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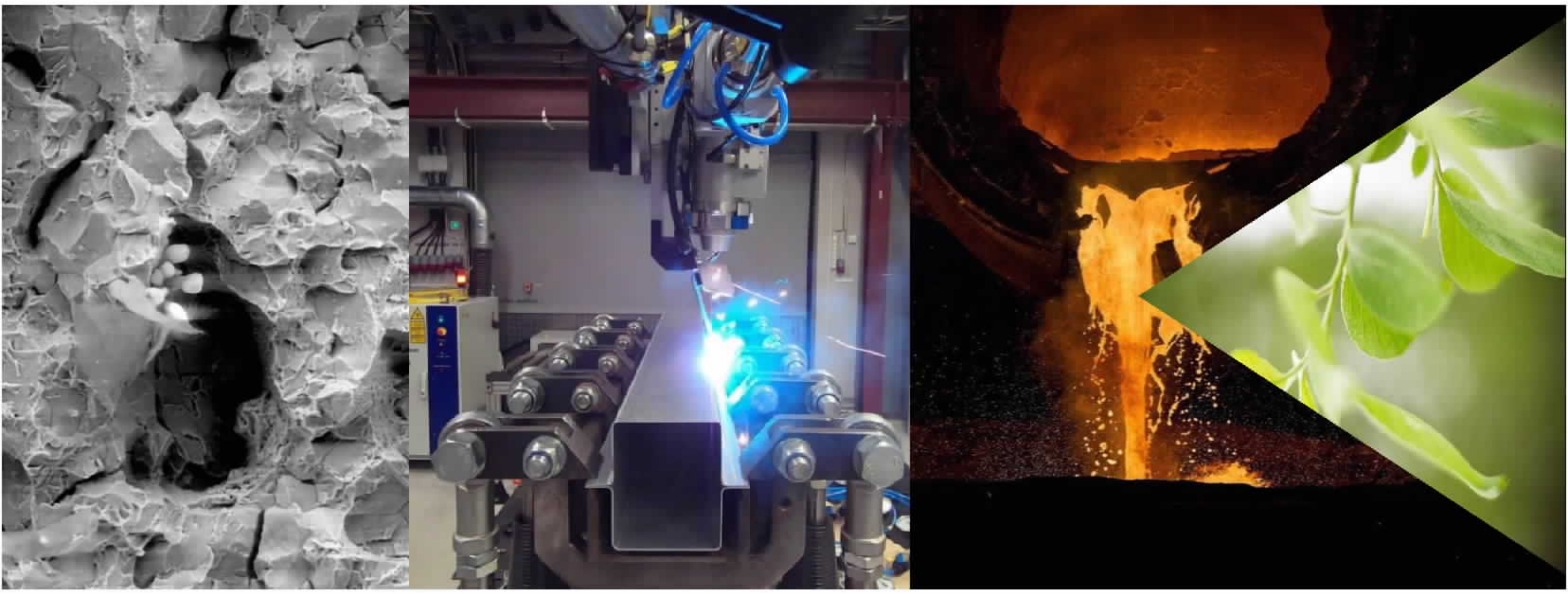

Agglomerates for Next Generation Lignin Based Steel making

Elsayed Mousa, Karthik Manu, Daniela Rusanova-Naydenova, Marcus Elmer

Report number. Swerim-2024-253

05-09-2024

Research Report

Public

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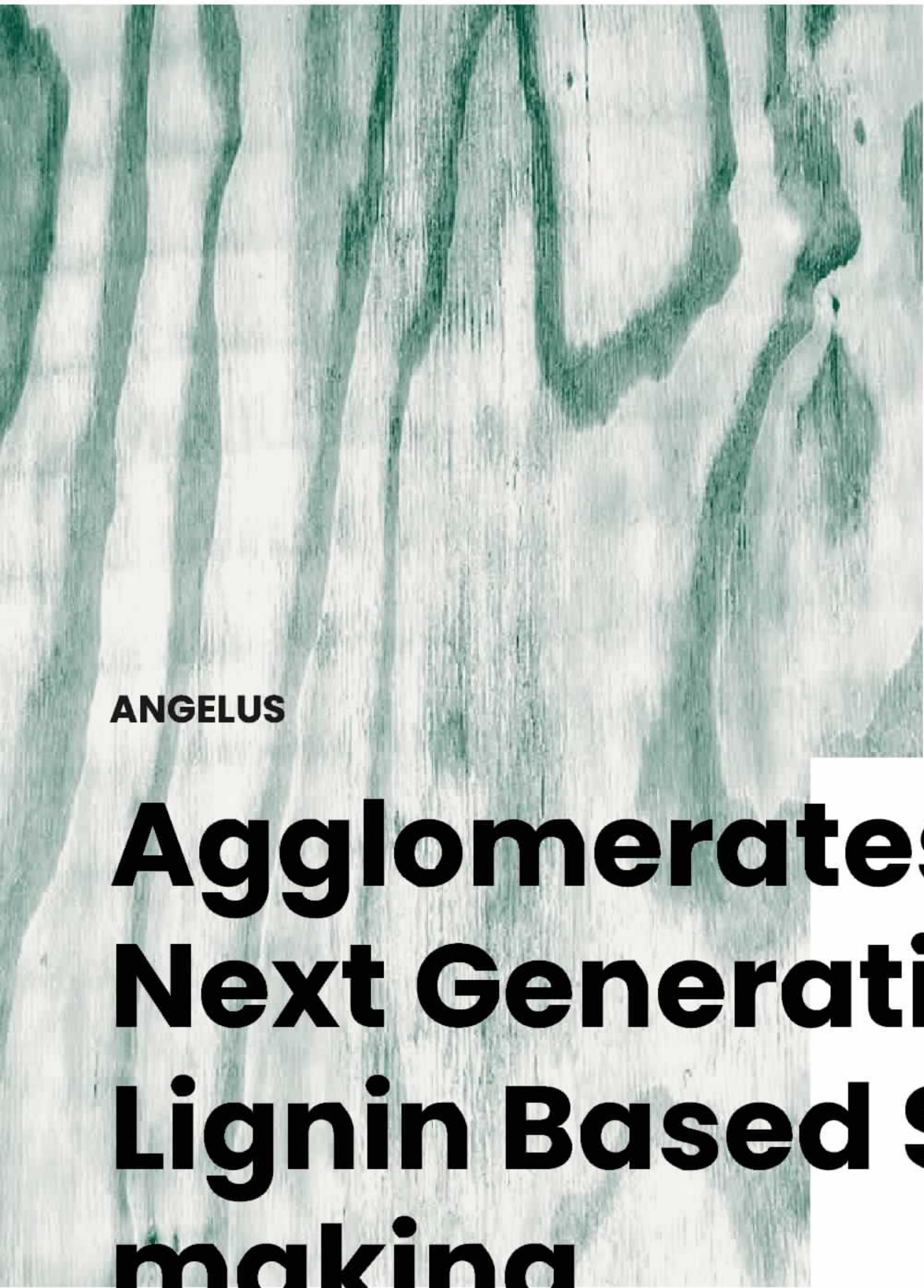
Title	Agglomerates for Next Generation Lignin Based Steel making
Author	Elsayed Mousa, Karthik Manu, Daniela Rusanova-Naydenova, Marcus Elmer
Publication date	05-09-2024
Report number	Swerim-2024-253
Status	Public
	[Open from]
Project number	103787
Project leader	Elsayed Mousa
Business Area	Metallurgy
Research Area	Resources, recycling and agglomeration
Member program	Metallurgy
Financing	RE:Source
Distribution	RE:Source, Swedish Energy Agency, marcus@suncarbon.se;daniela@suncarbon.se
Approved by	2024-09-10 X Signerat av: Mikael Larsson Business area manager
Research committee	
[Names of members]	[Corresponding companies]



ANGELUS

Agglomerates for Next Generation Lignin Based Steel making

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1. Introduction

The Swedish steel industry is actively pursuing the goal of introducing fossil-free steel into the global market. This ongoing transformation towards sustainable steel production is underpinned by circular economy principles, emphasizing the reuse and recycling of available by-products (Lavers et al., 2022). Notably, lignin, a substantial by-product derived from the pulp and paper industry, holds unexplored potential as a carbon carrier for diverse applications within the steel industry (Marakana et al., 2021; 'Mastrolitti et al., 2021). The primary objectives of this study are to devise strategies for optimizing the recycling of steel residues by employing lignin as a binding agent, examining its efficiency as a reducing agent for iron oxides, and probing its potential as a carbon source. This feasibility study encompasses a comprehensive survey, coupled with the design, fabrication, and evaluation of lignin-loaded agglomerates tailored for the next generation of steel production.

The global endeavor to promote material reuse and recycling has garnered significant attention in the past decade, as it is instrumental in fostering a sustainable society. Prolonging the life of materials not only contributes to a reduction in landfills but also mitigates the depletion of natural resources. This work addresses the efficient management of resources in two of Sweden's most prominent export-oriented industrial sectors: the pulp and paper industry and the steel industry (Lavers et al., 2022). Notably, slag, a predominant by-product of traditional steel production, constitutes a substantial portion of gangue oxides due to the application of inorganic binders (Schwelberger et al., 2017). Various iron and steel-making residues such as pellet fines, filter dust, BF flue dust, BOF sludge (coarse and fine), lime, iron ore fines, mill scale, and coke fines are typically recycled internally within the steel plant. On the other hand, by-products like slag and EAF dust find external applications, while the remaining unutilized portion, including sludge, is consigned to landfills.

The recycling of valuable steel residues and fines revolves around the fundamental principle of agglomeration, which requires a range of inorganic and organic binders to enhance the mechanical and thermal properties of agglomerates (Halt & Kawatra, 2014). Innovations have enabled the extraction of lignin from black liquor with low ash and sulfur content. The agglomeration of metallurgical residues and fines with binders can be executed through an assortment of techniques, influenced by the physical, chemical, and mineralogical composition of the residues, as well as the prescribed product quality for the subsequent recycling process. In Sweden, the recycling of steel residues predominantly involves the production of cold-bonded briquettes through vibro presses using cement as a binder. In our previous study (E. A. Mousa et al., 2017), we demonstrated that it was possible to replace up to 25% of cement with lignin without compromising the quality in terms of strength. Furthermore, the lignin blend briquettes showed improved performance in terms of reduction. However, it is paramount to note that this type of briquette, although suitable for blast furnace implementation, may not be adequate for H_2-based direct reduction processes. These processes necessitate more robust briquettes following reduction to maximize resource efficiency and minimize energy consumption and CO_2 emissions in the electric arc furnace (EAF) (Marakana et al., 2021; 'Mastrolitti et al., 2021).

Carbon charged into the EAF is a significant contributor to direct greenhouse gas emissions in steelmaking. Carbon consumption from charged coal and coke typically ranges from 3 to 12 kg per ton of liquid steel, with a recovery rate of 30% to 80%, contingent upon particle size and charging mode. Biocarbon, in the form of lignin, is an appealing alternative to fossil carbon, even though comprehensive information comparing its performance to conventional fossil carbon materials under extreme steelmaking conditions is limited(Drobíková et al., 2018).

Previous research works (Elsadek et al., 2024; Manu et al., 2023) has confirmed that the usage of lignin contributed to briquettes with superior green strength (strength of briquettes directly after production). Hence, this study will examine the strength variation when lignin is combined with other inorganic binders in order to obtain high dry strength. As suggested by (Mousa et al. 2017; Mennani et al., 2024), lignin also have potential to act as a reductant during the reduction process in the furnace.

In view of this setting, the overarching objectives of the current ANGELUS project are to encompass three key aspects: firstly, to propose schemes for the partial or complete utilization of steelmaking-generated residues and by-products customized to the portfolio of each company. Such an approach is anticipated to conserve virgin materials, optimize economic gains, and minimize environmental impacts. Secondly, to recommend an optimal method for agglomerating unused residues and by-products in steel plants, employing lignin as a binder and, optionally, as a carbon source. Thirdly, to identify the lignin characteristics that influence the performance and product quality of agglomerates. Namely, moisture content, drying behaviour, binder type, binder ratio, and the compaction pressure. In the long term, the project's impact can be assessed through a series of considerations: Sweden's aspiration to produce approximately 10 million tons of crude steel aligns with the sustainable development goals of the European Union. Initiatives like HYBRIT and H2 Green Steel intend to produce 10 million tons of crude steel by 2030 (Sweden Could Become a Pioneer in Green Steel Production, 2021), emphasizing the growing demand for carbon in steel production(E. Mousa et al., 2022). To address this demand, the incorporation of lignin, which is generated as a co-product from the pulp and paper industry, could present an interesting supplementary biocarbon source for the steel industry. For the production of 10 million tons of crude steel, the anticipated generation of approximately 700,000 tons of pellet fines (Prusti et al., 2022), necessitates further reprocessing. Similarly, an expected generation of 164,000 tons of mill scales and 246,000 tons of direct reduced iron (DRI)/hot briquetted iron (HBI) fines per year, requiring additional valorization processes (Pei et al., 2020).

Figure 1 illustrates the by-products and the generated residues in an integrated steel plant. As the steel industry undergoes a green transition, many plants will adopt more environmentally friendly production methods, including the use of Directly Reduced Iron (DRI) as a raw material. Even with the shift from blast furnaces to Electric Arc Furnaces (EAFs), which is a key step in this transition, the production of mill scales and pellet fines will persist, as pellets are a primary charge material in EAFs. Therefore, this study focuses on mill scales and pellet fines as the residues of interest, given their inevitable generation in this new production paradigm.

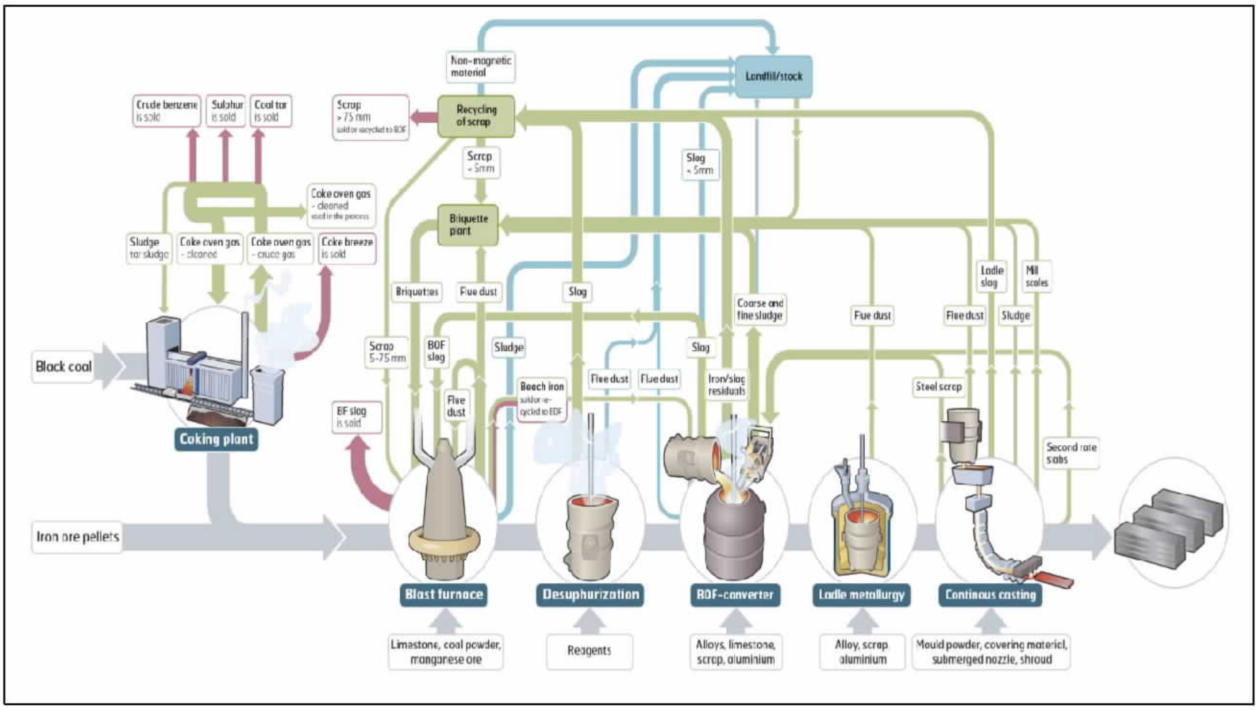


Figure 1: By-products and residue generation in an integrated steel plant

2. Material and Method

2.1. Material Characterisation

The pellets fines and mill scales are sourced from steel producers and the supplied materials were subjected to elemental composition identification using X-Ray Fluorescence (XRF).

Table 1: Chemical composition of the supplied pellet fines

Components	Fe total %	CaO %	SiO_2 %	MnO %	P_2O_5 %	Al_2O_3 %	MgO %	K_2O %	V_2O_5 %	TiO_2 %	Cr_2O_3 %
Pellet fines	66.58	0,48	1,98	0,1	0,02	0,42	1,16	0,03	0,21	0,22	0,03
Mill scales	74,3	0,63	0,68	0,55	0,01	0,14	0,08	0,01	0,015	0,018	0,068

Particle size distribution (PSD) largely influences the surface area, compaction, and mechanical properties of the final agglomerates. The extent of finer particles influences the degree of densification for the processed briquettes. Hence, in order to attain an overview of the size ranges of the samples (mill scale and pellet fines), a mechanical sieve shaker (Retach AS200 basic) was used in this work to determine the PSD of the supplied raw materials. From **Figure 2**, it can be confirmed that the mill scales were mainly composed of particles in the size range of 1 to 2 mm (~ 70%). Whereas, particle size distribution of pellet fines, confirmed the presence of fine particles in the size range of less than 0,063 mm (~40%) and a larger fraction of particles in the size range of 1,0 to 5,6 mm. Apart from the chemical analysis and PSD, moisture content variation for each of the prime materials along with the binders were determined using a Mettler Toledo moisture analyzer. As **Table 2** suggests, three different lignin types namely lignin 1 (soda pulping), lignin 2 (kraft lignin), and lignin 3 (?) sourced from different suppliers were considered throughout the work along with partial additions of three other binders (sodium silicate, hydrated lime and calcium stearate).

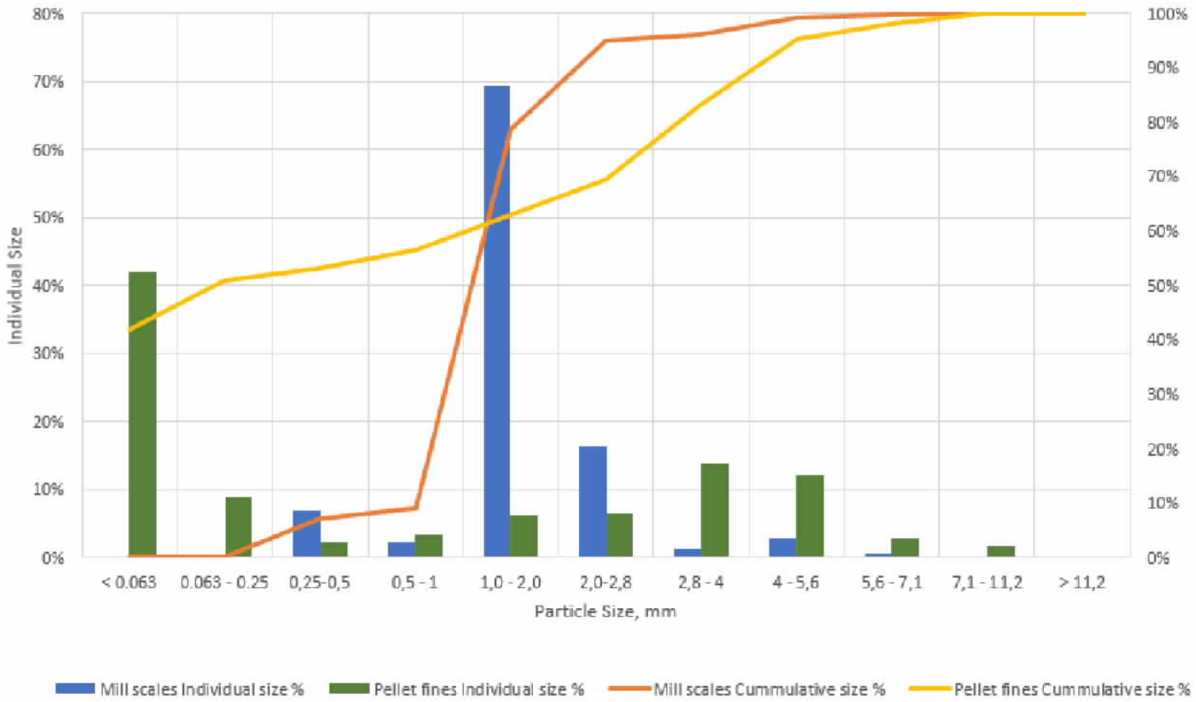


Figure 2: Particle size distribution of the raw materials

Table 2: Moisture content of supplied material.

Material	Moisture %	Type
Mill scale	2,41	Prime material
Pellet fines	0,03	Prime material
Sodium silicate	1,23	Inorganic binder
Hydrated lime	0,51	Inorganic binder
Calcium stearate	2,51	Organic binder
Lignin 1	4,42	Organic binder – Soda pulping lignin
Lignin 2	4,55	Organic binder – Kraft lignin
Lignin 3	2,17	Organic binder - kraft/pyrolysis lignin
Biocarbon	0,11	Pyrolyzed biocarbon

2.2. Briquetting process

The briquettes were produced into cylindrical shaped briquettes using a hydraulic piston press (Herzog, HERZOG Maschinenfabrik GmbH & Co. KG, Osnabrück, Germany). Approximately 20 g of material was loaded into the mold with a diameter of 2 cm for each press. Compression force of 100 or 200 kN was applied, to investigate the effect of the compaction pressure on the strength of the briquettes. A hydraulic compression testing machine (ENERPAC Applied Power GmbH, Düsseldorf, Germany) was used on each briquette to determine Cold Compressive Strength (CCS) and Splitting Tensile Strength (STS). For measuring strengths below 1 bar, a Newton compression tester was used since the hydraulic compression testing machine only measures pressures above 1 bar. For CCS measurement, the briquettes were compressed in the longitude standing position, whereas for the STS measurement, briquettes were compressed in a horizontal laying position. To obtain a reliable strength value, three briquettes were tested for each CCS and STS measurement, and the resultant average value is plotted.

2.3. Reduction and smelting trials

Thermogravimetric analysis (TGA) was performed on each of the promising recipes from mill scales and pellet fines using thermogravimetric equipment coupled with a quadrupole mass spectrometer (TGA-QMS, Netzsch thermal analysis STA 409). One out of the produced mill scale and pellet fines recipe that developed decent green strength (strength of the briquette resulted directly after production) and dry strength (strength of the briquette resulted after 2 hours of oven drying at 85°C) were selected for further reduction trials. Reduction trials were carried out in TGA at 15°C/min heating rate until a temperature of 1400°C was attained. Parallelly, smelting trials for the best-performing recipe were carried out in Tammann furnace at a heating rate of 10°C/min until the temperature reached 1000°C and maintained that temperature for 1 hour to give sufficient time for the self-reduction in nitrogen flow (~7 liter/min) atmosphere. Thereafter, the temperature was raised ~1500°C to completely melt the briquettes. After the furnace cooled down and the successful collection of the crucibles, slag and the metal were separated and characterized further.

3. Results and Discussions

3.1. Briquetting and testing

3.1.1 Mill scales

In this study, 3 different types of lignin were tested for briquetting of mill scale. In addition, based on the literature survey and our previous work, three other binders (Ca-stearate, hydrated lime, and sodium silicate) were selected and tested for briquetting of mill scale either individually or in conjunction with lignin. **Table 3** depicts the developed recipes with regards to determine the effect of binder type in combination with other additives such as Ca-stearate, hydrated lime and sodium silicate.

Due to the production of higher number of recipes which resulted in more data, as an overview, **Table 4** showcases the recipes to compare and their respective intent.

From **Figure 3** it can be ascertained that the dry density of the developed briquettes will always be slightly lower compared to the wet density due to the effect of moisture in the briquettes. It can also be concluded that increasing lignin addition from 0-10% further decreases the density of the briquettes. All of the lignin-containing (10wt.%) briquettes developed density in the range of 3-3.8 g/cm^3 whereas every briquette without lignin addition (with other binder addition) possessed density of 4.5-5 g/cm^3.

From the moisture content variation (**Figure** 4), it can be inferred that most of the recipes were developed with higher amount of moisture in the mix, which then resulted in water escaping out of the mould while briquetting and consequently lower moisture in the green briquettes. The comparison of recipes with trace amounts of sodium silicate addition has confirmed that the incorporation of sodium silicate helps the briquettes maintain moisture content within the briquettes. In other words, the addition of sodium silicate stabilizes the moisture levels within the briquettes.

Table 3: Developed recipes for mill scales being the prime material

	Mill scales	**Calcium stearate**	**Hydrated lime**	**sodium silicate**	**lignin 1**	**lignin 2**	**lignin 3**
Sl. No.	**wt.%**						
R1	100						
R2	99	1					
R3	99		1				
R4	99,8			0,2			
R5	95			5			
R6	90				10		
R7	90					10	
R8	90						10
R9	89	1					10
R10	89	1					10
R11	89	1					10
R12	89	1					10
R13	89	1					10
R14	89		1				10
R15	89		1		10		
R16	89		1			10	
R17	88		2				10
R18	85		5				10
R19	75		5				20
R20	85		5			10	
R21	88		2				10
R22	88		2				10
R23	93		2				5

R24	88,8		1	0,2		10	
R25	89,8			0,2			10
R26	89			1		10	
R27	85			5		10	
R28	90			5		5	
R29	85			5		10	

Table 4: Recipes and their corresponding intent

Recipes	Parameter variation	Intention
R1-R8	➢ R1 is reference recipe with 100% mill scales. ➢ R2-R5 different binder addition ➢ R6-R8 different type of lignin	To infer the effect on strength by varying type of binder used
R9-R13	➢ Addition of 1% calcium stearate to 10% lignin containing briquettes with varying moisture content ➢ R10, R13 produced at 100kN compaction pressure. ➢ R11, R12 produced at 200kN compaction pressure	To infer the effect of addition of calcium stearate, moisture content, and compaction pressure on briquette strength
R14-R23	➢ Addition of 1, 2 and 5% hydrated lime to different types of lignin	To infer the effect of hydrated lime addition to each lignin type
R24-R29	➢ Addition of 0.2, 1 and 5% sodium silicate to the different types of lignin	To infer the effect of sodium silicate addition to each lignin type

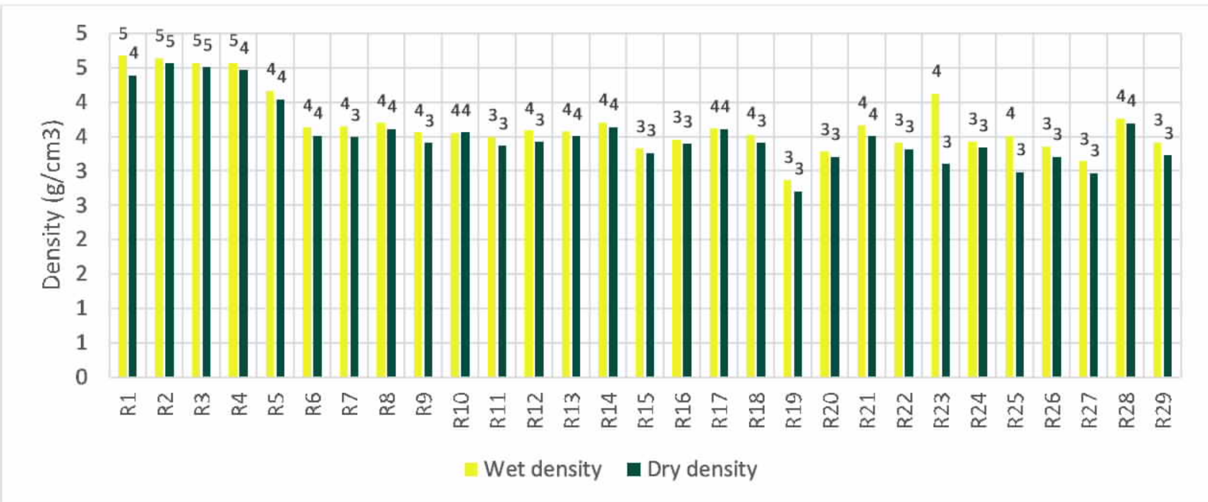


Figure 3: Variation of dry and wet density for the developed recipes

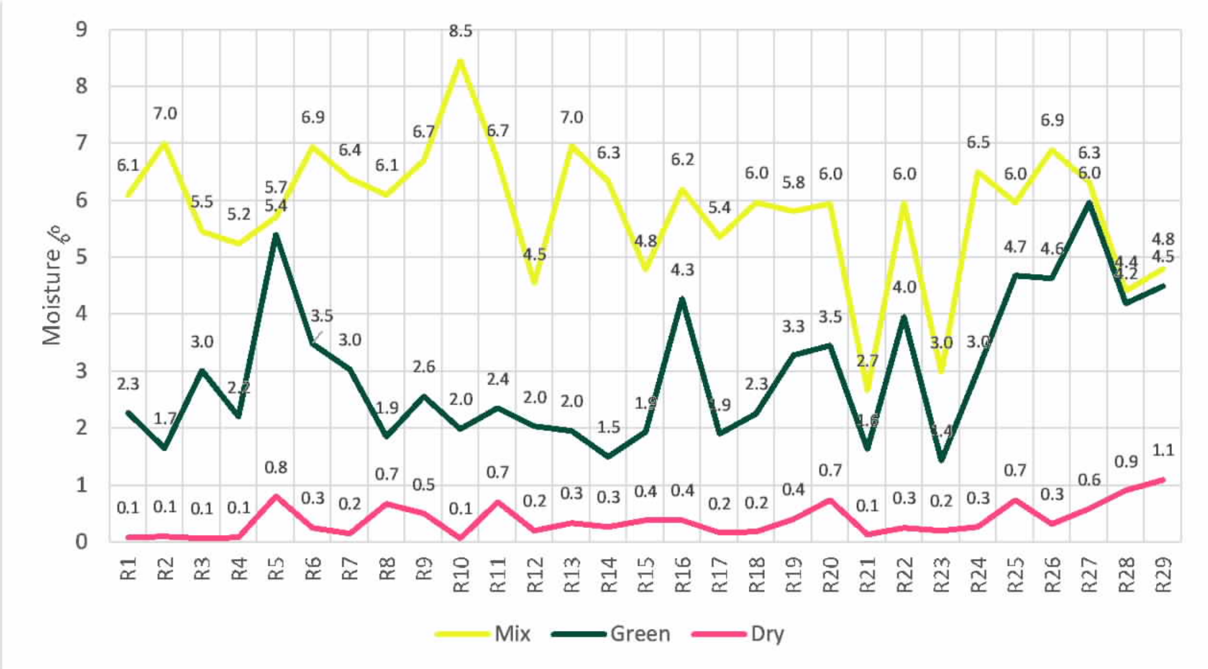


Figure 4: Moisture content variation in the mix, green and dried briquettes

After successfully producing briquettes, CCS and STS of the developed briquettes were determined just after production (green strength) and after drying briquettes in the oven at 85°C (dry strength). **Figures 5 and 6** depict the green and dry strength for all of the 29 developed recipes. Some of the major conclusions that can be made from the plots are as follows:

- The addition of lignin, irrespective of lignin type, significantly increased the green strength of the developed briquettes. Increasing sodium silicate content from 0.2 to 5 wt.% have increased dry strength remarkably.
- Addition of 1% hydrated lime depicted superior strength when compared to briquettes with 1% calcium stearate to 10% lignin containing briquettes.
- Recipes produced at 200kN (R10 and R13) showcased slightly better strength than the recipes being produced at 100kN (R11 and R12).
- Addition of 1% hydrated lime to lignin 3 depicted dominant strength when in comparison to other lignin types (lignin 1 and lignin 2).
- Increasing hydrated lime content from 1-5% and fix lignin3 at 10%, the strength was slightly dropped. Parallelly, increasing lignin 3 content from 10-20% have dropped the final briquette strength.
- Increasing lignin content (irrespective of the type) adversely affects the dry strength of the briquettes, whereas positively increases the green strength.

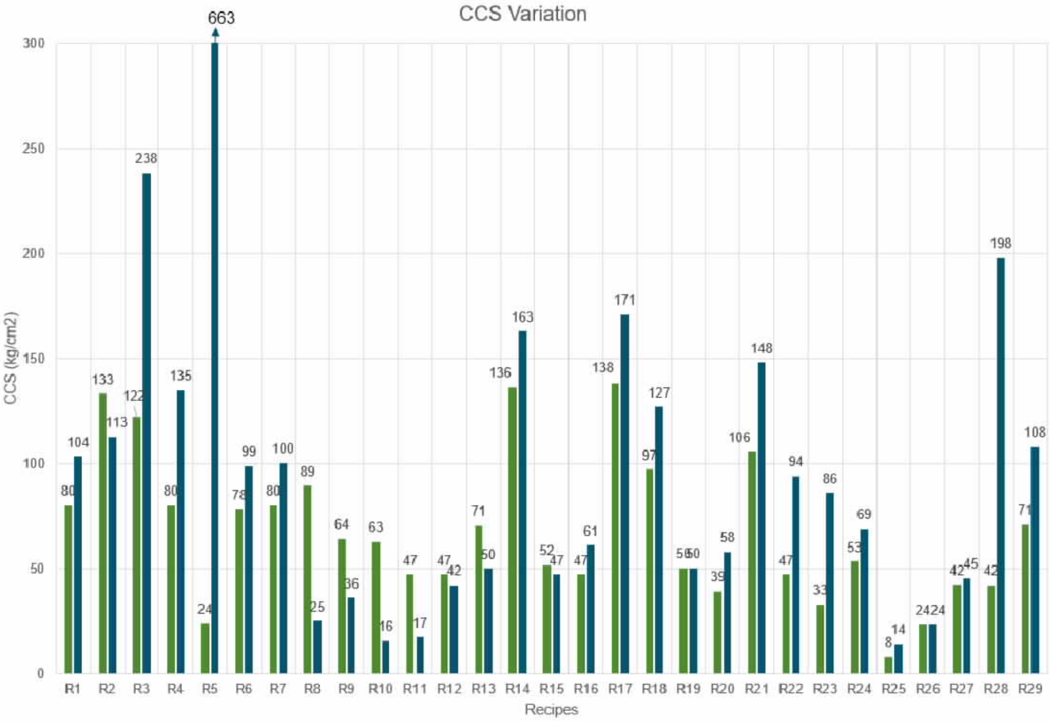


Figure 5: CCS variation for the developed recipes

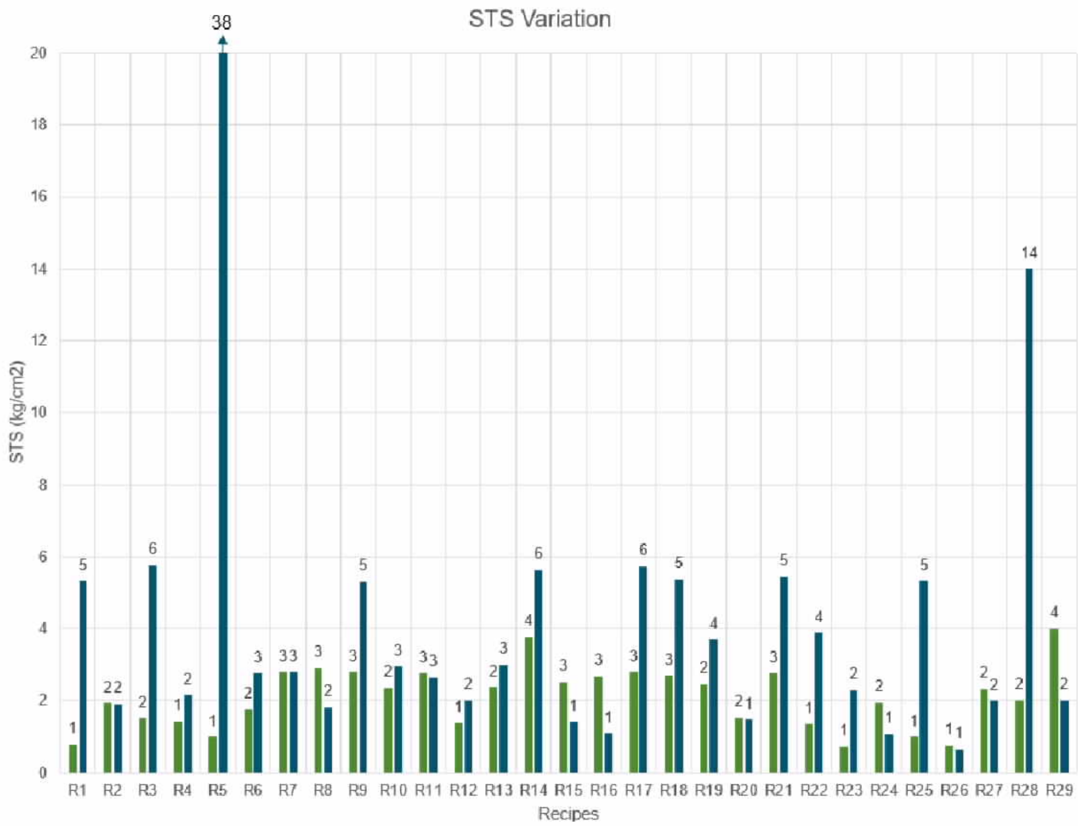


Figure 6: STS variation for the developed recipes

3.1.2. Pellet fines

From the results of mill scale recipes, the addition of 1% hydrated lime to the lignin-containing briquettes proved to develop decent green and dry strength for the final briquettes. Hence, that specific composition was aimed to be tried out on pellet fines recipes. **Table 5** represents the recipes that were produced with pellet fines as prime material with biocarbon addition. The aim of adding biocarbon is to increase the C-fix in the briquette and consequently enhance the reduction of iron oxide, which is present in higher concentrations in pellet fines compared to mill scale.

Table 5: Developed recipes for pellet fines being the prime material

Recipe	pellet fines	Hydrated lime	Lignin 2	Lignin 3	biocarbon
R1	100				
R2	89	1	10		
R3	89	1		10	
R4	84	1		10	5
R5	94	1			5
R6	85			10	5

Figure 7 depicts the density variation for the developed recipe, which in turn confirms that the magnitude of the wet density is slightly higher than that of dry density. Parallelly, it can also be ascertained that the reference recipe (without any binder) showed higher density compared to other recipes containing 10% lignin. During the briquetting process of pellet fines, there was very minimal observance of water coming out of the mould. This attributes to the fact that the moisture content in the mixture and green briquette is almost similar (see **Figure 8**).

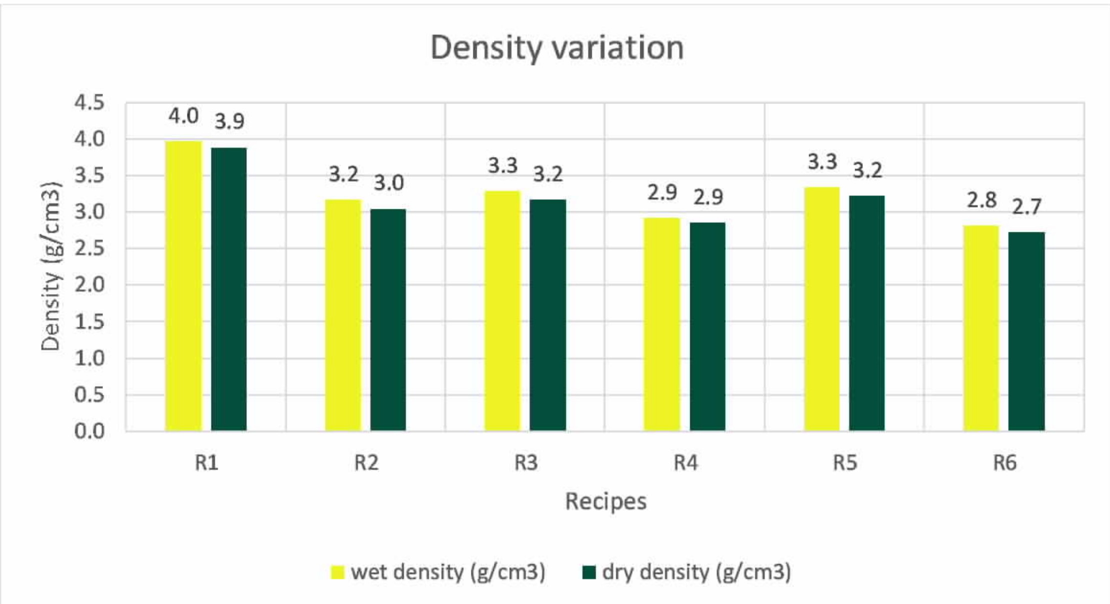


Figure 7: Density variation for the developed recipes

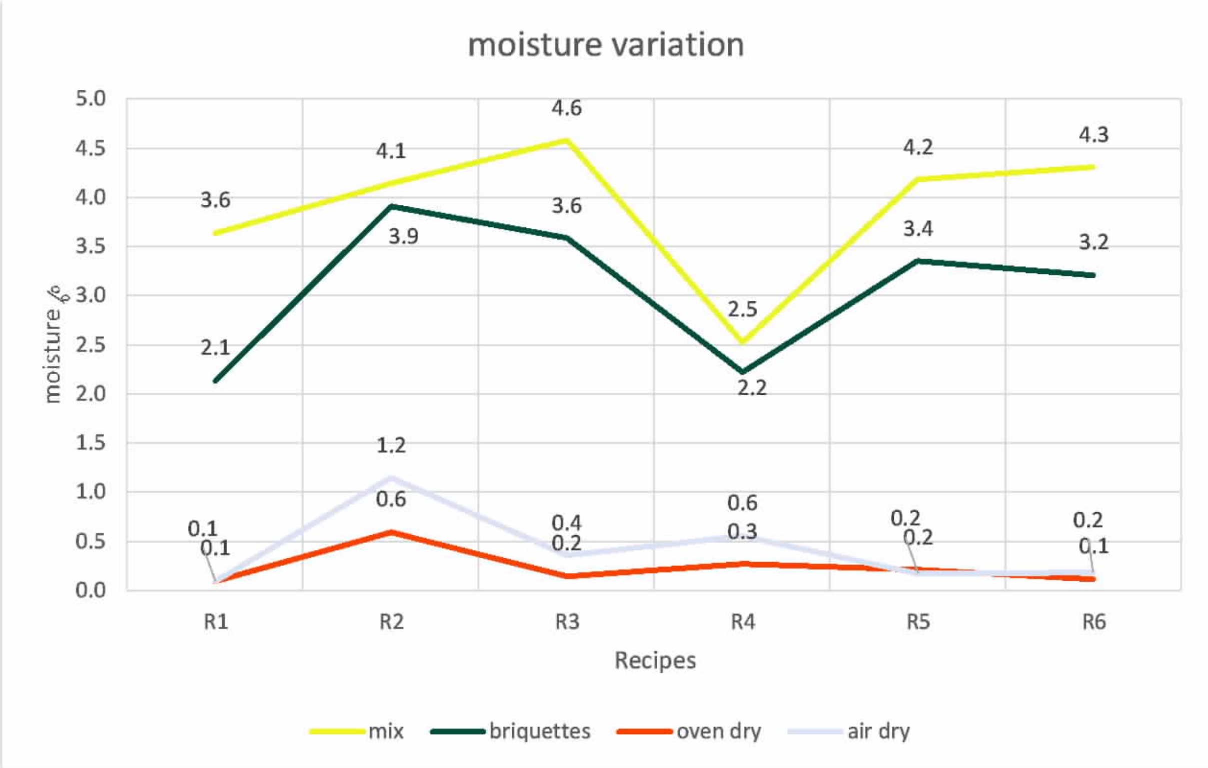


Figure 8: Moisture variation for the developed recipes

In addition to green strength and oven dry strength, the natural air drying strength of the briquettes after 72 hours was also determined to obtain more understanding of how the extent of drying time influences the final briquette quality. As seen from **Figure 9 and 10**, recipe R3, with 1% hydrated lime and 10% lignin 3 proved to be the best recipe out of the developed recipes for further reduction trials. In the view to achieve complete reduction by addition of biocarbon, effect on strength of the briquettes while adding biocarbon has also been explored. Results confirmed that the addition of biocarbon adversely affects the briquette strength although it will be beneficial for the reduction process. Lastly, on comparing R2 to R3, lignin 3 was capable to develop superior quality briquettes with higher strength when in comparison with lignin 2.

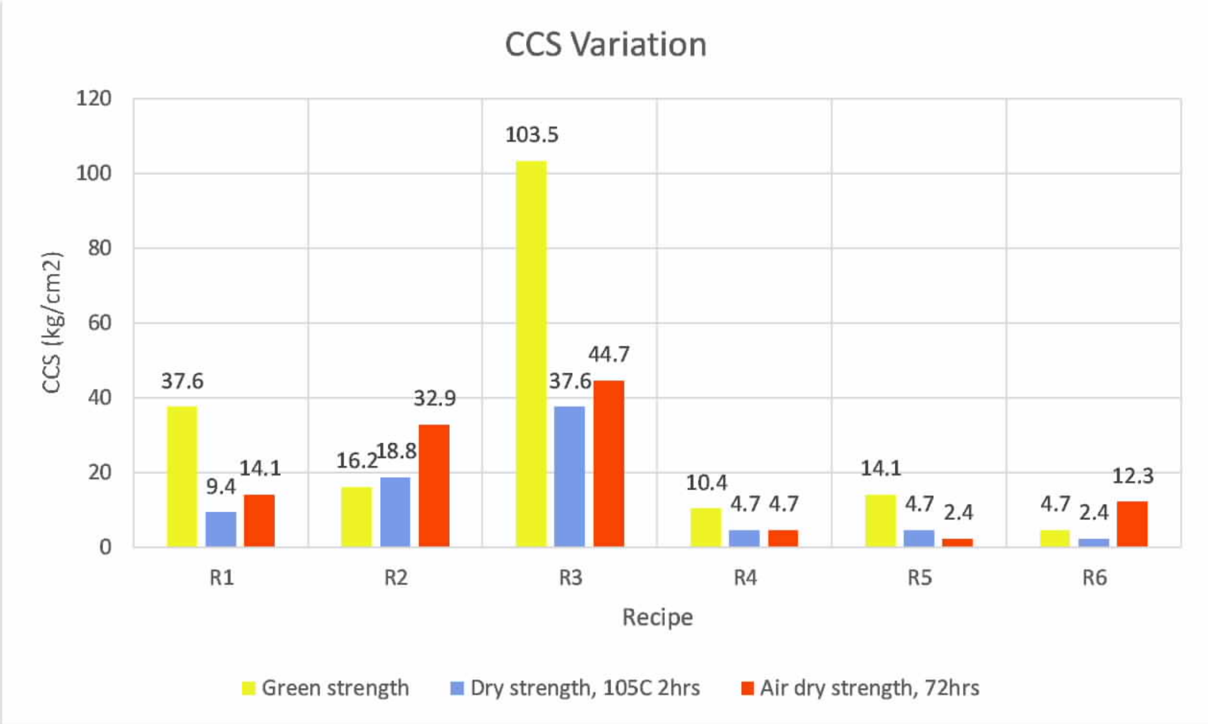


Figure 9: CCS variation for the developed recipes

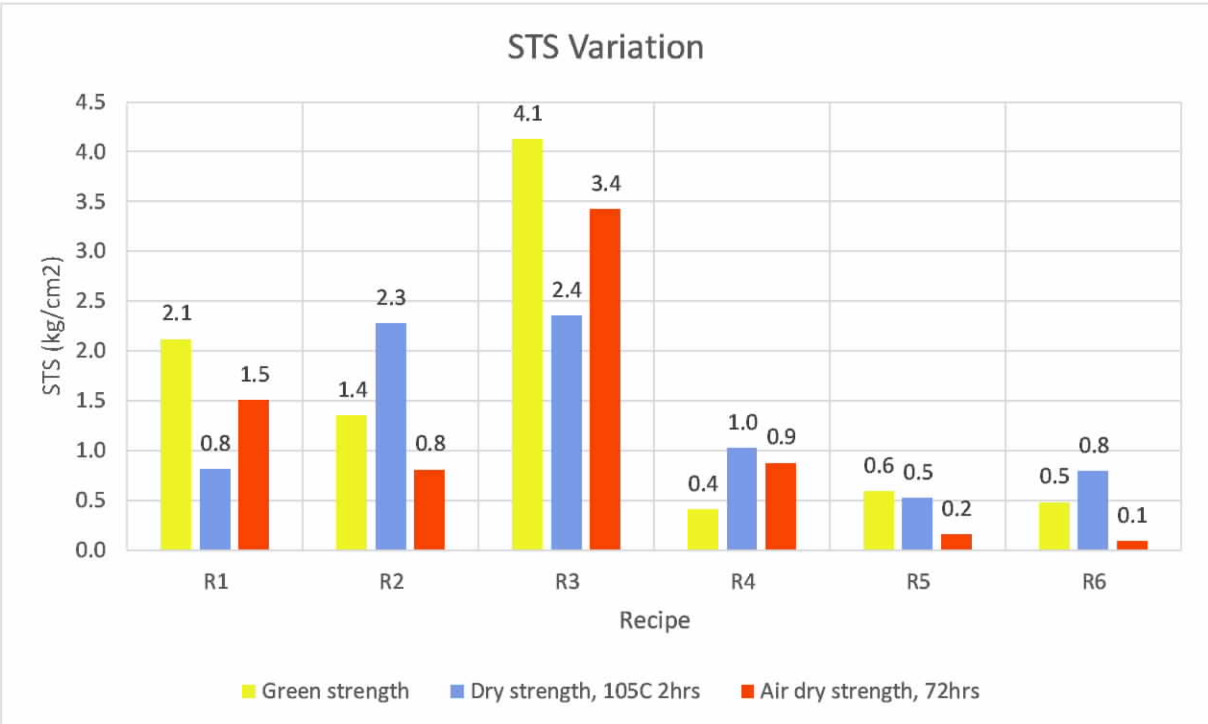


Figure 10: STS variation for the developed recipes

3.2. Reduction and smelting trials results

Table 6 represents the recipes selected for TGA analysis, and the TGA plot for the developed recipes R10_mill scale, R3_pellet fines along with the supplied lignin 3 are plotted in **Figure 11 , 12 and 13**, respectively.

Table 6: Recipes selected for reduction trials

Recipes	Mill scales	Pellet fines	Hydrated lime	Lignin 3
R10_mill scale	89	0	1	10
R3_pellet fines	0	89	1	10

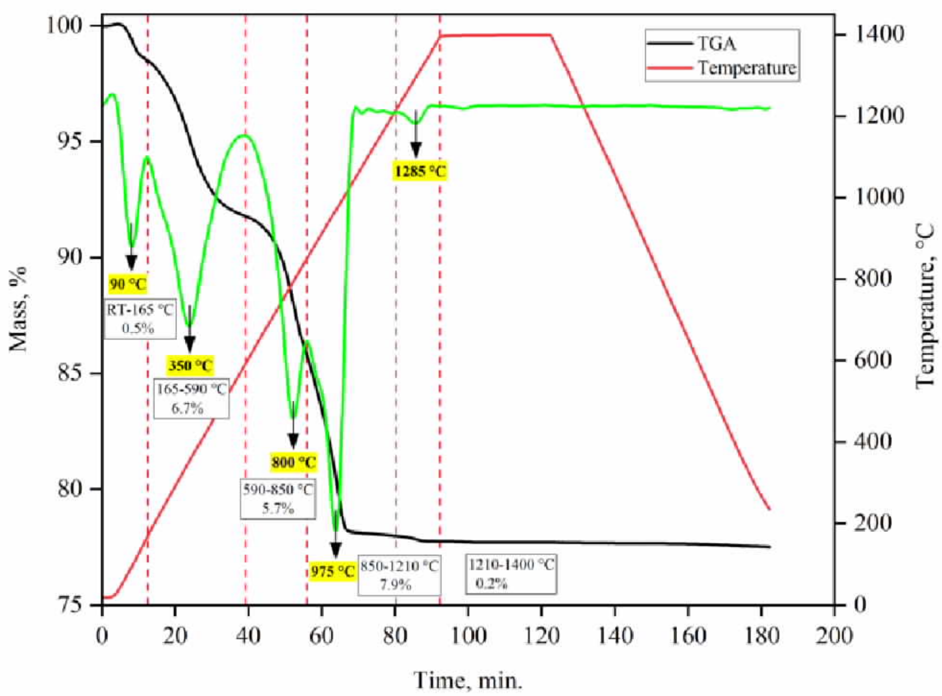


Figure 11: TGA plot for recipe R10, with mill scales

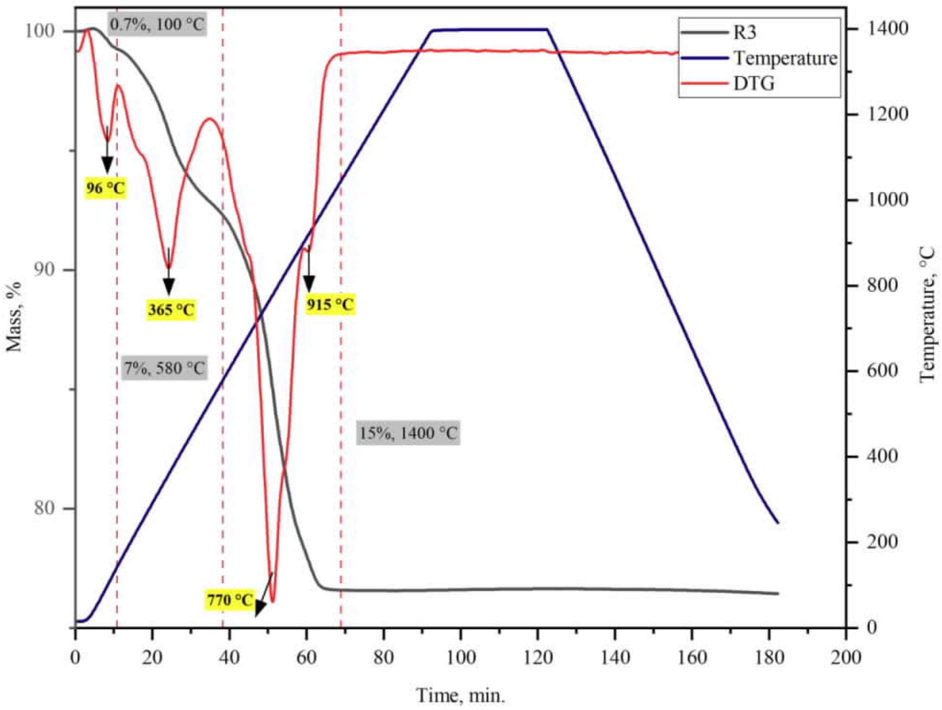


Figure 12: TGA plot for recipe R3, with pellet fines

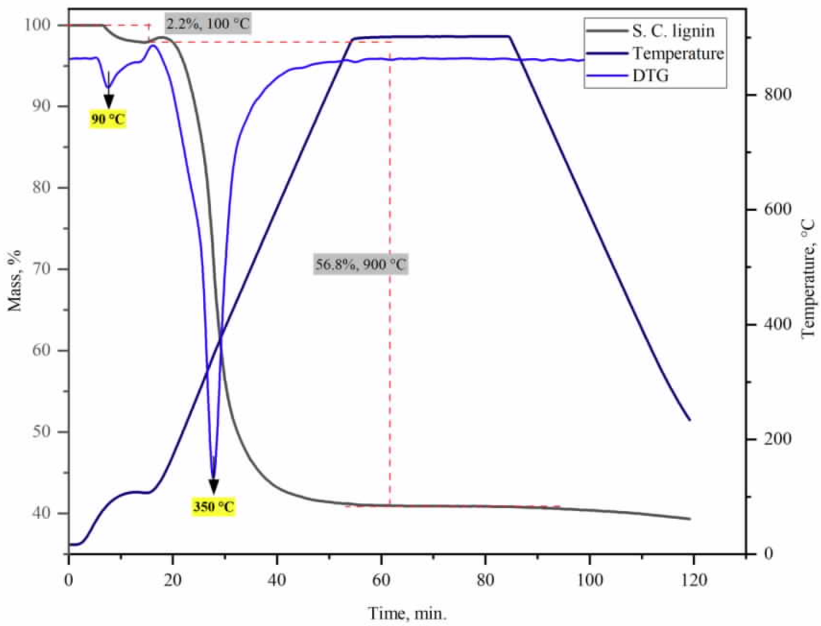


Figure 13: TGA plot for lignin 3

From **Figure 11** and **12** it can be ascertained that a weight loss percentage of 22.5% and 23.5% can be achieved. Whereas previous literature (Elsadek et al., 2024) (Manu et al., 2023) suggests that recipes with mill scales and pellet fines (come from same sources as that tested in this study) must attain ~31.67% and ~35.83% as weight loss percentage, respectively, for complete reduction. Efforts has been made to correlate TGA results to achieve complete reduction, it can be inferred that only 71% and 65.5% of reduction took place for recipes R10_mill scale and R3_pellet fines, and the amount of biocarbon addition needed to achieve complete reduction was theoretically determined to be 11.42%, and 16.6, respectively. TGA analysis in **Figure 13** revealed that lignin type 3 experienced a weight loss of 61% after 1 hour at 900°C in an inert atmosphere. This indicates that the fixed carbon and ash content is approximately 39%. However, this carbon content is insufficient to achieve the complete reduction of iron oxides in the briquettes.

FactSage calculations for mill scale, shown in **Figure 14**, suggest that 15 g of lignin alongside 15 g of biocarbon is needed to fully reduce 100 g of mill scale FeO. This translates to a requirement of approximately 11.5% biocarbon in the recipe to achieve complete reduction. **Table 7** depicts the recipes that were selected (R10 & R16 for mill scale and R2 for pellet fines) from previous recipes for the smelting test. In addition, two new recipes were designed with biocarbon (R10b for mill scale & R3b for pellet fines) to enhance the reduction process based on the TGA results.

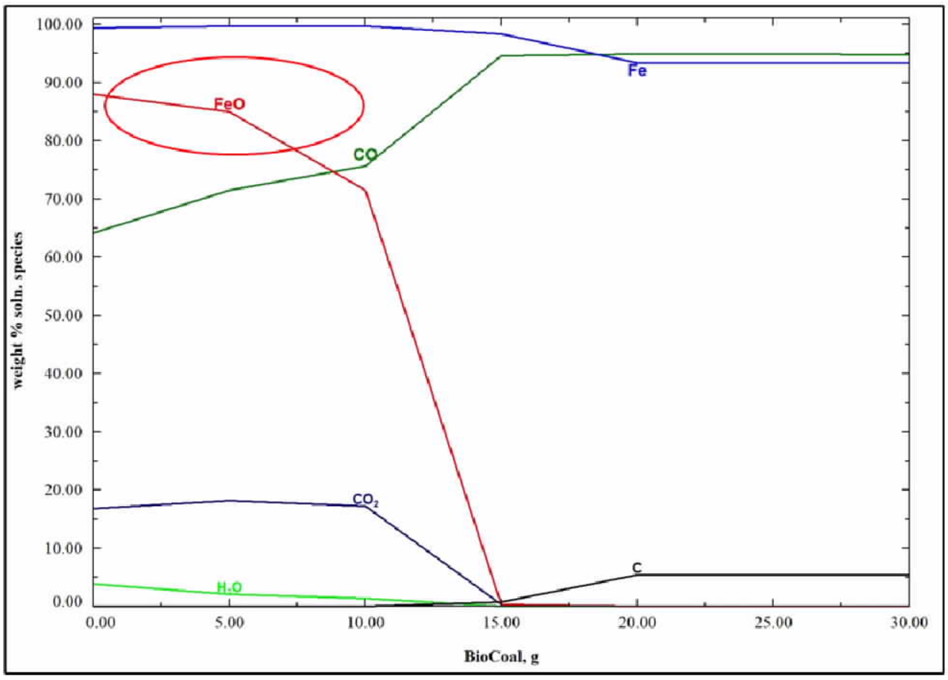


Figure 14: FactSage calculation for reduction of mill scale

Table 7: Recipes selected for smelting trials

Recipes	Mill scales	Pellet fines	Hydrated lime	Lignin 2	Lignin 3	biocarbon
R10_mill scale	89		1		10	
R16_mill scale	89		1	10		
R10b_mill scale	76,1		1		11,42	11,42
R2_pellet fines		89	1		10	
R3b_pellet fines		72,4	1		10	16,6

After achieving a complete melt of briquettes in the crucible, slag and metal resulted in the crucible were separated by breaking the crucible. **Table 8** depicts the weight loss behavior of each recipe during smelting trials. Crucibles containing recipes R10b_mill scale and R3_pellet fines possessed a metal chunk, which was much easier to separate from the crucible and some trace amount of carbon on top of the metal. This can be attributed to the achievement of a complete reduction of the biocarbon-containing recipes. The required weight loss percentage for the mill scales and pellet fines recipes, as per TGA analysis, has been achieved for recipes R10b_mill scale and R3b_pellet fines subsequently strengthening the assumption that complete reduction is being achieved.

Table 8: Weight loss percentage after reduction trials

Recipe	Before smelting trials Weight of sample, g	After smelting trials		
		Slag weight, g	Metal weight, g	wt. loss, g
R10_mill scale	78	44	14	20
R16_mill scale	78.7	18.8	16.2	43.7
R10b_mill scale	64.4	0	38.2	26.2
R2_pellet fines	54	8	7	39
R3b_pellet fines	37	9	12	16

After successfully collecting the samples (slag and metal) from the crucible, usage of Swerim portable XRF confirmed the following elements in the samples, as shown in **Table 9** and **Table 10**. Additionally, XRD analysis on R10_mill scale, R16_mill scale and R2_pellet fines slag have been determined and the occurrence of dominant phases has been identified as shown in **Figures 15-17**. It must be noted that the occurrence of the phase $FeAl_2O_4$ was due to the incorporation of the alumina crucible and its possible reaction with the briquettes during heating.

Table 9: Elemental composition of the metal samples after reduction trials

Recipe	C %	S %	Fe %	Al %	Ti %	Cr %	Mn %
R10_mill scale	0	0.09	96.46	1.34	0.15	0.1	0.01
R16_mill scale	0	0.06	98.49	0.56	0.02	0.01	0.01
R10b_mill scale	1.26	0.12	97.11	0.36	0.05	0.01	1.37
R2_pellet fines	0	0.06	90.18	6.07	0.26	0.01	0.06
R3_pellet fines	4.51	0.03	90.58	6.15	1.1	0.03	0.07

Table 10: Elemental composition of the slag samples after reduction trials

Recipe	S %	FeO %	Al_2O_3 %	CaO %	MnO %	SiO2 %
R10_mill scale	0.77	98.52	2.59	0.92	1.12	2.23
R16_mill scale	0.15	79.71	13.5	2.03	1.1	1.42
R2_pellet fines	0.06	67.43	7.63	4.06	0.18	4.62

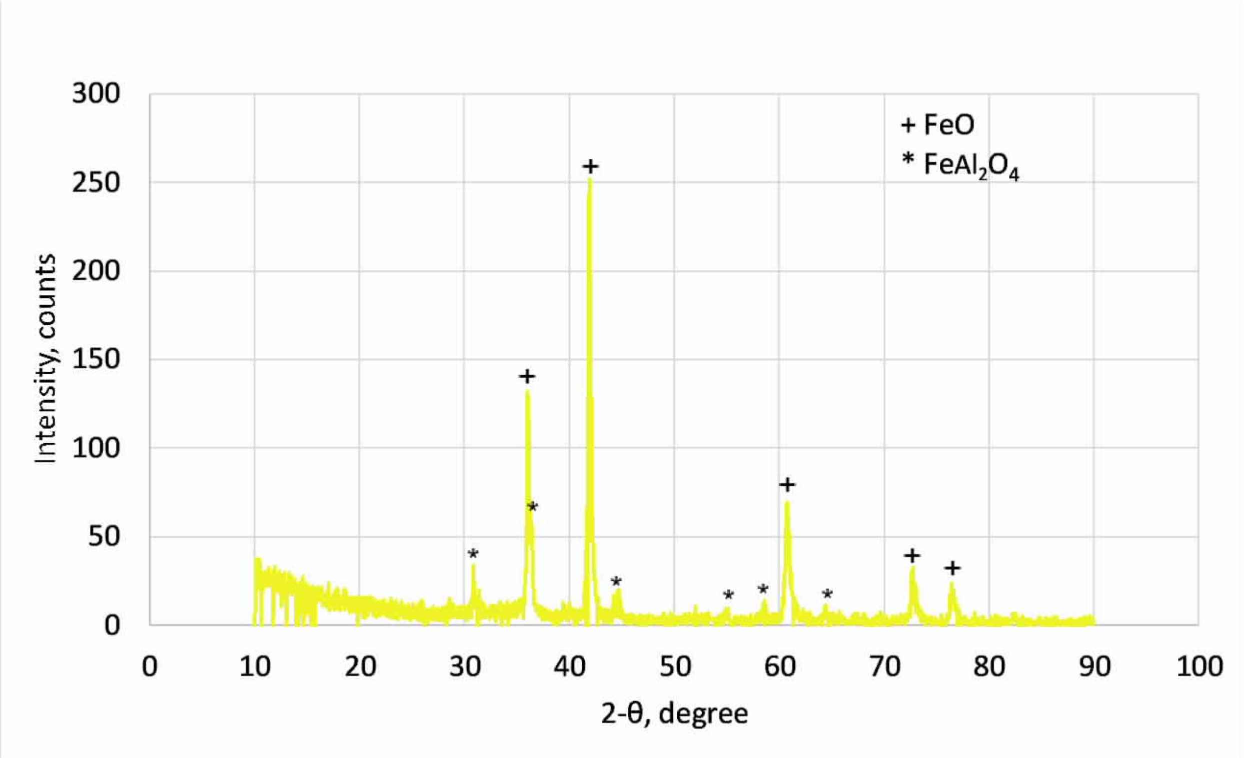


Figure 15: XRD plot for recipe R10_mill scale slag

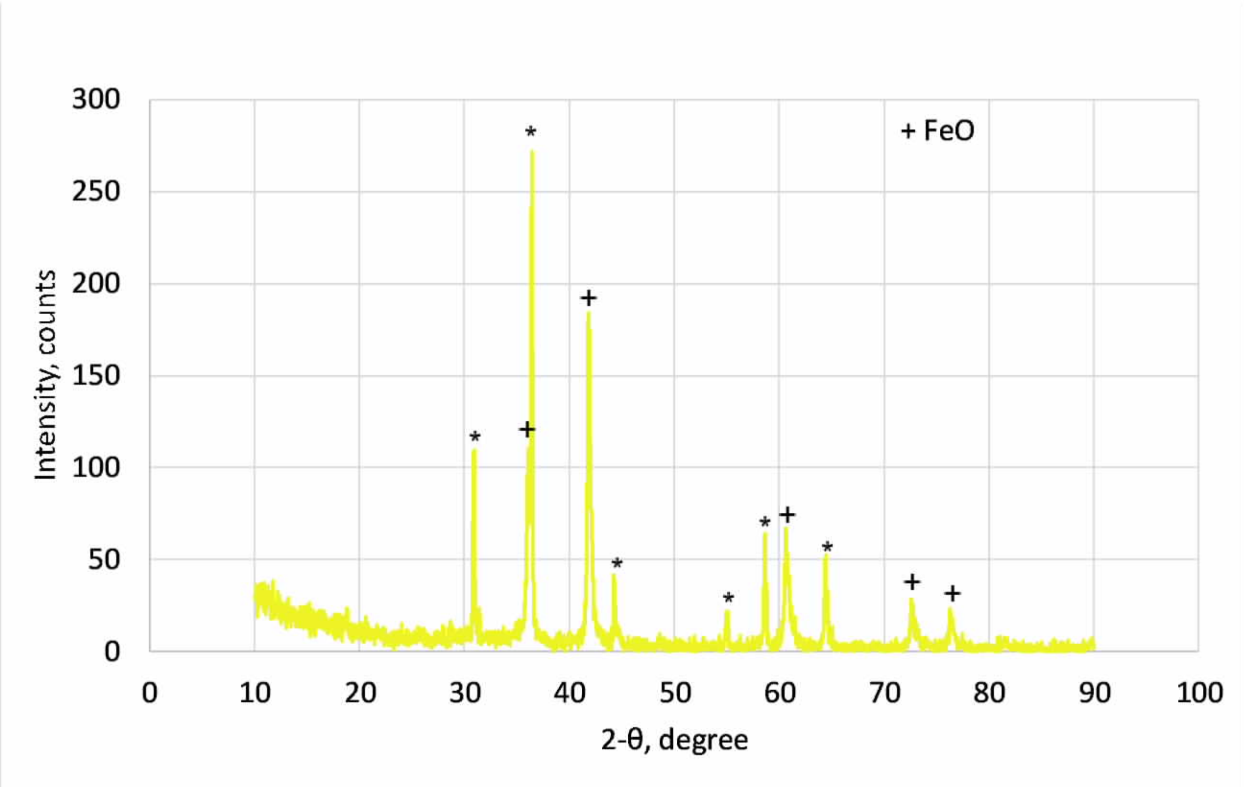


Figure 16: XRD plot for recipe R16_mill scale slag

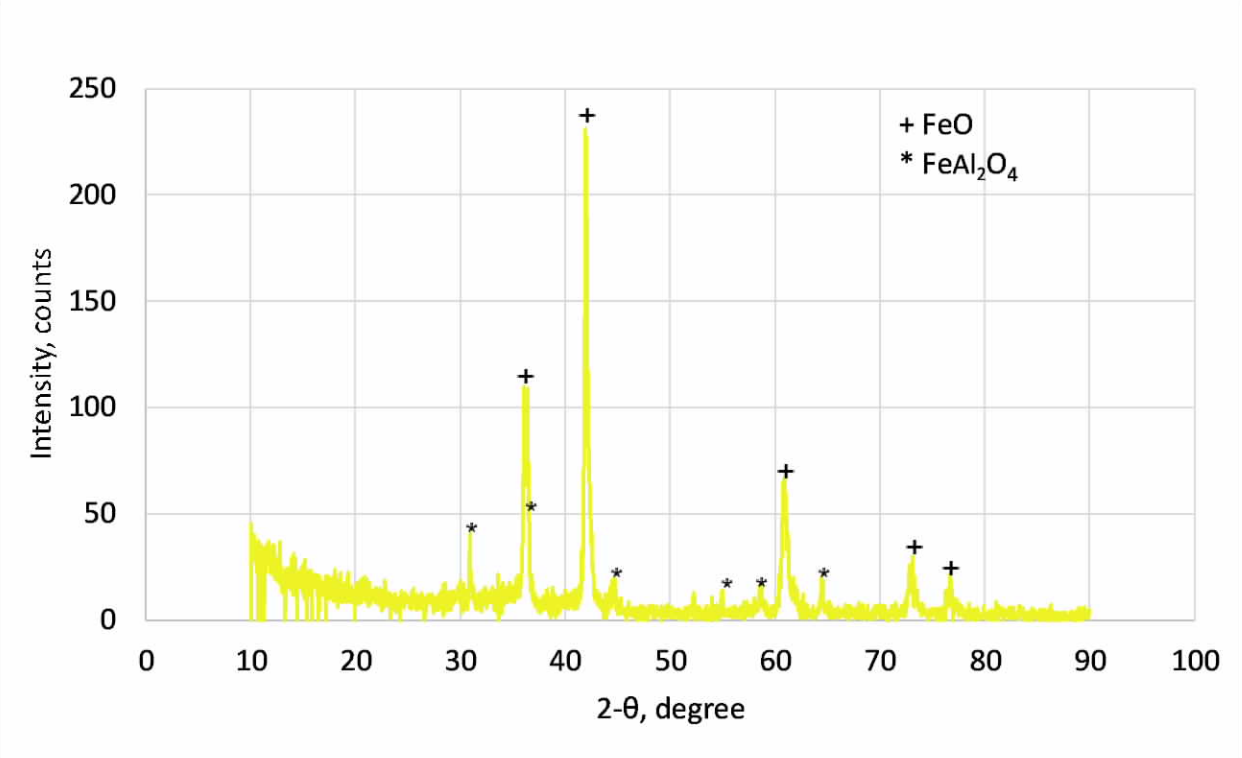


Figure 17: XRD plot for recipe R2_pellet fines slag

4. Techno-economic and environmental assessment

A simplified techno-economic analysis and environmental assessment have been conducted to evaluate the potential of utilizing lignin from the pulp and paper industry as a binder and neutral carbon carrier for recycling steel mill residues and pellet fines. This innovative approach aims to contribute to the circular economy within the steel sector while simultaneously addressing waste management challenges and reducing carbon emissions.

The ANGELUS project's experimental work, conducted on a small laboratory scale, has yielded promising results. The optimal recipe for the recycling process consists of 10% lignin, 10-15% biocarbon, and 80-85% mill scale or pellet fines. However, it is crucial to note that further technical trials using roller presses and extruders are necessary to determine the most effective techniques and operating conditions, including more precise OPEX/CAPEX figures.

Based on Sweden's planned annual steel production of 10 million tons (Mt), the preliminary economic analysis indicates significant potential for material recycling. This production scale is expected to generate approximately 0.5 Mt/year of pellet fines (3% of total pellet production) and 0.1 Mt/year of mill scales (1% of total steel production), resulting in a total of 0.6 Mt/year of residual materials. Processing this volume would require an estimated 60,000 tons/year of lignin and 90,000 tons/year of biocarbon for briquetting.

Around 70 Mm^3fub (fixed under bark) is annually harvested in Sweden. This corresponds, very roughly, to an estimated amount of 12 million tonnes of lignin. Around half of the harvested wood is directed towards sawn timber products and half to pulp production. Most of the pulp production is based on chemical pulping, where the lignin is liberated from the cellulose and dissolved in the black liquor stream. The black liquor is then incinerated in a recovery boiler for energy generation and to recover the cooking chemicals. The lignin studied in this project is retrieved from the black liquor stream and therefore redirected from energy generation. In a study conducted by AFRY (Thuresson, 2016) it was investigated how much lignin could be sustainably retrieved from the kraft pulp mills in Sweden, see **Figure** . The two most likely options discussed in the study are:

1 – Retrieve lignin from pulp mills with surplus energy, thus not needing to replace the lost energy source or

2 – Assume that the energy of the lignin retrieved can be replaced with other sources of energy while still being able to regenerate the cooking chemicals

Assuming that the energy content of lignin is around 26 MJ/kg and 6.7TWh of lignin is sustainably available, close to a million tons of lignin is available. In the more conservative scenario with 0.8 TWh available, the number is around 100,000 tons/year, which is still well within the range necessary to supply the needed volumes of pellet fines and mill scales of the steel industry.

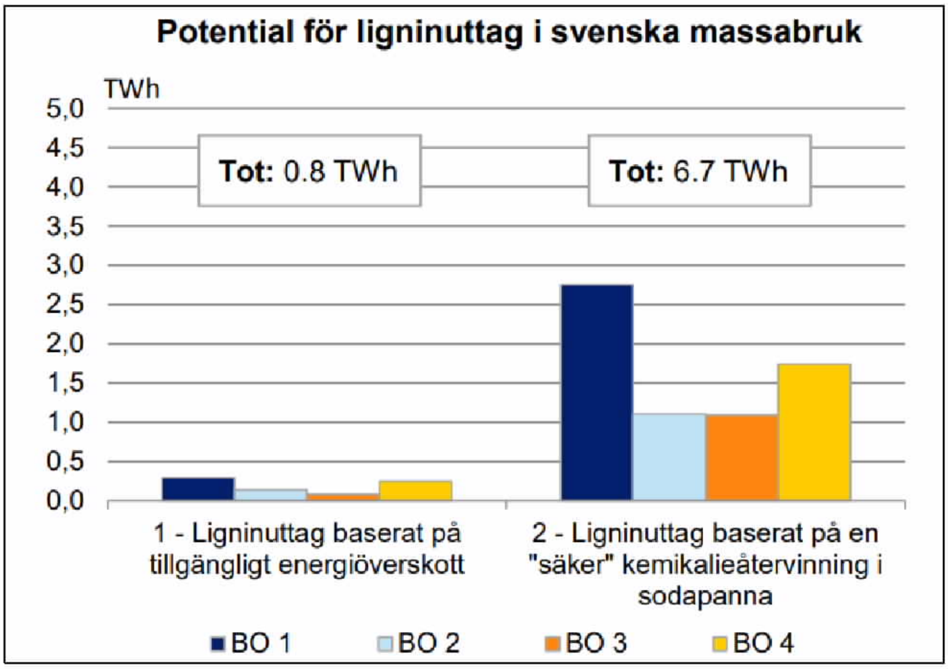


Figure 18 Scenarios for sustainable lignin output from Swedish kraft pulp mills, divided into the 4 main geographical areas (BO)

With lignin costs estimated at 600 €/ton, the annual lignin expense would amount to 36 million €/year. This investment could potentially be valorized within the steel sector, as the recycled materials could contribute to the production of 0.38 Mt of crude steel annually. However, it is important to note that the economic viability of this process is subject to steel market price fluctuations, necessitating ongoing market analysis for accurate revenue projections.

The economic benefits of this approach are multifaceted, including reduced raw material costs for steel production, potential revenue from recycled steel sales, and decreased waste disposal expenses for pellet fines and mill scales. From an environmental perspective, the process offers significant advantages. The production of 0.38 Mt/year of steel from recycled materials could potentially reduce CO2 emissions by more than 600,000 tons annually, based on an estimated 1.6 tons of CO2 emissions per ton of steel produced.

Additional environmental benefits include reduced landfill usage for steel mill residues, conservation of virgin raw materials, and the utilization of bio-based materials (lignin and biocarbon) as alternatives to fossil-based binders. These factors contribute to a more sustainable and environmentally friendly steel production process.

Despite its potential, the process faces several challenges and considerations. These include the impact of steel price fluctuations on economic viability, the need for stringent quality control to meet industry standards, ensuring a stable supply of lignin and biocarbon, and the potential requirement for process optimization to enhance efficiency.

In conclusion, the valorization of lignin for recycling steel mill residues demonstrates promising economic and environmental potential. To fully realize these benefits, several recommendations are proposed for the next stage of the ANGELUS project:

1. Conduct a detailed market analysis for accurate revenue projections.
2. Investigate potential government incentives for CO_2 reduction initiatives.
3. Explore partnerships with pulp and paper industries to secure a stable lignin supply.
4. Conduct pilot-scale trials and industrial campaigns to optimize the process and assess product quality.
5. Perform a comprehensive LCA (life cycle assessment) and techno-economic analysis (TEA) to quantify all environmental and economic impacts.

Looking to the future, this technology has the potential to play a crucial role in the steel industry's transition towards more sustainable practices. As environmental regulations become more stringent and the demand for low-carbon steel increases, innovative processes for valorizing secondary carbon resources (e.g. lignin) become increasingly valuable, positioning the industry for a more sustainable and economically viable future.

5. Conclusions

This study explored the viability of using lignin as a binder and a reducing agent, as well as its ability to fix carbon in the melt during the reduction process. The key findings are as follows:

5.1. Briquetting and reduction of lignin-mill scale

The main findings for this part can be summarized in the following points:

1. **Impact of lignin content and compaction force**
   - Increasing lignin content enhances green strength but adversely affects dry strength.
   - 10% lignin combined with 1% hydrated lime showed superior strength compared to 1% calcium stearate or 10% lignin alone.
   - Recipes produced at 200kN (R9 and R12) exhibited marginally better strength than those at 100kN (R11 and R13).

2. **Lignin type and additive optimization:**
   - Lignin type 3 with 1% hydrated lime demonstrated the best strength among all lignin types.
   - Increasing hydrated lime content from 1% to 5% or lignin type 3 from 10% to 20% slightly decreased briquette strength.
   - The optimal recipe among 29 tested was 10% SC lignin with 1% hydrated lime.

3. **Reduction performance:**
   - TGA analysis of the best-performing recipe showed only 22.5% weight loss (71% reduction extent), indicating the need for additional biocarbon for self-reducing briquettes.
   - The Tammann furnace smelting tests indicated that the complete reduction was achieved with 11.42wt.% biocarbon, 11.42wt.% lignin type 3, and 1% hydrated lime, with excess biocarbon remaining post-reduction.

5.2. Briquetting and reduction of lignin-pellet fines

The key findings of the briquetting and reduction of lignin-pellet fines can be summarized in the following points:

1. **Optimal composition:**
   - 1% hydrated lime and 10% lignin type 3 dominated in terms of Cold Compression Strength and Splitting Tensile Strength.

2. **Reduction characteristics:**
   - TGA results indicated a need for additional biocarbon, as only 23.5% weight loss (65.5% reduction) was achieved.

- Complete reduction was attained with 10% lignin type 3, 16.6% biocarbon, and 1% hydrated lime, resulting in excess biocarbon post-reduction.

5.1 Techno-economic and environmental assessment

The valorization of lignin showed strong economic and environmental potential, positioning the steel industry for a more sustainable future amid increasing demand for low-carbon steel. The key findings can be summarized in the following points:

1. **Material Recycling Potential:** Sweden's projected annual steel production is 10 million tons, with an estimated 0.6 million tons/year of residual materials (pellet fines and mill scales) available for recycling, requiring 60,000 tons/year of lignin and 90,000 tons/year of biocarbon.
2. **Sustainable Lignin Availability**: Sweden's annual harvest yields around 12 million tons of lignin, with an energy content of 26 MJ/kg, providing 6.7 TWh, sufficient for steel production needs.
3. **Financial Implications:** Lignin costs are estimated at €600/ton, leading to an annual expense of €36 million, potentially enabling the production of 0.38 million tons of crude steel, subject to market price fluctuations.
4. **Environmental Benefits:** Potential reduction of over 600,000 tons of CO_2 emissions annually, reduced landfill usage for steel mill residues, and conservation of virgin raw materials.
5. **Challenges:** Price volatility, quality control, and ensuring a stable supply of lignin and biocarbon remain significant concerns.

6. Suggested continued work

The initial findings of this study provide a solid foundation for further research and development on the usage of lignin in the steel industry. This work investigated the effect of lignin on briquette strength, revealing that different types of lignin, particularly when combined with hydrated lime, exhibited varying degrees of mechanical strength development. Investigations into the long-term performance and stability of lignin-containing briquettes under various storage and processing conditions would provide valuable insights for industrial implementation.

Moving forward, several research avenues warrant exploration:

1. Expanded Lignin Variety: While this study considered three types of lignin, future research should investigate a broader range of lignin types, particularly those with low impurities (e.g., low sulphur content). This expansion could uncover more effective and environmentally friendly options for the steel industry.
2. Upscaling Production: The most promising recipe that demonstrated the highest strength during lab-scale briquetting should be tested at a larger scale. This step is crucial for assessing the viability of industrial application.
3. Optimizing Reduction and Smelting: The reduction and smelting trials indicated that the carbon fixation (C-fix) of lignin alone is insufficient for complete reduction of iron oxides, necessitating compensation with high C-fix biocarbon. Further research should focus on optimizing this balance to achieve efficient reduction while maximizing the use of lignin.

4. Slag Foaming Potential: The high volatile matter (VM) content in lignin shows potential for beneficial use in slag foaming during steel production. This aspect requires more in-depth investigation to quantify its effectiveness and optimize its application.
5. Technical Scale Trials: Swerim proposes a continued study to evaluate the slag foaming capability of different lignin types during steel production. This research should be coupled with upscaling the small-scale production to a technical scale using extruders and/or roller presses.
6. Life Cycle, Environment, and Techno-Economic Assessments: Future work should conduct detailed market analysis, explore government incentives, establish partnerships with pulp and paper industries, conduct larger-scale trials, and perform comprehensive life cycle assessments (LCA) and techno-economic analyses (TEA).
7. By addressing these research gaps, the steel industry can move closer to integrating lignin as a sustainable and effective component in its processes, potentially leading to significant environmental and economic benefits

7. Acknowledgments

The authors would like to acknowledge RE:Source and Swedish Energy Agency for funding and making this project possible. Additionally, a special thanks to SunCarbon for providing us with the essential material, data and feedback throughout the project.

8. References

Drobíková, K., Vallová, S., Motyka, O., Mamulová Kutláková, K., Plachá, D., & Seidlerová, J. (2018). Effects of binder choice in converter and blast furnace sludge briquette preparation: Environmental and practical implications. *Waste Management*, *79*, 30–37. https://doi.org/10.1016/j.wasman.2018.06.051

Elsadek, M., Mousa, E., & Ahmed, H. (2024). Green approach to ironmaking: Briquetting and hydrogen reduction of mill scale using novel binders. *International Journal of Hydrogen Energy*, *62*, 732–738. https://doi.org/10.1016/j.ijhydene.2024.03.152

Halt, J. A., & Kawatra, S. K. (2014). Review of organic binders for iron ore concentrate agglomeration. *Mining, Metallurgy & Exploration*, *31*(2), 73–94. https://doi.org/10.1007/BF03402417

Lavers, J. L., Bond, A. L., & Rolsky, C. (2022). Far from a distraction: Plastic pollution and the planetary emergency. *Biological Conservation*, *272*, 109655. https://doi.org/10.1016/j.biocon.2022.109655

Manu, K., Mousa, E., Ahmed, H., Elsadek, M., & Yang, W. (2023). Maximizing the Recycling of Iron Ore Pellets Fines Using Innovative Organic Binders. *Materials*, *16*(10). https://doi.org/10.3390/ma16103888

Marakana, P. G., Dey, A., & Saini, B. (2021). Isolation of nanocellulose from lignocellulosic biomass: Synthesis, characterization, modification, and potential applications. *Journal of Environmental Chemical Engineering*, *9*(6), 106606. https://doi.org/10.1016/j.jece.2021.106606

'Mastrolitti, S. ', 'Borsella, E. ', Giuliano, A. ', 'Petrone, M. T. ', 'De Bari, I. ', 'Gosselink, R. ', 'van Erven, G. ', 'Annevelink, E. ', 'Triantafyllidis, K. S. ', 'Stichnothe, H. ', 'Storz, H. ', 'Lange, H. ', & 'Bell, G. '. (2021). *Sustainable lignin valorization Technical lignin, processes and market development*.

Mennani, M., Kasbaji, M., Ait Benhamou, A., Boussetta, A., Kassab, Z., El Achaby, M., Grimi, N., & Moubarik, A. (2024). The potential of lignin-functionalized metal catalysts - A systematic review. *Renewable and Sustainable Energy Reviews*, *189*, 113936. https://doi.org/10.1016/J.RSER.2023.113936

Mousa, E. A., Ahmed, H. M., & Wang, C. (2017). Novel approach towards biomass lignin utilization in ironmaking blast furnace. *ISIJ International*, *57*(10), 1788–1796. https://doi.org/10.2355/isijinternational.ISIJINT-2017-127

Mousa, E., Ahmed, H., & Söderström, D. (2022). Potential of Alternative Organic Binders in Briquetting and Enhancing Residue Recycling in the Steel Industry. *Recycling*, *7*(2), 21. https://doi.org/10.3390/recycling7020021

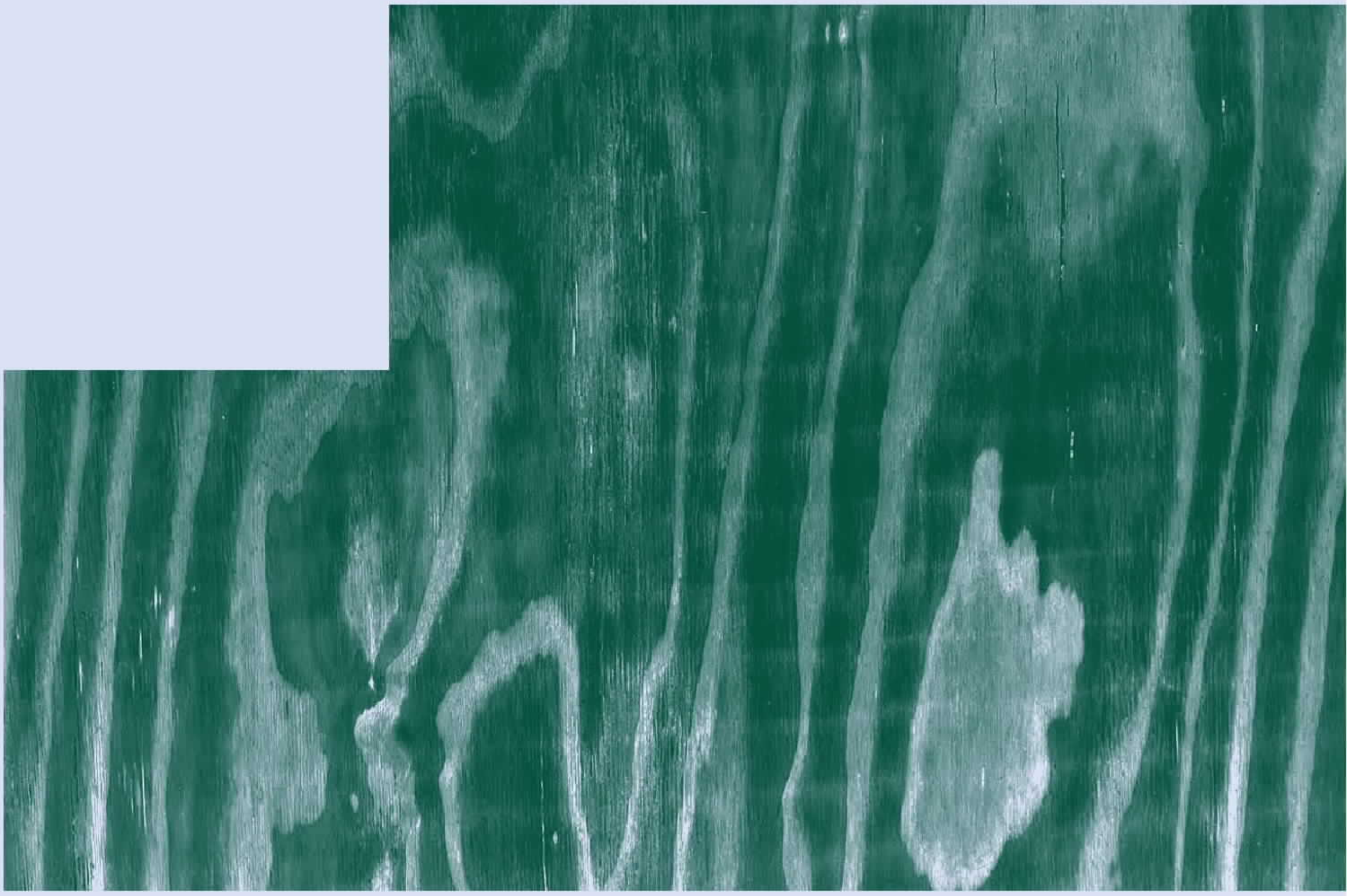
Pei, M., Petäjäniemi, M., Regnell, A., & Wijk, O. (2020). Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland. *Metals*, *10*(7), 972. https://doi.org/10.3390/met10070972

Prusti, P., Barik, K., Sahu, D. K., Soren, S., Meikap, B. C., & Biswal, S. K. (2022). *Recycling and Reuse of Iron Ore Pellet Fines* (pp. 179–187). https://doi.org/10.1007/978-981-16-3297-6_17

Schwelberger, J., Wimmer, G., Brunner, C., & Fleischanderl, A. (2017). INNOVATIVE SOLUTIONS FOR RECYCLING OF BYPRODUCTS*. *Anais Do Seminário de Aciaria, Fundição e Metalurgia de Não-Ferrosos*, 636–644. https://doi.org/10.5151/1982-9345-26947

(Thuresson, 2016)

Sweden could become a pioneer in green steel production. (2021, December 21). Wood Mackenzie.



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