

Article

Developing Iron Ore Pellets Using Novel Binders for H₂-Based Direct Reduction

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Abstract: The transformation from traditional iron- and steelmaking technologies to green H₂-based new technologies will require an improvement in the quality and purity of iron ore burden materials. Iron ore pellets are essential inputs for producing direct reduced iron (DRI), but the conventional binders, used in iron ore pelletizing, introduce gangue oxides to the DRI and consequently increase the slag generation and energy consumption in the steelmaking unit. Partial and/or full replacement of the traditional binders with novel organic binders would significantly contribute to improving the process efficiency, particularly in the next-generation H₂-based direct reduction technology. This study illustrates the feasibility of pelletizing magnetite iron ore concentrate using four organic binders: KemPel, Alcotac CS, Alcotac FE16, and CMC, in comparison to bentonite as a reference. The study explores the influence of binder type, binder dosage, and moisture content on the characteristics and properties of the pellets. The efficiency of binders was characterized by the moisture content, drop number test, cold compression strength, and H₂ reduction of pellets. For dry pellets, CMS was superior among other binders including bentonite in developing dry strength. After firing, the pellets produced by the partial replacement of bentonite with 0.1 wt.% KemPel demonstrate a performance nearly identical to the reference pellets. While the complete replacement of bentonite with organic binder shows a lower performance of fired pellets compared to the reference, it may still be suitable for use in DR shaft furnaces. The cold-bonded pellets demonstrate a superior reduction rate compared to fired pellets.

Keywords: pelletizing; magnetite concentrate; agglomeration; organic binders; strength; H₂; direct reduction; CO₂ emission



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1. Introduction

In recent times there has been an outstanding shift from the traditional coke-based iron- and steelmaking process to a more environmentally friendly green H₂-based direct reduction process. This shift is primarily motivated by the significant reduction in the carbon emissions achieved by the H₂-based technology where the carbon emissions decrease significantly, dropping from 1600 kg CO₂ per metric ton of steel produced to just 25 kg CO₂ per metric ton of steel produced [1,2]. However, iron ore pellets will be the exclusive feed material that fits this green transition due to their special properties such as high porosity—better reducibility, uniform chemical composition, better strength, better permeability, enhanced steel yield, and increased metallization rate compared to other feeds such as lump iron ore and sinter [3]. Forecasts suggest that by 2050 global steel demand will see further growth and will have increased by one-third of what it is today (1950 Mt) [4]. With the growing demand for steel and the transition towards the green H₂-based direct reduction process, there is a significant expected increase in the demand for iron ore pellets. In 2020, the demand for iron pellets was approximately 400 Mt, and it

is projected to rise to 540 Mt by the year 2027. This substantial increase in demand reflects the shift in manufacturing preferences and highlights the crucial role that iron pellets will play in meeting the requirements of the evolving steel industry [5].

Pelletizing is the technique of rolling fine-grained iron ore concentrates with adequate size distribution into small balls of the desired size using a wetting agent and a binder [6]. The most common and traditional binder is bentonite; the wetting agent is usually water. Bentonite consists of alumina and silica and is generally added at a concentration between 0.5 and 1.5% of the iron ore concentrate [7]. This increases the gangue materials of iron ore and consequently decreases the iron content. The addition of 1% bentonite decreases the iron content by about 7 kg/ton of iron ore [8]. Currently, 3.2 Mt of bentonite is used for pelletizing iron for ironmaking. Lime also has to be added while pelletizing with bentonite to adjust the basicity, which increases the amount of slag generated and the CO₂ emissions [5]. For every ton of crude steel produced, approximately 500 kg of solid wastes (slag) are generated [9,10]. One possible solution to reduce the undesirable gangue constituents, including alumina, silica, and calcium, in the final product is to explore alternative binders that can replace or decrease the usage of bentonite.

Several studies and research have already been conducted to test organic binders as alternative binders to bentonite [11–21]. A combination of boron compounds with organic binders such as carboxymethyl cellulose (CMC), starch, dextrin, and some organic-based binders was tested [13,14]. It was found that the produced pellets show a good metallurgical and chemical quality when compared with bentonite-bonded reference pellets. Moreover, CMC organic binder was used to produce iron ore pellets, and it showed better mechanical properties and satisfactory metallurgical properties when compared with bentonite. The only problem was with its fired compressive strength and tumbling resistance [17]. Moreover, there are several organic binders markedly accessible for iron ore pelletization such as BASF's Alcotac[®] CS and FE-16, which have been successfully used as alternatives for bentonite for iron ore pelletization [20]. Additionally, the polymer-based binder, KemPel[™] from Kemira, has shown promising results in partially replacing bentonite without compromising pellet qualities and properties [21].

According to the authors' knowledge, organic binders have been seen as a promising replacement for bentonite in iron ore pelletizing. There exist some novel and innovative organic binders, of which some have been specifically designed for iron ore pelletizing. However, relatively little research has been conducted on utilizing new and innovative organic binders in iron ore pelletizing as a substitute for bentonite and examining their impact on the reduction behavior for the next generation of H₂-based ironmaking. Working towards more sustainable ironmaking in Sweden, CO₂ emission reduction strategies include the adoption of breakthrough low emission technologies, which completely transform the industry. These breakthrough technologies include H₂-based ironmaking. Additionally, the use of organic binders during pellet production could provide a sustainable option for decreasing the emissions resulting from mining activities of inorganic binders. Hence, the current work mainly concentrates on the evaluation of using four selected innovative organic binders for magnetite ore pelletization. The study explores the influence of binder type, binder dosage, and moisture content on the characteristics and properties of the pellets. The physical and mechanical properties of the produced pellets were studied before and after the firing of the pellets. Additionally, the reducibility of both the green and fired pellets was explored using H₂ gas to check whether the produced pellet fulfilled the prerequisite strength before and after reduction.

2. Materials and Methods

2.1. Materials

Magnetite iron ore concentrate received from Kaunis Iron AB, Sweden, was used in this study. In addition, commercial bentonite was used as a reference binder to compare the performance of selected organic binders in the pelletizing process.

By reviewing prior research studies and collaboration with the expertise of binder developers, four binders, Table 1, were chosen to be investigated for partial and/or full replacement of bentonite in this study.

Table 1. Selected binders for pelletization.

Selected Binders	Composition	Source
KemPel	Anionic polyacrylamide	Kemira, Helsinki, Finland
Alcotac CS	Modified anionic polyacrylamide	BASF, Heidelberg, Germany
Alcotac FE16	Anionic polyacrylamide	BASF, Heidelberg, Germany
CMC	Carboxymethyl cellulose	Commercial product

2.2. Characterization

The magnetite concentrate and bentonite were subjected to chemical analysis using X-ray Fluorescence (XRF) techniques to determine the concentration of various components present in the sample. Additionally, mineralogical analysis was carried out using a Malvern Panalytical X-ray diffractometer (XRD) in 2 θ geometry with Cu tube K α radiation ($\lambda = 0.154184$ nm) and a beam current and voltage of 40 mA and 45 mV, respectively. This analysis aimed to identify the mineral composition of the magnetite concentrate both before and after thermal treatment. Moreover, the particle size distribution analysis of the magnetite ore concentrate was carried out using Retzsch Camsizer XT (Retzsch Technology GmbH, Haan, Germany).

2.3. Recipes

The recipes shown in Table 2 were designed to investigate the feasibility of replacing the bentonite partially or fully with the selected organic binders. One reference recipe, namely R1, was designed using 1% bentonite and 99% magnetite. The recipe named K refers to the recipes pelletized using KemPel; similarly, H refers to Alcotac FE 16, C refers to Alcotac CS, and U refers to CMC. The pelletizing conditions were not optimized for all the recipes in this study; however, it could be an interesting topic to be investigated in further studies.

Table 2. Designed recipes for binders screening.

Recipes	Magnetite (g)	Bentonite (%)	KemPel (%)	Alcotac CS (%)	CMC (%)	Alcotac FE16 (%)
R1	2000	1	0	0	0	0
K1	2000	0.265	0.1	0	0	0
K2	2000	0.5	0.1	0	0	0
K3	2000	0.2	0.1	0	0	0
H1	2000	0	0	0	0	0.05
H2	2000	0	0	0	0	0.1
H3	2000	0.265	0	0	0	0.05
H4	2000	0	0	0	0	0.5
H5	2000	0	0	0	0	0.75
H6	2000	0.1	0	0	0	0.5
H7	2000	0.1	0	0	0	0.3
C1	2000	0.5	0	0.04	0	0
C2	2000	0.3	0	0.04	0	0
C3	2000	0.4	0	0.06	0	0
C4	2000	0.4	0	0.1	0	0
C5	2000	0	0	0.1	0	0
C6	2000	0	0	0.5	0	0
C7	2000	0	0	0.75	0	0
C8	2000	0.3	0	0.5	0	0
U1	2000	0.25	0	0	0.1	0
U2	2000	0.5	0	0	0.25	0
U3	2000	0	0	0	1	0
U4	2000	0.25	0	0	0.5	0
U5	2000	0	0	0	0.5	0
U6	2000	0	0	0	0.75	0

2.4. Pelletization and Testing

The magnetite concentrate and respective binders were homogeneously mixed using an Eirich mixer according to the recipe composition (Table 2). Then, these mixtures were fed

into the bottom part of a laboratory scale pelletizing disc of diameter 35 cm, an inclination angle of 45°, and the rotation speed was set at 50 rpm. Along with feeding the mixed recipe, water was sprayed into the disc pelletizer. When the pellets started forming and attained a specific size, they were taken out and sieved using the mechanical sieving method (Retsch AS200 basic). The sieves were of the sizes 20 mm, 16 mm, 12.5 mm, 10 mm, 9 mm, 6.3 mm, 5 mm, 2.8 mm, 1 mm, and 0.5 mm. The pellets in the size range of 9–16 mm were taken out and kept aside, while both the undersized and oversized pellets were crushed and put back into the pelletizer. When most of the pellets acquired the desired size range, the pelletizer was stopped, and all the pellets were taken out and kept aside in a metal tray for drying in air for 4 h. The moisture content of produced pellets before and after drying was determined by accurately weighing and placing it into a Mettler Toledo moisture analyzer (Mettler-Toledo HB43 Laboratory & Weighing Technologies, Greifensee, Switzerland) equipped with a halogen heating unit. After drying in the air, the pellets were further dried in the oven at 105 °C for 2 h. The dry pellets were then sieved mechanically into different size fractions, weighed, and stored in zip lock bags in a dry location. Next, a set of ten pellets within the size range of 9–12.5 mm were selected for testing their cold compressive strength using a hydraulic compression tester (ENERPAC hydraulic center, Düsseldorf, Germany) and a drop test from a height of 45 cm onto a steel plate. The cold compressive strength (CCS) was determined by placing a single pellet on a fixed metal plate and compressing it with a movable piston at a velocity of approximately 20 mm/min. The compression force values in Newtons (N) were automatically recorded during the test [22,23]. These tests were conducted in accordance with the ISO 4700–2015 [24]. To ensure reliable strength measurements, ten pellets were tested for each CCS and drop measurement, and the results were subsequently averaged. The selected recipes that showed the highest CCS values and drop numbers were subjected to firing under airflow, 5 l/min in a muffle furnace (ENTECH, ECF 20/17, Eurotherm 2408 P4, Sweden). The heating rate was set to 10 °C/minute until it reached the peak temperature of 1250 °C. The residence time at the peak temperature was set to be 20 min. The cooling rate was also set to 10 °C/minute. After the furnace had cooled down to room temperature, the samples were taken out. Moreover, the fired pellets were subjected to CCS and drop test measurements as with dried pellets.

The reduction progress of dried and fired pellets was tracked through non-isothermal thermogravimetric analysis using a Netzsch STA 409 instrument (Erich NETZSCH GmbH & Co. Holding KG, Selb, Germany) with a detection limit of $\pm 1 \mu\text{g}$. The schematic and equipment setup are presented elsewhere [25]. A single dried/fired pellet was placed on alumina plate inside the TGA with the thermocouple positioned underneath. The pellet was then exposed to a thermal profile comprising a constant heating rate of 20 °C/min until reaching a temperature of 950 °C and holding at 950 °C for one hour, in which 100 mL/min H_2 gas flow was maintained throughout. The reduction extent, RE, was calculated based on the reducible oxygen eliminated from the pellets using the following Equation (1):

$$\text{RE} = \frac{W_0 - W_t}{x * y * W_0} \times 100 \quad (1)$$

where W_0 is the initial mass of the pellet, W_t is the weight of pellet at a certain time (t), and x factor is the theoretical reducible oxygen ratio for hematite (0.30) and for magnetite (0.28). The y factor is the concentration fraction of magnetite in the dried pellet (0.91) and of hematite in the fired pellets (0.95). Hematite and magnetite fractions are calculated based on total iron content as affirmed from XRF analysis assuming that all Fe is in the form of magnetite in the dried pellets and hematite in the fired pellets.

3. Results and Discussion

3.1. Sample Characterization

The chemical compositions of the magnetite iron ore concentrate and bentonite are given in Table 3. It is observed that the magnetite concentrate is of high grade with small impurities of magnesium oxide and silica, which may have resulted from the presence

of the associated gangue of olivine mineral. For the phase composition of magnetite concentrate, Figure 1 depicts only the presence of magnetite as the main phase. The particle size distribution analysis of the magnetite ore concentrate shows that 98 wt.% of the magnetite ore concentrate particles were below 100 μm and 84.6 wt.% of the particles were under 50 μm .

Table 3. Chemical composition of magnetite concentrate and bentonite.

Materials	Chemical Composition, wt.%							
	Total Fe	SiO ₂	CaO	MgO	Al ₂ O ₃	K ₂ O	Na ₂ O	TiO ₂
Magnetite concentrate	66.16	1.60	0.15	1.81	0.18	0.03	0.06	0.014
Bentonite	3.22	59.6	0.1	3.1	21.9	0.5	3.1	0.8

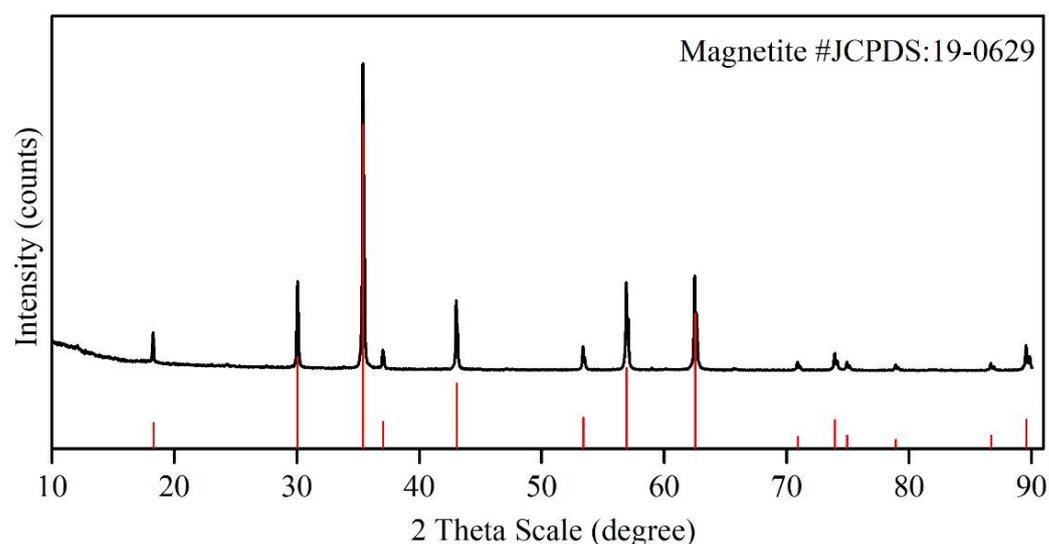


Figure 1. Phase composition of magnetite concentrate. Red: standard diffraction data of magnetite mineral according to JCPDS:19-0629; Black: diffraction lines of the sample.

3.2. Moisture Content of Green and Dry Pellets

Figure 2 shows the moisture content of the green and dried pellets produced from all recipes. It is evident that the quantity of water needed for each recipe varies based on the quantity and type of binder used. It is worth mentioning that the amount of water required to activate the binder is dependent on its nature and composition. Recipes that included CMC (U1–U6) required a higher amount of water addition, resulting in the highest moisture content in green pellets, ranging from 12 to 18 wt.%. This can be attributed to the chemical composition of CMC, where it contains several hydroxyl groups that bond with several water molecules by hydrogen bonds. Moreover, the swelling/dissolution phenomenon is where CMC fibers require water to swell and dissolve, but the fibers swell first before they dissolve [26]. The KemPel recipes (K1–K3) show a moisture content of 12–14 wt.%. Both Alcotac FE 16 (H1–H7) and Alcotac CS (C1–C8) show a moisture content between 8 and 11 wt.%. All dry recipes contain less than 0.5 wt.% moisture content after drying the pellets for 2 h at 105 °C.

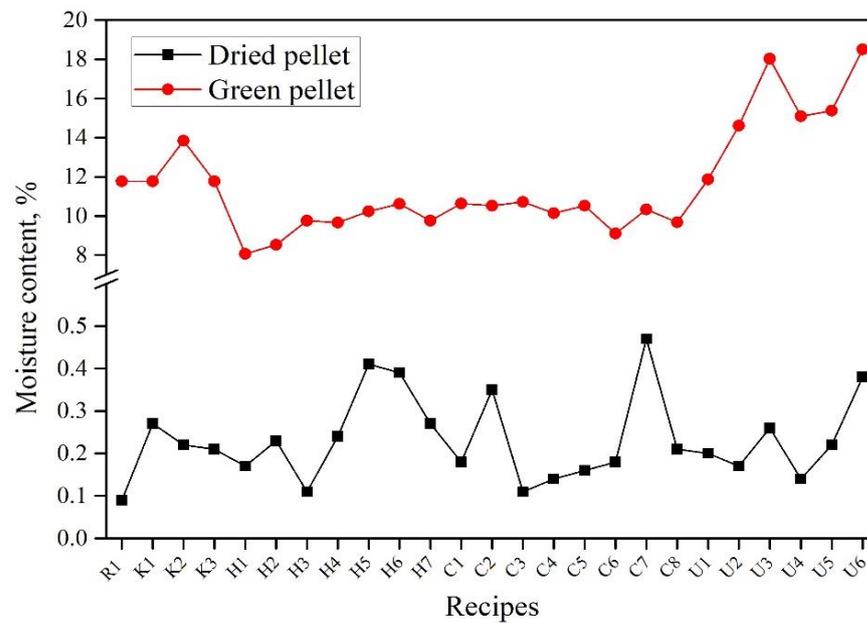


Figure 2. Moisture content of green and dried pellets of all recipes.

3.3. Pellet Size Distribution

The pellet size distribution of all recipes was measured to detect the yield of the desired size range (9–16 mm). Figure 3 shows the yield of all recipes divided into four groups according to the added organic binder. As the pelletizing conditions differ for each of the recipes, the yield also differs accordingly. Thus, while it is not entirely appropriate to compare the yield of different recipes, it is worth noting that in terms of ease of pelletizing, Alcotac FE 16 (H) showed the best performance, followed by Alcotac CS (C). The lowest yield resulted from using CMC binder (U), and this could be attributed to using excessive water, which causes wet pellets to cohere with each other and difficulties with it being discharged from the balling disc [27]. As mentioned before, this result cannot be generalized as the pelletizing conditions and techniques differ from one recipe to the other.

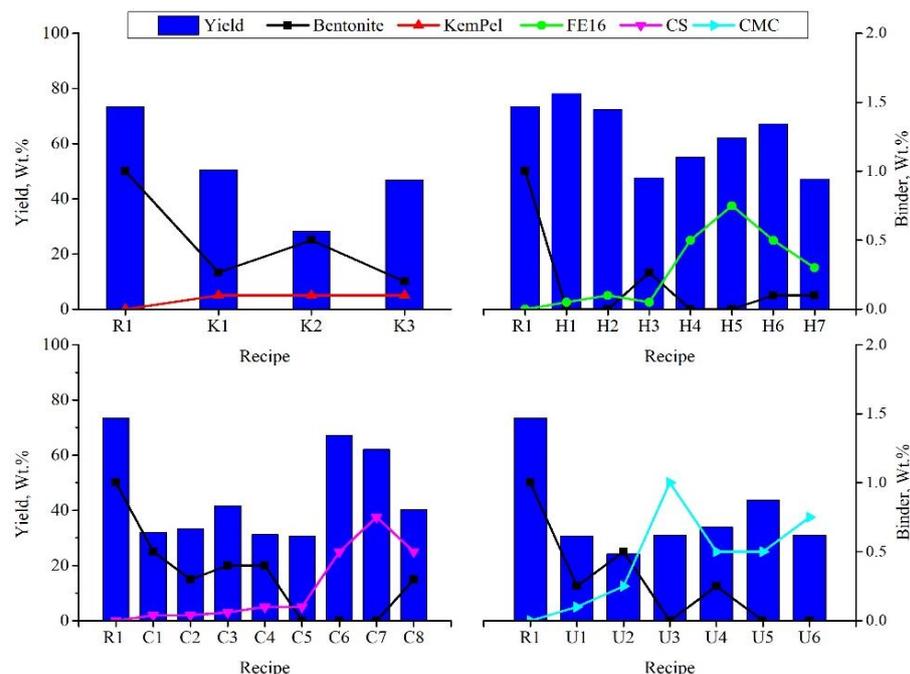


Figure 3. Variation in the yield of the desired pellet size for all recipes.

3.4. Drop Test Measurement of Dry Pellets

Ten over-dried pellets from the size range of 9–12.5 mm were subjected to the drop test, where the number of drops each pellet could withstand without breaking was counted. The final drop number value is the average drop number of 10 pellets. Figure 4 presents the drop test results for all recipes. The KemPel recipes (K) that represent partial replacement of bentonite showed good drop test results in comparison with the reference recipe, R1, while the drop test results of recipes with complete replacement of bentonite by Alcotac FE 16, Alcotac CS, and CMC are in order of CMC > Alcotac CS > Alcotac FE16.

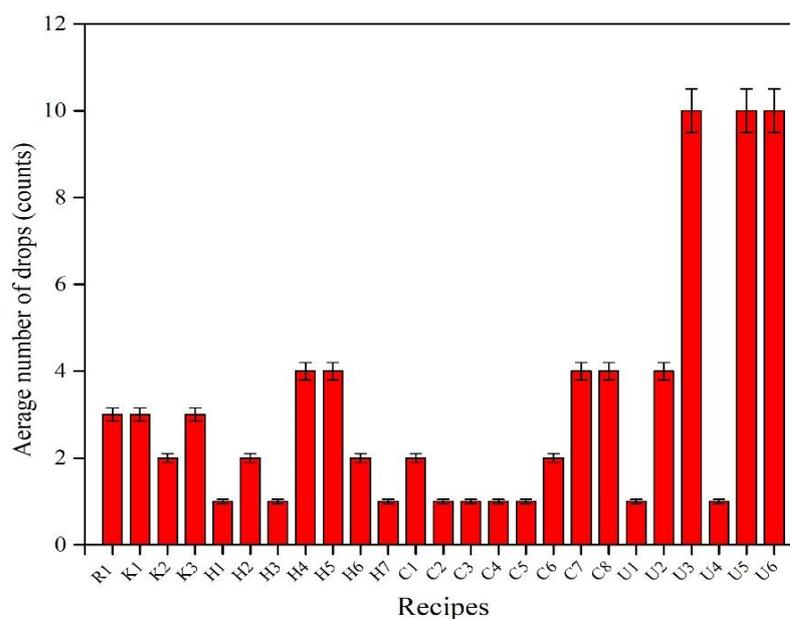


Figure 4. Drop test of dried pellets of all recipes.

In addition, the drop test of fired pellets was carried out using 10 pellets of each fired R1, K1, H4, C7, and U5 recipe. The test was performed from a height of 2 m onto a steel plate, and the number of drops they could withstand without breaking was noted. It was observed that all recipes could withstand 15 drops. Some of the pellets could also withstand more than 15 drops, but a limit of 15 was set for the measurement. Thus, the firing increases the drop number for all pellets drastically.

3.5. Cold Compression Strength (CCS) of Dry and Fired Pellets

The CCS of dry and fired pellets was measured for a total of 10 pellets with a diameter of 9–12.5 mm for all recipes. Figure 5 shows the variation in CCS of all produced recipes. It can be seen that recipe K1 in which 73.5 wt.% of bentonite in the R1 recipe was replaced with 0.1 wt.% of KemPel, showed comparable CCS to the reference recipe (R1), while the other two recipes (K2 and K3) had poor results when compared to K1 and the reference recipe. When using CMC, it can be observed that all the recipes except U1 had either comparable or better results than the reference recipe with bentonite. If we look at recipes U3, U5, and U6, where there is no bentonite at all, and the amount of CMC is increased from 0.5 to 1 wt.%, it can be seen that by increasing the amount of CMC, the CCS increases. With the addition of 1 wt.% CMC, the CCS increases significantly. A similar result can be seen in recipes H4 and H5 with Alcotac FE16. Neither H4 nor H5 contain any bentonite, and the amount of Alcotac FE 16 is 0.5 wt.% and 0.75 wt.%, respectively. As the amount of Alcotac FE 16 increases, the CCS also increases. On the other hand, the recipes that contain Alcotac CS show a lower CCS than the reference recipe. The recipes, C6, C7, and C8 were the recipes that demonstrated a better CCS compared to the other recipes with Alcotac CS. According to the CCS results of dried pellets, the best CCS recipes (R1, K1, H4, C7, and U5) were subjected to firing followed by CCS testing.

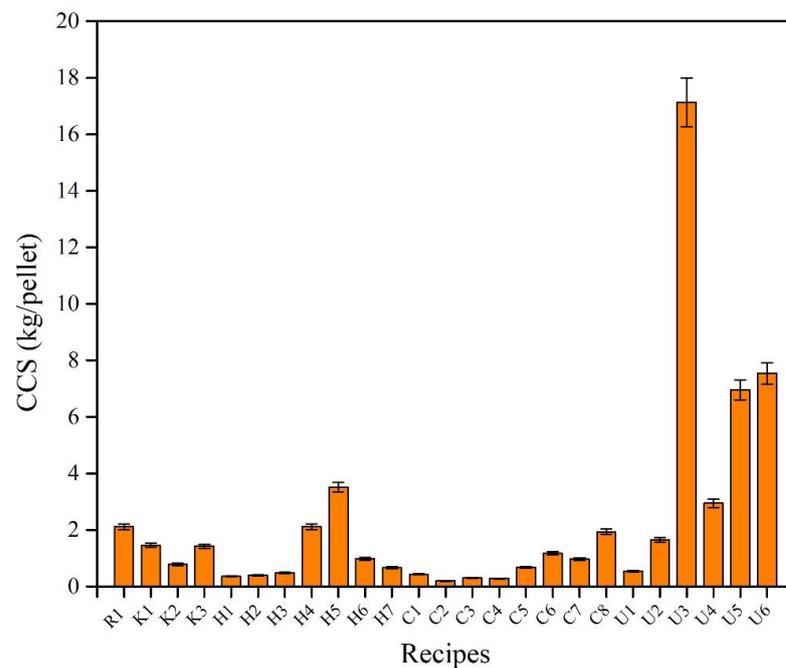


Figure 5. CCS of dried pellets of all recipes.

Figure 6 shows the CCS of the fired recipes R1, K1, H4, C7, and U5. Ten pellets each from the size ranges 9 to 12.5 mm were subjected to the CCS measurement, and an average was taken as the final value. It was noticed that the CCS values of all selected recipes were improved after firing. The reference recipe (R1) with bentonite displayed the highest value of CCS in comparison with other organic-bonded recipes. For organic-bonded recipes, the CCS values can be described in the order of K1 > C7 > H4 > U5. Although the K1 recipe saves 73.5% from used bentonite in R1, it still shows high CCS with only an 8% decrease compared to that of R1. By fully replacing bentonite with organic binders in C7 (0.75% Alcotac CS), H4 (0.5% Alcotac FE 16), and U5 (0.5% CMC), the CCS value decreased by 37.5%, 41.66%, and 75%, respectively, when compared to the reference recipe, R1. However, while the CMC recipe U5 showed the most promising dry CCS results compared to all the other recipes, even the reference recipe (R1), it shows the worst CCS after firing; this may be due to the complete decomposition of CMC at a low temperature, 390 °C [28].

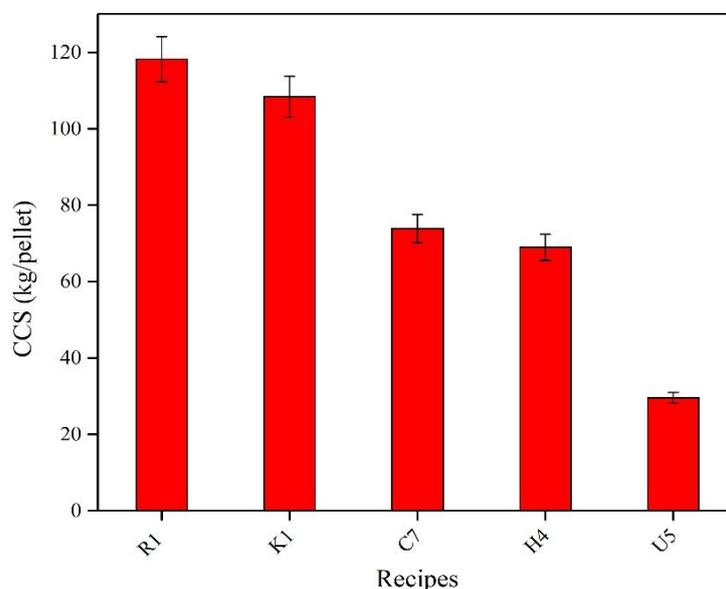


Figure 6. CCS of selected fired pellets.

3.6. Reducibility of Dry and Fired Pellets as well as CCS after Reduction

The reduction behaviors of selected recipes R1, K1, H4, C7, and U5 were tested using non-isothermal thermogravimetric analysis in H₂ gas as a reducing atmosphere at temperatures up to 950 °C. This test was performed for the dried and fired recipes under the same conditions. Figure 7 depicts that the dried pellets, in general, show better reducibility than fired pellets. At any given time and temperature, the reduction extent is always higher for dried pellets compared to the fired pellets. During the non-isothermal heating stage, the reduction extent of dried pellets was in the order of U5 > C7 > H4 > K1 > R1, where a 55% reduction extent was achieved by organic-bonded pellets (U5, C7, and H4), and the lowest reduction extent, 35%, was displayed by the bentonite-bonded pellet (R1) and partially bentonite-bonded pellets (K1). During the isothermal stage at 950 °C, the same trend was observed where R1 and K1 pellets needed 41 min to approach the complete reduction, while U5, C7, and H4 needed approximately 19 min until complete reduction. This trend can be attributed to the porous structure resulting after the thermal decomposition of the organic binder, which facilitates the H₂ diffusion and enhances the reduction of the pellets. In contrast, the fired pellets showed an opposite order. During the non-isothermal stage, a 50% reduction was observed in the case of the bentonite-bonded pellet (R1), and the lowest value, 32%, was displayed by the Alcotac FE 16-bonded pellet (H4). Thus, the reduction extent order was as follows R1 > C7 > K1 > U5 > H4. Moreover, during the isothermal stage, at 950 °C the same trend was observed, where R1- and C7-fired pellets needed 37 min to reach the complete reduction, while K1, U5, and H4 needed 56 min until complete reduction. This behavior can be attributed to the effect of different parameters such as the gangue associated with magnetite ore and binder composition, for example, the presence of magnesium oxide gangue, which reacts with the iron oxide during the firing process of pellets and eventually forms islands of magnesioferrite (Mg₂Fe₂O₄) surrounded by hematite [29,30]. When the reduction takes place at 800 °C, the temperature allows for the slow diffusion of magnesium from the magnesioferrite into the surrounding iron oxides. This diffusion is slightly more pronounced if hematite is reduced to wustite instead of magnetite. At 900 °C, the diffusion of magnesium was accelerated, leading to the disappearance of the boundaries of magnesioferrite islands. It was reported that the structure formed within the magnesioferrite phase during sintering remained unaffected by the reduction treatment up to 900 °C [30]. The presence of bentonite in the sintering process hinders the formation of magnesioferrite during sintering, thereby promoting the reduction of bentonite-bonded fired pellets. This demonstration was confirmed by XRD analysis of the reduction products of dried and fired R1 and H4 pellets, see Figure 8. It was observed that the phase compositions of the reduction products of the dried R1, dried H4, and fired R1 pellets revealed that the only detected phase is the metallic iron (Fe), while the reduced fired H4 shows the presence of a metallic iron phase with traces of a magnesium iron oxide phase (MgO_{0.77}FeO_{0.23}), which supports the formation of hardly reduced magnesium ferrite [31].

The CCS results for the reduced fired and dried pellets are given in Figure 9. For reduced fired pellets, it can be observed that all the organic- and bentonite-bonded pellets, except the CMC-bonded pellets, manifest low CCS values after reduction. For the CMC-bonded pellets (U5), there was no change in the CCS value after firing and reduction. However, the CCS value was still less compared to the other organic-bonded and reference pellets. The bentonite-bonded (R1), KemPel-bonded (K1), Alcotac FE 16-bonded (H4), and CMC-bonded (U5) pellets showed a similar CCS value after reduction, and it was approximately 30 kg/pellet. The Alcotac CS-bonded (C7) pellets showed even less strength, and it was approximately 15 kg/pellet. On the other hand, the dried pellets showed a higher strength after reduction. The highest increase in the CCS value was for the reference recipe (R1) followed by KemPel-bonded pellets (K1), Alcotac FE 16-bonded pellets (H4), Alcotac CS-bonded pellets (C7), and CMC-bonded pellets (U5), respectively.

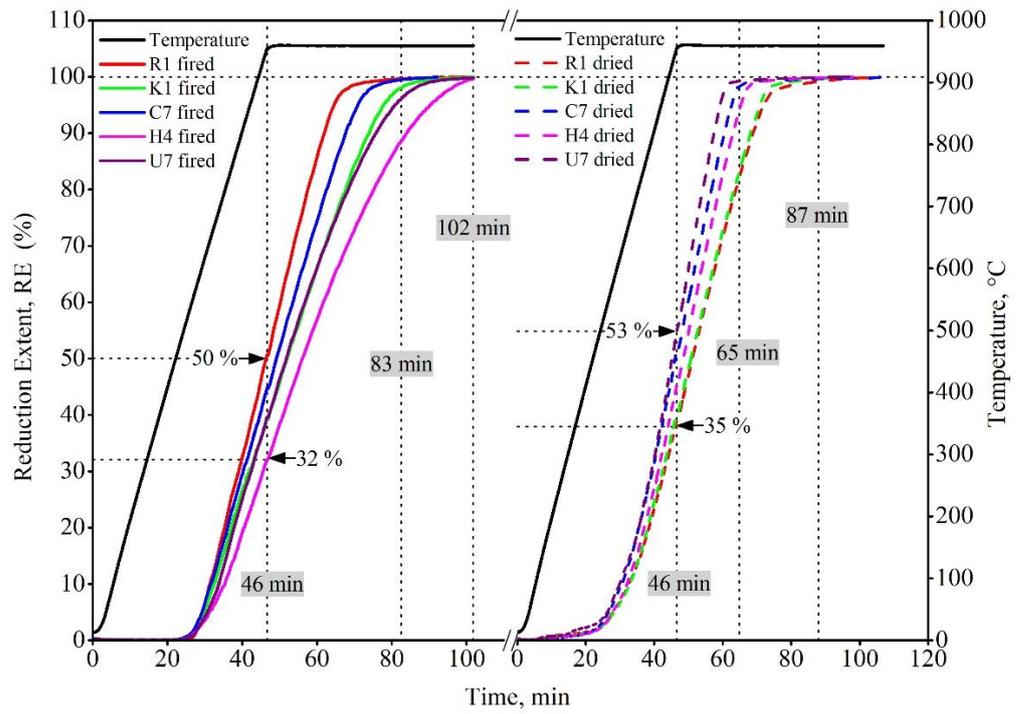


Figure 7. TGA of selected dried and fired pellets.

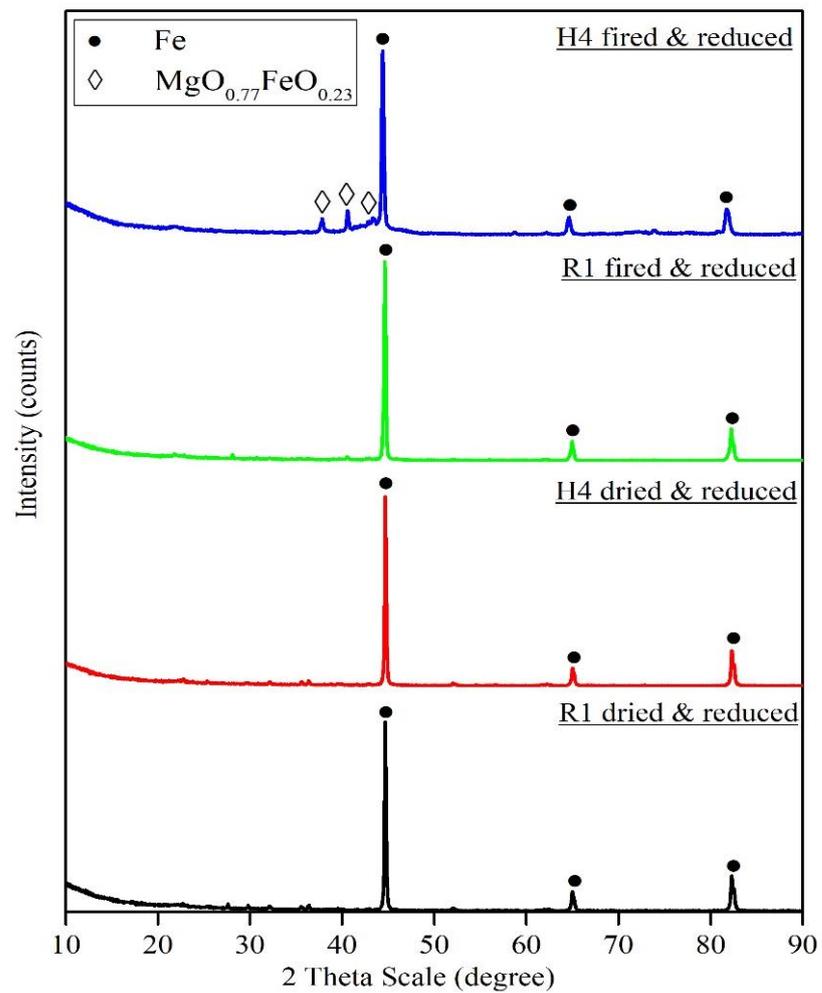


Figure 8. Powder XRD patterns of reduction products of dried and fired R1 and H4 recipes.

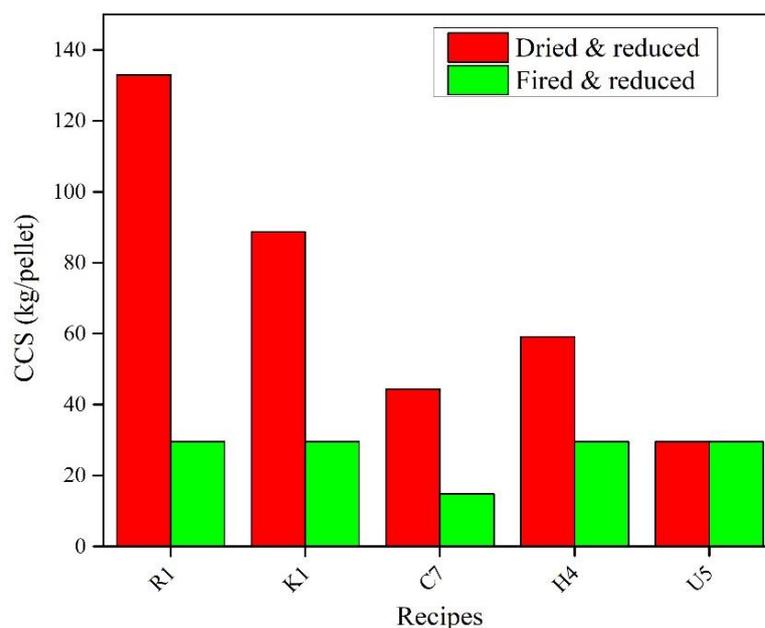


Figure 9. CCS of selected reduced dried and fired pellets.

3.7. Potential Saving of Bentonite

To summarize, a preliminary assessment of the potential bentonite savings by replacing the reference bentonite-based recipes with the top-performing recipes based on each of the four selected organic binders was performed. However, to gain more comprehensive insights, a more detailed techno-economic analysis is required.

Based on the estimated demand of iron pellets (540 Mt) by the year 2027 [4,5], Table 4 reveals that substituting the reference recipe (R1), which is based on bentonite, with the KemPel recipe (K1) would result in a reduction of 3.97 million tons of bentonite consumption. On the other hand, if we replace the same bentonite-based recipe (R1) with any of the other three organic binder-based recipes (C7, U5, H4), the consumption of bentonite could be decreased by 5.4 million tons, as none of these organic binder-based recipes contain bentonite.

Table 4. Amount of Bentonite Saved.

Recipe	Binder	Amount of Organic Binder Required (Million Tons)	Amount of Bentonite Required (Million Tons)	Amount of Bentonite Saved (Million Tons)
R1	Bentonite (1%)	0	5.4	0
K1	KemPel (0.1%) + Bentonite (0.265%)	0.54	1.43	3.97
C7	Alcotac CS (0.75%)	4.05	0	5.4
U5	CMC (0.5%)	2.7	0	5.4
H4	Alcotac FE 16 (0.5%)	2.7	0	5.4

4. Conclusions

Since iron ore pellets are a crucial feed material for the DRI process, enhancing the properties of the pellets and minimizing the amount of slag produced is imperative. With the replacement of bentonite with an organic binder, the amount of slag generated would reduce significantly, resulting in a product of greater quality while decreasing the energy consumption. The current study involved the utilization of four organic binders for the pelletization of magnetite concentrate in comparison with bentonite. The major conclusions inferred from this work are as follows:

- i. CMC gave the best dry strength results among the four organic binders as well as bentonite. A full replacement of bentonite with 0.5 wt.% of CMC showed very promising results. Alcotac CS and Alcotac FE16 showed good dry strength-wise results comparable to the reference recipe with full replacement of bentonite with 0.75 wt. % and 0.5 wt.% of the organic binders, respectively. KemPel showed good dry strength-wise results comparable to that of the reference recipe by replacing 73.5% of bentonite with 0.1 wt.% of the organic binder. The Alcotac CS and Alcotac FE16 recipes had the best yields among the binders.
- ii. The recipe (K1) in which 73.5% of bentonite was replaced with 0.1 wt.% of KemPel showed very good results after firing and reduction with H₂, which were almost the same as the reference recipe (R1). Similarly, both Alcotac CS (C7) and Alcotac FE 16 (H4) showed lesser strength than the reference (R1) and the KemPel recipe (K1) but better results than the CMC recipe (U5). Recipe (U5) with CMC, which showed the best dry pellet strength, did not perform well after the oxidation and reduction trials.
- iii. The dry pellets bonded with organic materials exhibited the highest reduction extent, with the order being U5 > C7 > H4 > K1 > R1. This was attributed to the porous structure resulting from the thermal decomposition of the organic binder, which facilitated H₂ diffusion and enhanced pellet reduction. Conversely, the organic-bonded fired pellets had a lower reduction rate compared to the bentonite-bonded fired pellets due to the formation of magnesioferrites, which hindered the reduction process by creating a hard reducible magnesium iron oxide phase (MgO_{0.77}FeO_{0.23}).

As per the results, the optimal recipe was K1, which utilized a partial replacement of bentonite with 0.1 wt.% of KemPel. Moreover, when employing organic binders with the complete replacement of bentonite, recipe H4, bonded by 0.5 wt.% Alcotac FE16, demonstrated superior properties, exhibiting a high CCS compared to all other organic-bonded pellets, both before and after reduction for both dried and fired pellets.

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