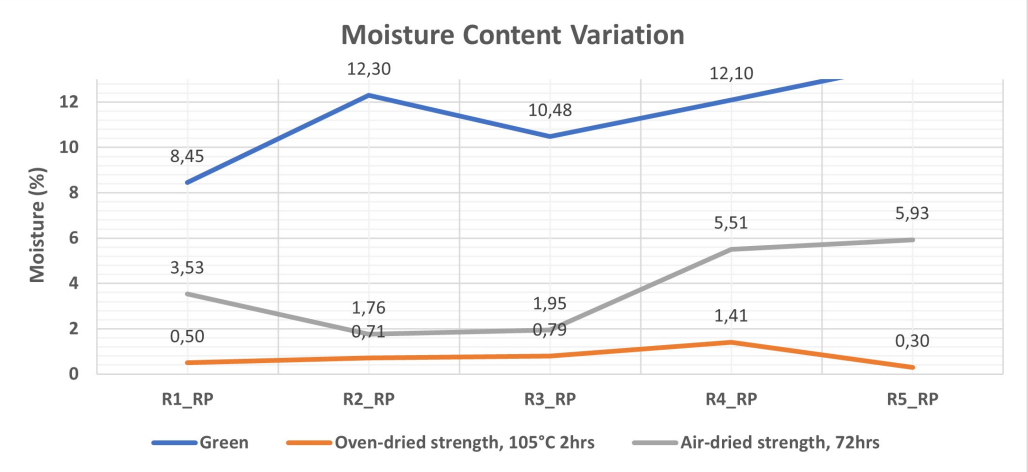

Fig. 28 The moisture content variation of the 5 different recipes carried in the Roller Press.

Another method for testing the strength of the briquettes, which was also performed on the five recipes of the RP, involves conducting a drop test for the air-dried briquettes. This was accomplished by placing a two-meter-long metal cylinder on top of a metal plate, then dropping the briquettes from the top twice, weighing the remaining whole briquettes after each drop, and measuring the disintegration percentage. The equation used for the disintegration percentage was:

$$\frac{\text{Initial Wt.} - \text{Final Wt. above 11.2mm after the 2}^{nd}\text{ drop}}{\text{Initial Wt.} * 100}$$

The recipe with the highest disintegration percentage was R5, and the lowest was R1, as shown in **Table 8**.

Table 8. Disintegration calculated from the drop test at 2 meters (%).

Recipe	R1_RP	R2_RP	R3_RP	R4_RP	R5_RP
Disintegration %	0.61	1.66	9.93	1.01	35.96

During the VP, several recipes were tested in the pre-trial on an industrial scale (the best two were shown previously in Table 4). The briquettes' density, moisture content, and mechanical strength were also evaluated, Tumbler Index, and drop tests. The results indicated that R9_VP exhibited the best performance, making it the chosen recipe for upscaling in the SAF. The mechanical strength results of the industrial-scale briquettes will be discussed in elsewhere (Report of FEMOST project).

3.2 Reduction Behaviour using H_2

In the reduction trials, the gas mixture of 90% H_2 and 10% Ar was used for the pre-reduction. In this trial, the aim was to evaluate whether H_2 can pre-reduce mill scales while saving the biocarbon to reduce the chromite ore in the SAF.

To test the behavior of the briquettes before reduction, XRD was performed on the samples containing 20% and 10% biocarbon, labelled R3_RP and R9_VP, respectively (as shown in **Figures 17 and 18** above). R3_RP before reduction exhibited the highest peak, which was $FeCr_2O_4$, or iron chromium oxide, commonly referred to as chromite ore; peaks at $AlFe_2O_4$ and FeO were also observed. The presence of FeO primarily results from adding mill scale to the chromite-biocarbon mix. R9_VP before reduction showed $FeCr_2O_4$ as its highest peak, representing chromite ore, followed by $AlFe_2O_4$, which signifies aluminium iron oxide, commonly found in chromite ore. **Figure 29** compares the reactions with an isothermal step at 650°C of R3_RP and R9_VP, and **Figure 30** compares the linear reactions of R3_RP and R9_VP.

For the R3_RP isothermal reaction, during the first heating phase before 650° C, it lost about 15% of its mass. For one hour, the temperature was maintained at 650°C; the mass was slightly changed 1-3%. The mass remained unchanged until the temperature was raised to 850°C, where there was more mass loss and then stable during the holding step at 1100°C. The linear response was quite similar; the initial mass loss was 10%, but because there was no isothermal step, the mass continued to lose more than 10%. The mass loss then was stable until the temperature reached 850°C and it reached 80% of the initial mass. R3_RP displayed the same behavior in both reactions apart from the linear reaction ending early since there was no holding at 650° C as the isothermal stop, so the reaction ended faster. R3_RP reached 68% of its initial mass, meaning 32% mass loss has been achieved.

For R9_VP, during the initial heating stage of 650°C in the isothermal reaction, it lost 15% of its mass. Following that, the mass stabilized for a while until the temperature reached 850°C, and then a sharp increase in mass loss occurred until the sample dropped to 76% of its initial mass, indicating a 24% mass loss. Both isothermal and linear reactions displayed the same behavior as R3_RP. The mass of R9_VP in both reactions was stabilized before R3_RP, suggesting that the reaction ceased prior to R3_RP. This is attributed to R3_RP having a higher amount of mill scale than R9_VP, and R9_VP having a lower biocarbon content than R3_RP, which was crucial for the ongoing reduction process. Once the reducing agent was depleted, the reaction halted. This will be further discussed in the gas analysis.

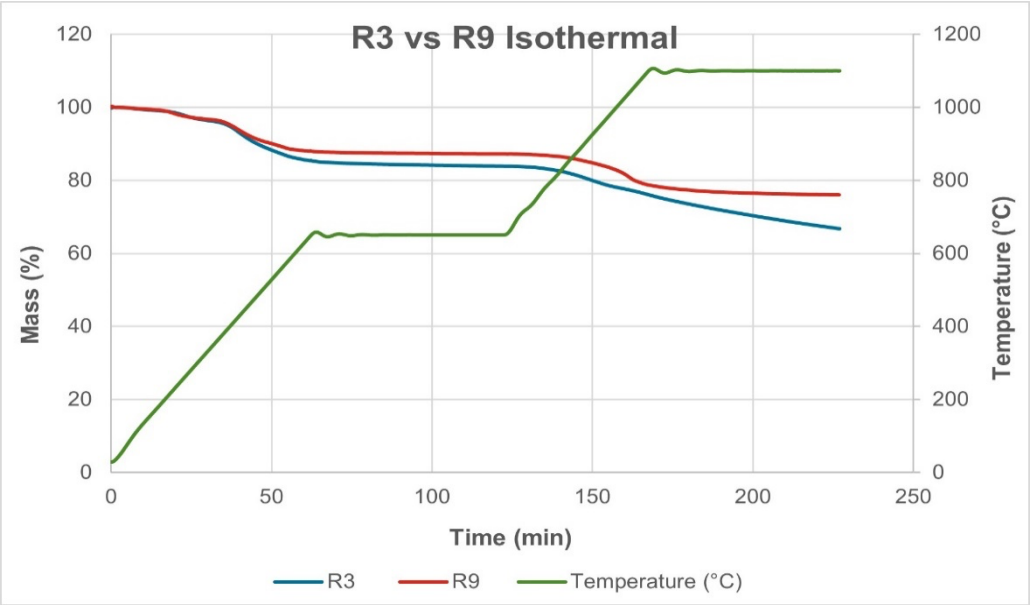

Fig. 29 Comparison of R3_RP and R9_VP reactions with the isothermal step, where R9_VP had a faster reaction rate, where C, the reducing agent, was utilized in oxides reduction.

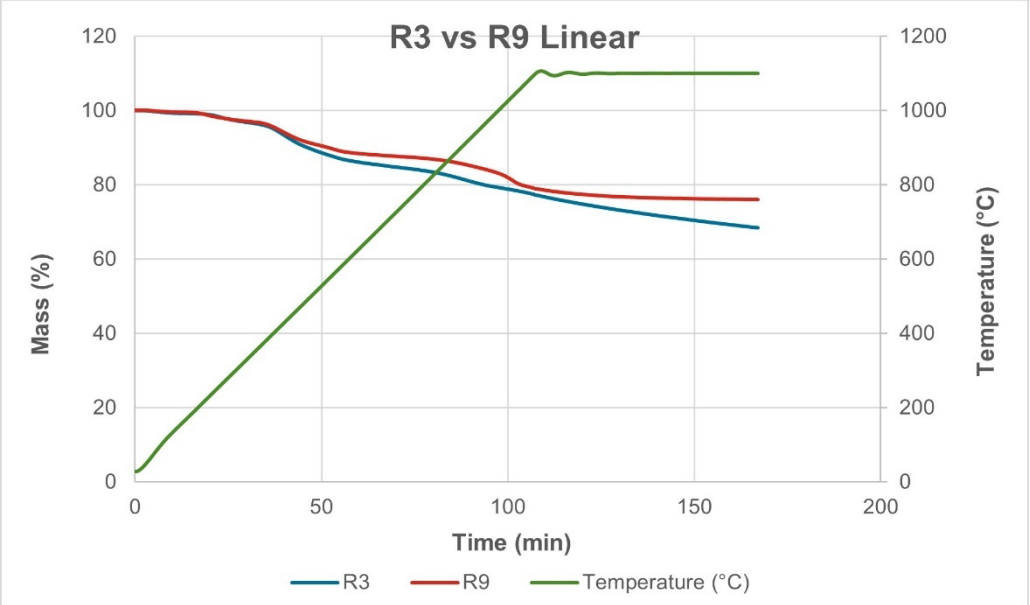

Fig. 30 Comparison of R3_RP and R9_VP linear reactions, where R3_RP had higher mass loss due to a higher amount of the reducing agent (C) in its composition.

The graphs of the gas analysis are presented below in **Figures 31, 32, 33, and 34**. In R3_RP, the H_2O peaks during the initial 400°C indicate that the initial mass loss resulted from the breakdown and removal of volatiles, organic binders, and water added during mixing. The CH_4 detected during the initial heating stage was due to the decomposition of the hydrocarbons present. As the temperature increased, the biocarbon acted as a reducing agent, leading to the observed CO peaks during the reduction stage of $FeCr_2O_4$ at 850°C. Additionally, some CH_4 formed when C and/or CO reacted with H_2 to produce CH_4. The two consecutive CO peaks observed in R3_RP reactions, as noted in the previous FactSage experiments, may be attributed to the first peak resulting from $FeCr_2O_4$ being only partially reduced to Cr_2O_3 and Fe, while the second peak arises from the partial reduction of Cr_2O_3. Gas analysis graphs of R3_RP are shown in **Figures 31 and 32**.

R9_VP had the first peaks at m/z 16 and 18 CH_4 H_2O before reduction; this is due to the decomposition of hydrocarbons, volatiles, and organic matter breaking down; the peaks present from 400°C to 600°C at m/z 16 and 28, CH_4, CO are due the reduction of FeO using C. In the isothermal graph, no peaks were present during the holding step, indicating no reduction took place. However, in the linear graph, the H_2O peak ended where the peak of CO appeared at 850°C where reduction of $FeCr_2O_4$ took place, and the above mass loss graphs further support this. The appearance of CO during the reduction temperatures indicated by the mass loss graphs further confirms that the reducing agent was, in fact, C and not H_2. The m/z 16 peaks are due to the reaction of biocarbon and or CO from the reduction process with the introduced H_2 to produce CH_4. After 1100°C, no more CO comes out, and the weight loss is stabilized, which indicates that the reaction stopped, and all reducible oxides are reduced. **Figures 33 and 34** show the gas analysis of R9_VP for the isothermal and linear reactions, respectively.

The theoretical mass loss was calculated and compared to the actual mass loss based on the compositions of the two samples, R3_RP and R9_VP. According to Figures 30 and 31, the actual mass loss for R3_RP was 32%, whereas the theoretical mass loss was 33.7%. This indicates that a nearly 95% reduction was accomplished, with all metals being able to recover. Although the theoretical mass loss in R9_VP was 42%, the actual mass loss shown was just 24%, indicating a mere 57% reduction, this might be because, in contrast to the FeO, the higher $FeCr_2O_4$ content (60.5%) is harder to reduce, especially with 10% biocarbon in the sample.

The next step is to conduct some XRD and LECO analysis on the reduced samples after reduction to precisely determine the phase compositions that exist, as these will indicate what has been reduced.

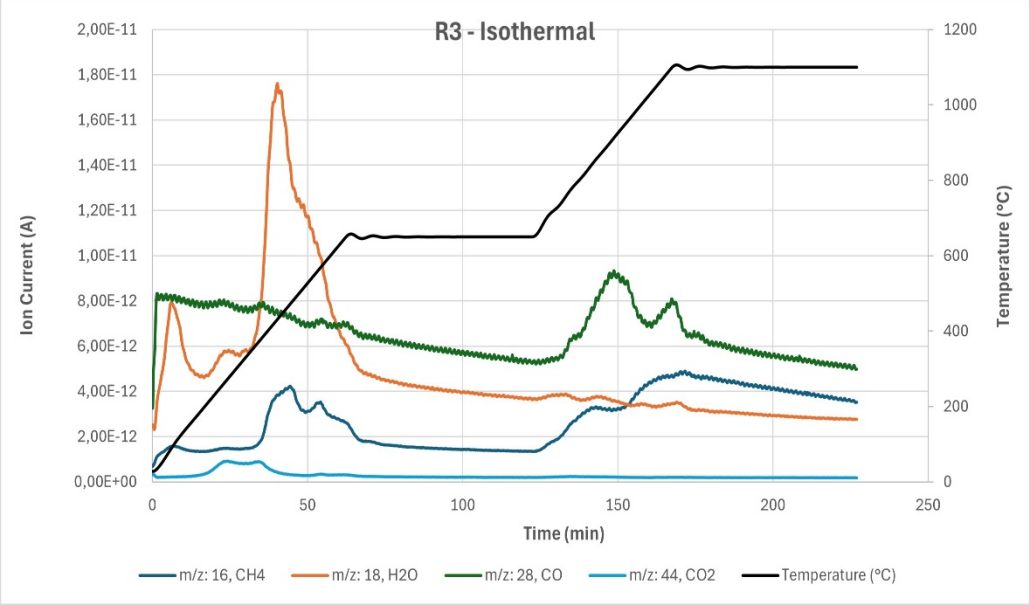

Fig. 31 Gas analysis of the isothermal reaction of R3_RP.

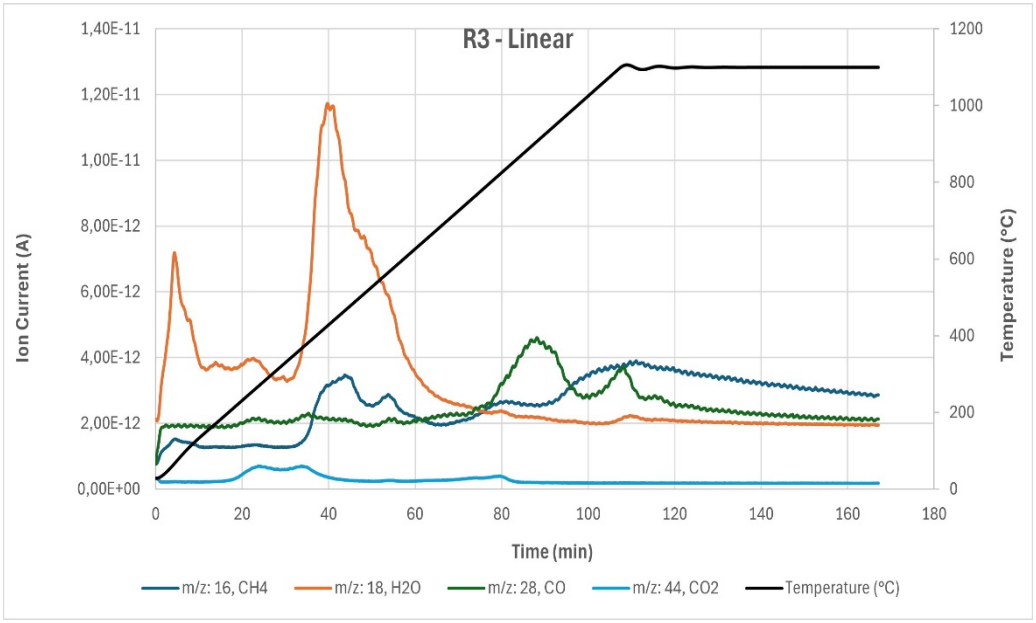

Fig. 32 Gas analysis of the linear reaction of R3_RP showing the continuous reactions, from H_2O to CH_4 and CO production before the reaction ceases.

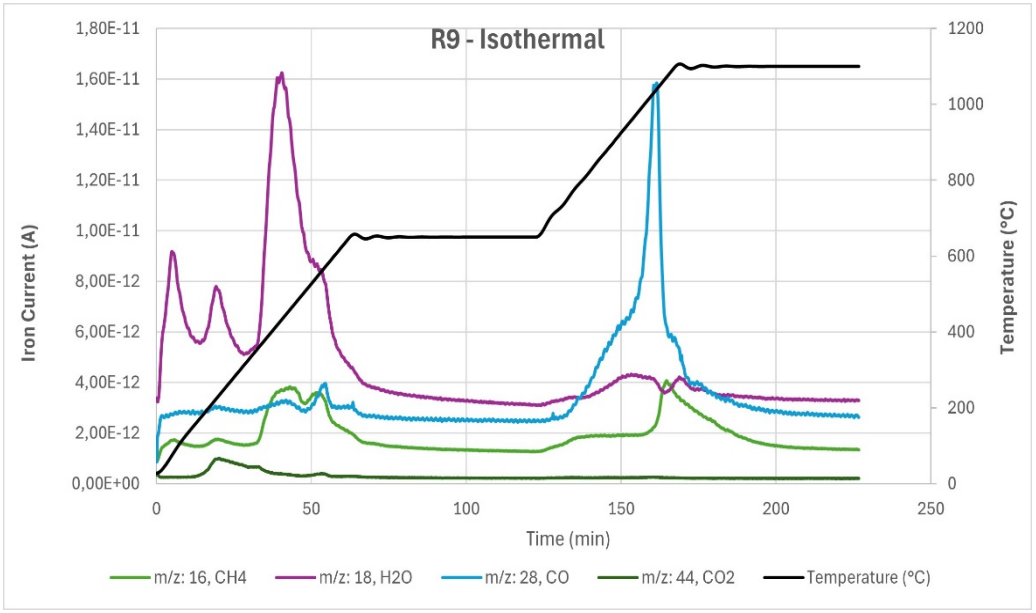

Fig. 33 Gas analysis of the isothermal reaction of R9_VP peaks at m/z 16, 18, and 28, CH_4, H_2O, and CO, respectively.

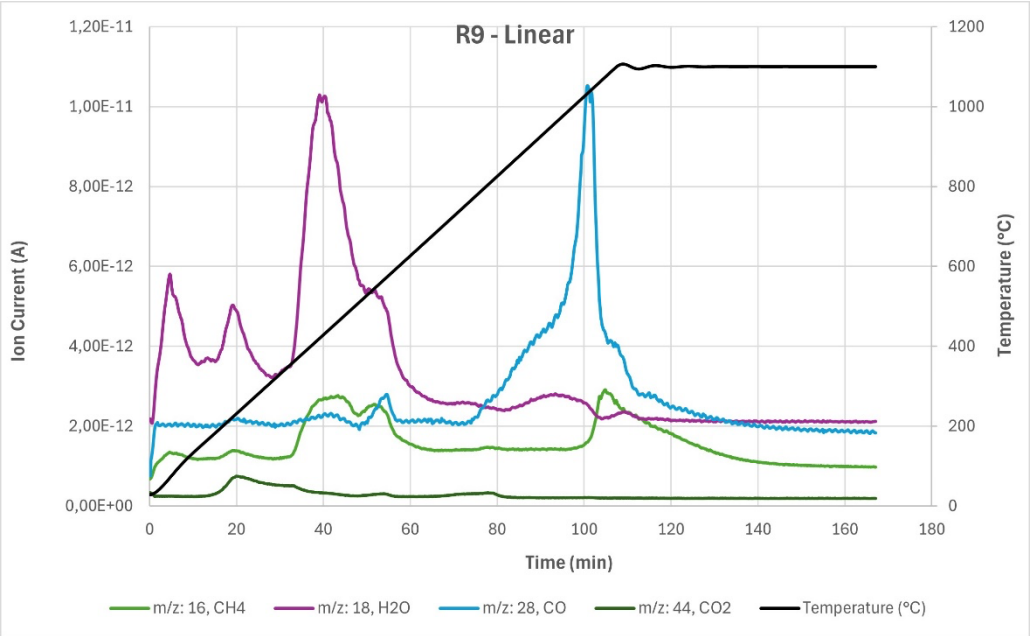

Fig. 34 Gas analysis of the linear reaction of R9_VP.

4 Conclusion

This thesis has provided a comprehensive study on the pre-reduction of a mixture containing chromite ore, mill scale, and biocarbon with H_2 for FeCr manufacturing, emphasizing the importance of briquetting and the application of extensive thermodynamic modeling. FactSage 8.2 was used for precise theoretical calculations and reaction behavior predictions, and they were subsequently contrasted with the actual data.

The study aimed to investigate the potential use of H_2 for reducing mill scale while conserving biocarbon for the reduction of chromite ore during smelting. The rationale for using H_2 as the reducing agent stems from its high sustainability and the fact that it does not contribute to the carbon footprint since its only product is water, aligning with global efforts toward cleaner industrial practices.

- Two samples with different compositions were tested for H_2 reduction in the TGA:
    - R3_RP, composed of 39% chromite ore, 30% mill scale, 20% biocarbon, and 11% binders/ additives.
    - R9_VP, composed of 60.5% chromite ore, 20% mill scale, 10% biocarbon, and 9.5% binders/ additives.
- The reduction was carried out in a TGA-QMS device where the gas used was composed of 90% H_2 and 10% Ar with a gas flow rate of 250mL/min and heating rate of 10°C/min.
- H_2 was able to perform the reduction of mill scale in the samples at a low temperature of 600°C while the biocarbon started to contribute to the reduction reaction of chromite ore as the temperature reached 850°C. As the temperature was high enough for biocarbon to interfere, it acted as the reducing agent and successfully reduced the metal oxides.
- The sample with the higher mass loss of 32% was R3_RP, which had a composition of 39% chromite, 30% mill scales, and 20% biocarbon. It achieved a 95% reduction.
- R9_VP, with the lower mass loss of 24%, even though reduction was achieved, the reaction ceased early, unlike R3_RP. This is because R9_VP had a lower amount of the biocarbon and mill scales, which acted as the reducing agent. R9_VP achieved only a 57% reduction.
- An isothermal step was tested at 650°C to test the effect of low temperature on reduction, it showed no difference in the final reduction percentage between this trial and the linear trial. The reduction of mill scale took place before 600°C, while the reduction of chromite took place at 850°C.

5 Future Studies

Further research is needed to explore the potential of using hydrogen to reduce the mixture, including mill scales, chromite ore, and biocarbon. The research should also focus on identifying the phase compositions formed during the process, besides investigating the reduction kinetics and mechanisms of the developed briquettes, supported by chemical analysis and microstructural investigations.

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