Physicochem. Probl. Miner. Process., 59(6), 2023, 176094

http://www.journalssystem.com/ppmp

Physicochemical Problems of Mineral Processing

ISSN 1643-1049

Investigating the effectiveness of organic binders as an alternative to bentonite in the pelletization of low grade iron ore

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Abstract: Bentonite is the traditionally used binder in iron ore pelletization. However, it consists of up to 85% silica and alumina which are undesired acidic gangue in iron-making. In this study, carboxymethyl cellulose, sodium lignosulfonate and cornstarch were used as acidic gangue-free organic alternatives to bentonite in synthesizing iron pellets. Iron ore, water and the corresponding binder were mixed and rolled in a pelletizing disk to form green pellets. The green pellets were dried and subsequently indurated in a furnace at 1200 °C to form indurated pellets. To evaluate the effectiveness of the organic binders, the pellets produced were tested on various pellet properties. Known industrial pellet property standards and the bentonite binder were used as references. Carboxymethyl cellulose, sodium lignosulfonate and corn starch produced green pellets with average drop numbers of 7.20 ± 0.84, 5.60 ± 0.89 and 6.00 ± 1.00 respectively, compared to bentonite's 5.00 ± 0.71. Dry pellets of average compressive strength 5.93 ± 0.09, 5.86 ± 0.03 and 11.52 ± 0.18 kg/pellet were produced by carboxymethyl cellulose, sodium lignosulfonate and corn starch respectively while bentonite's averaged 5.60 ± 0.08 kg/pellet. For indurated pellets, carboxymethyl cellulose (210.2 ± 1.88 kg/pellet) and sodium lignosulfonate (198.1 ± 2.49 kg/pellet) pellets were weaker than those of bentonite (250.4 ± 2.06 kg/pellet) but satisfied the industrial requirement of 181.4 kg/pellet. A boron oxide additive (0.1 wt. %) was used to boost the strength of carboxymethyl cellulose indurated pellets to 252.6 ± 1.32 kg/pellet, rendering them superior to those of bentonite.

Keywords: bentonite, iron ore, low grade ore, organic binders, pelletization, pellet evaluation, refractory ores

1. Introduction

Pelletization has increasingly become a popular method for the agglomeration of iron ore (Pal, 2018). This is because pelletization enables the exploitation of low grade iron ores, against a backdrop of rapidly declining reserves of high grade iron ores (Moraes, et al., 2018a). During pelletization, water, iron concentrate and a binder are mixed thoroughly and rolled in a pelletizing disk or drum to form moist, spherical pellets termed green pellets (Zhu, et al., 2015). The green pellets are then dried in an oven to form dry pellets (Sivrikaya & Arol, 2013a). The dry pellets are then subjected to thermal treatment in a furnace at 1200-1350 °C to strengthen them mechanically in a process known as pellet induration (Eisele & Kawatra, 2003). Indurated pellets are the main raw material for the blast furnace (Lu, et al., 2018).

Bentonite is the most used binder in iron ore pelletization (Lu, et al., 2018). Bentonite is a clay mineral that consists mostly of silica (~65%) and alumina (~20 %) (Devasahayam, 2018). Bentonite is used as a binder in pelletization for a number of reasons. Firstly, it is able to regulate the moisture content of the pelletization process quite effectively as it can expand and absorb water up to eight times its own mass (Eisele & Kawatra, 2003). Secondly, bentonite produces mechanically strong indurated pellets because it participates in slag bonding within the pellet microstructure during pellet induration (Sivrikaya & Arol, 2013b).

DOI: 10.37190/ppmp/176094

However, bentonite's main demerit is that it consists of up to 85% silica and alumina (Devasahayam, 2018). These constituents are undesirable acidic impurities that are removed from the iron ore in the preceding iron beneficiation steps. Therefore, use of bentonite in iron ore pelletization is counter-productive because it reintroduces/adds acidic silica and alumina gangue to the pellet feed. This acidic silica and alumina gangue requires more flux for the pellets to reach the basicity required in the reducing furnaces (blast furnace/DRI). The increased flux results in increased slag production. This in turn causes higher energy costs as more energy is wasted in melting the slag in the blast furnace (Kawatra, 2018). For direct reduced pellets, every percent of acid gangue added increases energy consumption by 30 kWh/ton of steel produced (Sivrikaya & Arol, 2013b). An increase of 1% in the silica content of the pellets increases the unit cost of steel making by USD 4-7 per ton (Sivrikaya & Arol, 2012). These margins are largely unsustainable as steel market competition increases. Furthermore, addition of 1% bentonite decreases the iron content of the pellet feed by 7 kg/ton of ore leading to production of diluted, uncompetitive pellets on the market (Schmitt, 2005) (Sivrikaya & Arol, 2013a). Also, the evolution of the iron and steel industry has seen iron-makers increasingly demanding reduced levels of silica and alumina in iron ore pellets as modern reduction chambers have limited slag handling ability (Moraes, et al., 2018b).

A binder that does not add these undesired acidic silica and alumina gangue or dilute the iron content of the pellets is ideal. Organic binders have potential in this regard. Unlike bentonite, organic compounds do not contain acidic silica and alumina impurities (Kumar & Suman, 2018). Elimination of these silica and alumina acidic impurities has been shown to reduce iron making costs by USD 2.50 per ton of hot metal produced (Schmitt, 2005). This is a significant margin.

Organic binders/compounds also have lower volatile points and are eliminated from the pellets during pellet induration. This means that, unlike bentonite, organic binders do not dilute the pellets' iron content or interfere in the subsequent iron-making processes after pelletization (Sivrikaya & Arol, 2013a). This is the ideal binder behaviour.

The objective of this study is to determine if certain organic binders are capable alternatives to the traditionally used binder bentonite in producing iron pellets. Carboxymethyl cellulose (CMC), sodium lignosulfonate and corn starch were selected as the organic alternatives to bentonite. These organic binders were selectively chosen because if effective, they can be easily manufactured from renewable resources such as sugar cane bagasse, saw dust and corn respectively. This also helps eliminate steep costs and availability challenges associated with bentonite. Known pellet property standards and the bentonite binder itself were used as references. If capable, these organic binders can potentially be used as acidic silica and alumina pollutant free binders in iron ore pelletization, reaping along the numerous benefits associated with such binders. Furthermore, as reserves of high grade, easy to process iron ores like magnetite continue to decline, refractory low grade iron ores such as goethite need to be sufficiently beneficiated to help keep up with the increasing market demand for iron (Sun, et al., 2020). At present there is no wide spread consensus on an effective beneficiation method for goethite limonite ores (Sun, et al., 2020). This study can serve as a developmental procedure for beneficiation and agglomeration through pelletization of low grade, refractory goethite limonite ores. The pellets produced can then be charged into the reduction chambers where they are reduced to form iron metal.

2. Materials and methods

2.1. Pre-treatment

A 75 kg iron ore mass of particle size 10-20 mm was procured from Ripple Creek Mine in Redcliff Zimbabwe. Using X-Ray Fluorescence (XRF S1 Titan 800), the iron ore was determined to be of grade 52.93% Fe with silica being the major gangue constituent. The mineralogy of the ore was determined by X-Ray diffraction pattern (XRD). As the ore was low grade and refractory in nature, it was beneficiated using magnetizing reduction roasting to produce a concentrate suitable for pelletization. Under roasting conditions of temperature 700 °C, duration of 45 minutes, a pulverized cow dung reductant to feed ratio of 0.3:1 and low intensity magnetic separation at 0.2 T, the ore was upgraded to a concentrate assaying 67.71% Fe at 85.56 iron recovery. The mineralogy of the concentrate was also determined using XRD.

2.2. Pelletization

The concentrate, whose size distribution is shown in Fig. 1 was then subjected to pelletization in a rotating pelletizing disk. The concentrate had a p80 value of 86 µm. The organic binders carboxymethyl cellulose (CMC), corn starch and sodium lignosulfonate were used in making the iron pellets, as was bentonite. Table 1 details the binders used in this study. Preliminary tests were carried out to determine the optimum dosage for each binder beforehand. The lowest binder dose at which green pellets satisfied the industrial green pellets requirements i.e. drop number and compressive strength of at least 4 and 1.0 kg/pellet respectively was deemed to be the optimal dose for that binder.

Table 1. Binders employed in this study

Name	Purity (%)	Particle size (µm)	Source
Bentonite	96	200	JoinedFortune Technology (Shen Yang) Co. Ltd, Liaoning, China
Carboxymethyl Cellulose	99.5	177	Wintercorn import & export global trading (Pty) Kimberly, South Africa
Sodium lignosulfonate	97	177	Moss Mekus Ventures Pty, Johannesburg, South Africa
Corn starch	99	177	Saproco International Johannesburg, South Africa

For each pelletizing procedure, 5 kg of iron concentrate was weighed, mixed with the corresponding binder and water. A stirrer was used to effectively mix the iron concentrate mixture with the binder fluid at 8-9.5% moisture level for 10 minutes. A pelletizing disk, of diameter 610 mm, rotating at 25 revs/min, inclined at 40^{o} to the horizontal was then used to produce the green (moist) pellets.

Initially, 200 g of the moist pellet feed was charged into the rotating pelletizing disk to act as pellet seeds. The rest of the mixture was then deposited gradually at 300 g/min for balling while the pelletizing disk rotated. Each pelletizing procedure lasted 25 minutes, producing the green pellets. A portion (250 g) of the green pellets produced by each binder was set aside for tests. The rest were dried in an oven at 105 °C overnight. A portion (250 g) of the dried pellets were set aside for compressive strength tests whilst the rest were indurated in a muffle furnace.

During the induration procedure, the dry pellets were immersed into the furnace at room temperature. They were then heated steadily until a firing temperature of 1200 °C was reached. The pellets were held at this temperature for 20 minutes to allow for pellet hardening. Finally, the indurated pellets were cooled down to room temperature. After the pelletization process was complete, the pellets were subjected to various pellet testing procedures as outline in the text below.

2.3. Drop number

Five green pellets of particle size range of 11-16 mm produced by each binder were used in this test. Each green pellet was dropped repeatedly onto a steel plate from a height of 46 cm until it fractured. The drop number is the number of drops a pellet takes to fracture. The average for each binder was calculated from the individual drop numbers and recorded accordingly.

2.4. Compressive strength

The compressive strengths of green, dried and indurated pellets made from each binder was determined by placing each pellet between two parallel plates of a pellet cold crushing strength test machine (Model No. CCS-77C). The pellet was then pressed steadily until it fractured, broke or when the gap between the plates reduced to 50% of the initial gap. The maximum load recorded during each pellet test was the pellet's cold crushing/compressive strength. Five pellets were used for each test and the average compressive strength calculated accordingly.

2.5. Porosity

Pellet porosity was determined gravimetrically following the ASTM method (ASTM C914-09, 2011). Five fired pellets made from each binder, of diameter 11-16 mm were weighed individually on a digital mass balance and their corresponding mass (m) recorded. Each pellet was coated with fully refined polyethene wax and was immersed completely in water of known volume under standard conditions. The rise in the water volume was recorded as the pellets' envelope volume Ve. Pellet porosity was deduced from equation 1. The average porosities of the pellets were then be calculated from the five pellet porosity experiments.

$$\varepsilon = \left(1 - {}^{m}\!/_{\rho V_e}\right) * 100 \tag{1}$$

where ε - Pellet porosity; m - mass of indurated pellet; ρ - concentrate density (mass/volume); Ve- pellet envelope volume; NB: pellet envelope volume is the change in volume of the liquid when a pellet is fully immersed in it. The wax coating was assumed to have negligible volume. Fig. 2 is a schematic diagram outlining the methods undertaken in this study.

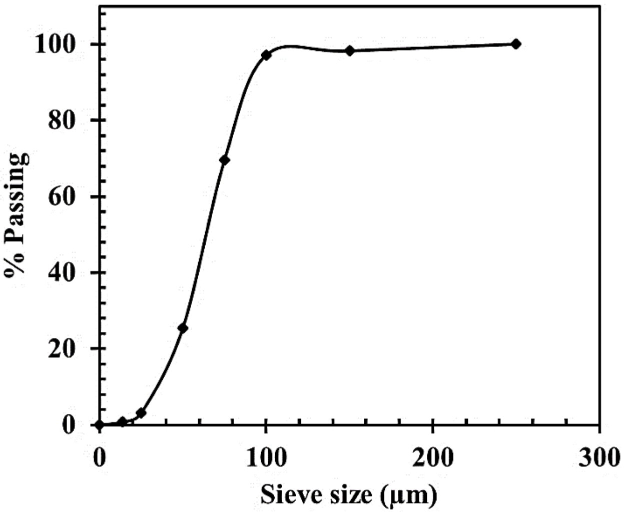

Fig. 1. Concentrate particle size distribution

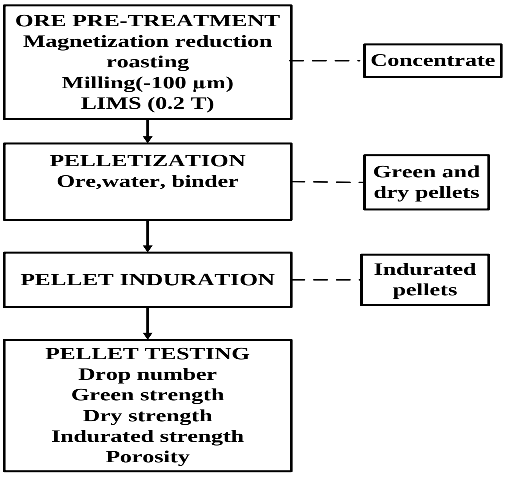

Fig. 2. Basic chronological overview of the methods undertaken in this study

3. Results and discussion

Fig. 3(a) shows the XRD pattern for the iron ore obtained. Goethite limonite was determined to be the predominant iron bearing mineral in the iron ore. Fig. 3(b) shows XRD pattern of the concentrate obtained after the ore had been subjected to magnetization reduction roasting. The diffraction pattern revealed magnetite to be the dominant iron bearing mineral in the iron concentrate. This showed that the reduction roasting procedure was effective in converting feebly magnetic goethite to ferromagnetic magnetite. This makes for more effective magnetic concentration of the ore. Table 2 shows the composition of the iron ore and the concentrate obtained respectively. The iron ore, through the reduction roasting procedure followed by low intensity magnetic separation was upgraded to a high iron grade concentrate assaying 67.71% Fe from a low grade ore assaying 52.93% Fe. The silica and alumina impurities were reduced from grades of 11.33% and 7.12% to 1.28% and 1.03% respectively. This is because these impurities are non-magnetic and are lost to the tailings during magnetic separation of the ferromagnetic magnetite from the gangue.

Table 3 shows the results of the binder evaluation tests carried out in the study. These results are discussed contextually in the text to follow.

Table 2. Chemical compositions of iron ore and concentrate

Element	Iron ore (%)	Iron concentrate (%)
Fe	52.93	67.71
Mn	1.87	-
Si	11.33	1.28
Al	7.12	1.03
S	<0.05	<0.05
P	<0.05	<0.05
LOI	6.71	-

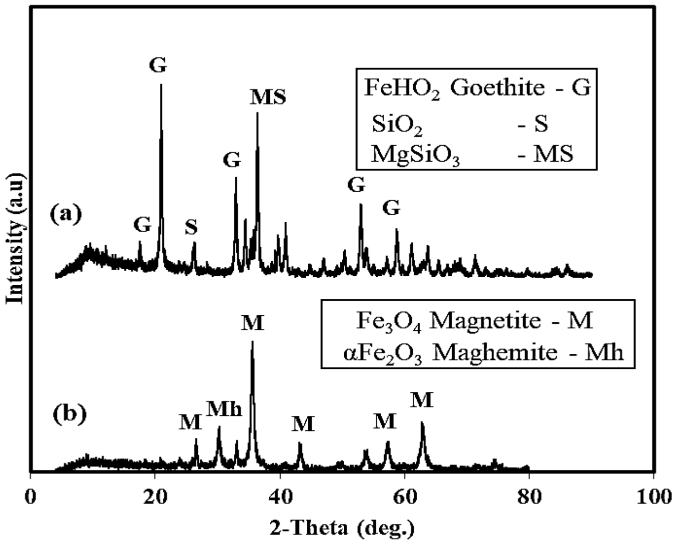

Fig. 3. XRD pattern of (a) iron ore and (b) iron concentrate

Table 3. Effectiveness of organic binders' investigation results at 95% confidence level

Binder code	Binder	Dose	Moisture level	Drop number	Wet strength (kg/pellet)	Dry strength (kg/pellet)	Indurated strength (kg/pellet)	Porosity (%)
1	No binder	0	7.1	2.60 ± 0.55	0.27 ± 0.02	0.88 ± 0.05	127.6 ± 2.26	28.6 ± 0.40
2	Bentonite	0.7	9.4	5.00 ± 0.71	1.70 ± 0.10	5.60 ± 0.08	250.4 ± 2.06	23.7 ± 0.38
3	CMC	0.1	8.9	7.20 ± 0.84	2.05 ± 0.10	5.93 ± 0.09	210.2 ± 1.88	26.0 ± 0.48
4	Corn starch	0.5	9.3	6.00 ± 1.00	1.98 ± 0.10	11.52 ± 0.18	148.0 ± 2.29	30.5 ± 0.53
5	Sodium lignosulfonate	0.5	8.1	5.60 ± 0.89	2.00 ± 0.06	5.86 ± 0.03	198.1 ± 2.49	30.3 ± 0.61

3.1. Drop number

Fig. 4 shows the average drop numbers of green pellets produced by bentonite and the different organic binders used in this study. When no binder (code 1) was used, the green pellets had an average drop number of 2.60 ± 0.55. When organic binders (code 3-5) were used, the green pellets average drop number increased to 7.20 ± 0.84, 6.00 ± 1.00 and 5.60 ± 0.89 for CMC, corn starch and sodium lignosulfonate binders respectively. These drop number values are above the industrially required minimal drop number of 4 (Sivrikaya & Arol, 2014), which is denoted by the dotted line in Fig. 4. Bentonite pellets (code 2) had an average drop number of 5.00 ± 0.71. The main limitation of this study is that it was conducted at laboratory scale. Larger scale studies are also relevant. Comparatively, in other investigations, sodium lignosulfonate, corn starch and CMC have produced green pellets with average drop numbers of 3.3, 4.0 and 4.7 in other studies respectively (Srivastava, et al., 2013; Sivrikaya & Arol, 2013a). These results broadly reaffirm that CMC and corn starch produce strong green pellets.

The drop number results obtained in this study show that each of the three organic binders produced green pellets with higher drop numbers than those of bentonite. Binders influence the drop strength of a green pellet by holding the pellet particles together by capillary forces (Halt & Kawatra, 2014). The binders interact with the moisture and pellet particles generating capillary forces and viscous forces that bond the particles together (Halt & Kawatra, 2014).

The high drop numbers achieved by the organic binders mean that they were able to generate greater capillary forces than bentonite. The effectiveness of the organic binders in generating capillary forces is attributed to their ideal chemical structure littered with several hydrophilic groups. These groups enable them to effectively disperse into the binder medium and achieve a good binding effect thus generating greater capillary forces within the green pellets (Kawatra & Claremboux, 2021). The impressive drop numbers achieved by the organic binders mean that their green pellets will remain intact during handling and drops in an industrial plant. This is vital because it minimizes material loss through fractures and breakage during green pellet handling (Sivrikaya & Arol, 2013b).

3.2. Wet strength

Fig. 5 shows the average compressive strengths of the green pellets produced in this study by the different binders. When no binder (code 1) was used in pelletization, the pellets had an average green compressive strength of 0.27 ± 0.02 kg/pellet. This was below the minimal required industrial value of 1 kg/pellet, which is denoted by the solid line in Fig. 5 (Sivrikaya & Arol, 2014). When organic binders (code 3-5) were used, the green strength increased from 0.27 kg/pellet to 2.05 ± 0.01, 1.98 ± 0.01 and 2.00 ± 0.06 kg/pellet for CMC, corn starch and sodium lignosulfonate green pellets respectively. These values were above the industrial minimal value of 1 kg/pellet (Sivrikaya & Arol, 2014). The organic binder made pellets also out-performed those of bentonite (code 2), which had an average wet strength of 1.70 ± 0.1 kg/pellet. The factors that impact pellet drop number also impact green pellet compressive strength.

3.3. Dry compressive strength

Fig. 6 shows the average compressive strengths of dry pellets produced in this study. Dry pellets produced without a binder (code 1) had a compressive strength of 0.88 ± 0.05 kg/pellet. This was far below the recommended industrial standard of 2.2 kg/pellet (Kotta, et al., 2017), which is denoted by the dotted line in Fig. 6. When bentonite was used as the binder (code 2), the dry strength of the pellets increased to 5.60 ± 0.08 kg/pellet. The organic binders CMC, corn starch and lignosulfonate (code 3-5) produced pellets with dry strengths of 5.93 ± 0.09, 11.52 ± 0.18 and 5.86 ± 0.03 kg/pellet respectively. These values were above the industrially required value of 2.2 kg/pellet (Sivrikaya & Arol, 2014). It is also notable that each of the three organic binders produced dry pellets that were stronger than those of bentonite. In other studies, CMC, corn starch and sodium lignosulfonate have produced dry pellets of average compressive strength 5.94, 12.2 and 3.22 kg/pellet respectively (Halt and Kawatra, 2016; Srivastava, et al., 2013; Sivrikaya & Arol , 2012). These investigations largely in agrrement with the findings of this study and re-affirm that sodium lignosulfonate, corn sarch and CMC produce dry pellets meeting the industrial strength standards of at least 2.2 kg/pellet.

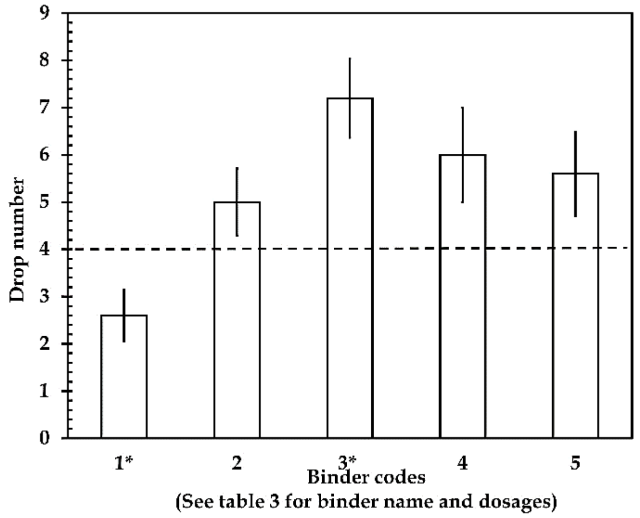

Fig. 4. Drop numbers of the pellets made by the different binders used in this study. Asterisks show statistically significant results

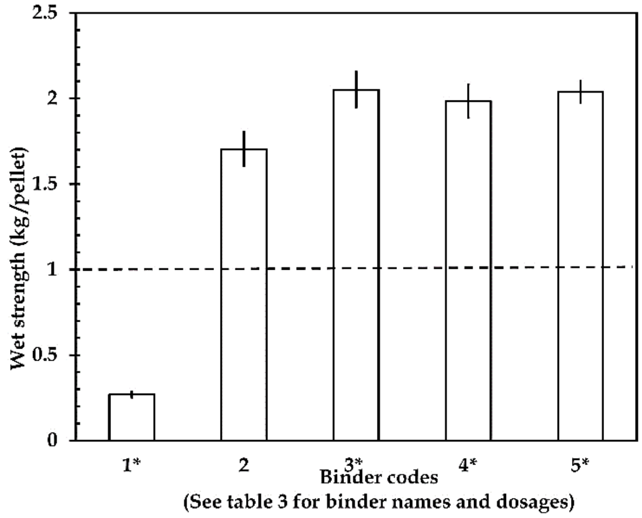

Fig. 5. Wet strengths of the iron oxide pellets. Asterisks indicate statistically significant results

The superior performance of the organic binders to the bentonite in this study is again attributed to the presence of several hydrophilic groups in their chemical structure. These allow for excellent binder dispersion into the binder medium allowing the organic binders to have a good binding effect and form many binder-pellet particle contact points (Kawatra & Claremboux, 2021). As moisture is removed from the pellets during drying, the organic binders are able to form more solid bridges with the pellet particles despite being administered at lower doses compared to bentonite. The results are mechanically strong dry pellets. Bentonite does not have an idealized chemical structure overladen with hydrophilic groups as do these organic binders (Eisele & Kawatra, 2003). This may hinder bentonite's dispersion into the binder medium and its subsequent formation of binder pellet particle bridges.

3.4. Porosity

Fig. 7 illustrates the average porosities of pellets produced in this study. Indurated pellets produced by bentonite (code 2) had a porosity of 23.7 ± 0.38%. The organic binders CMC, corn starch and sodium lignosulfonate (code 3-5) produced pellets with average porosities of 26.0 ± 0.48, 30.5 ± 0.53% and 30.3 ± 0.61% respectively. All the binders used in this study produced pellets within the industrially recommended porosity range of 18-32% (Kotta, et al., 2017). However, the porosities of pellets made by the organic binders were all greater than those of bentonite. This behaviour was expected because unlike bentonite, organic binders are eliminated from the pellets during pellet induration (Sivrikaya & Arol, 2013a). This results in a deficit of binder slag bonding thus producing more porous pellets (Sivrikaya & Arol, 2013a). High pellet porosity helps reducing gases diffuse into the pellet interior easily. It also helps oxygen diffuse out of the pellet efficiently (Kotta, et al., 2017). These two factors enhance pellets reduction in the blast furnace/direct reduction chamber (Kawatra & Halt, 2011). Other investigations have also seen CMC, corn starch and sodium lignosulfonate producing highly porous indurated pellets at 34%, 36% and 31%, porosity respectively (Sivrikaya & Arol , 2010; Srivastava, et al., 2013).

3.5. Indurated pellets compressive strength

Fig. 7 also shows the average compressive strengths of the indurated pellets produced by the different binders employed in this study. Without a binder (code 1), indurated pellets of average compressive strength of 127.6 ± 2.26 kg/pellet were produced. The industrial standard for indurated pellets is 181.4 kg/pellet (Kawatra & Claremboux, 2021). When organic binders were used (code 3-5), the average strength increased to 210.2 ± 1.88 , 148.0 ± 2.29 and 198.1 ± 2.49 kg/pellet for CMC, corn starch and sodium lignosulfonate respectively. Bentonite pellets (code 2) had an average indurated strength of 250.4 ± 2.06 kg/pellet.

Therefore, CMC and sodium lignosulfonate produced indurated pellets exceeding the industrial requirement of 181.4 kg pellet. This means that the two organic binders, though their pellets may be weaker than those of bentonite, are still effective and can possibly be used to produce the indurated pellets. Organic binders, unlike bentonite, are eliminated from the pellets during induration (Kotta, et al., 2017). This is the reason pellets produced by organic binders are more porous and hence more reducible compared to those of bentonite. However, it is also a limitation as the more porous a pellet is, the weaker it becomes, as Fig. 7 illustrates. A great binder has to satisfy the delicate balance between pellet porosity and strength. By producing pellets exceeding the industrial strength requirement, CMC and sodium lignosulfonate accomplished this balance.

Notably, corn starch pellets (code 4) produced the weakest indurated pellets of any binders used in this study. Furthermore, unlike those of CMC (code 3 at 210.2 ± 1.88 kg/pellet) and sodium lignosulfonate (code 5 at 198.1 ± 2.49 kg/pellet), the corn starch indurated pellets, with an average compressive strength of 148.0 ± 2.29 kg/pellet did not meet the industrial indurated pellet strength requirement of 181.4 kg/pellet. This behaviour is attributed to the corn starch binder producing the most porous indurated pellets of any binder as shown in Fig. 7.

For comparison's sake, in other investigations, CMC, corn starch and sodium lignosulfonate have produced indurated pellets of average compressive strength 301, 161.3 and 207.3 kg/pellet respectively (Sivrikaya & Arol , 2012; Srivastava, et al., 2013). The exceedingly high compressive strength of the CMC pellets was attributed to a very high induration temperature of 1300 °C used in that investigation (Sivrikaya & Arol , 2012). In this study a modest induration temperature of 1200 °C was used. However the findings of these studies are broadly consistent with those obtained in this investigation i.e. sodium lignosulfonate and CMC can be used to produce indurated pellets meeting/exceeding the industrial requirement of 181.4 kg/pellet.

3.6. CMC combined with boron containing additive

CMC was evaluated to be the best performing organic binder in this study because it out-performed the other organic binders in most of the investigations carried out. Therefore, the CMC was chosen as a suitable organic binder for further investigations with a boron containing additive to help boost the compressive strength of indurated pellets made by an organic binder.

Table 4 shows the properties of the pellets made with the CMC + 0.1wt % boron oxide additive. The pellets had an average indurated compressive strength of 252.63 ± 1.32 kg/pellet. This value was comfortably above the industrial requirement of 181 kg/pellet as outlined by Kawatra & Claremboux, (2021). The CMC + boron oxide pellets were also stronger than the bentonite pellets which had a compressive strength of 250.4 ± 2.06 kg/pellet.

The greater strength of the CMC + boron oxide additive pellets can be attributed to two factors. Firstly, in this study, the CMC has been shown to produce green and dry pellets with better values of compressive strength to those of bentonite. The action of the binder early on in pelletization helps improve impacts the properties of the indurated pellets (Zhu et al, 2015). Secondly, the boron additive slag bonds and the additional silica slag bonds it induces at lower induration temperatures help reinforce the pellets' compressive strength (Sivrikaya & Arol, 2010; Halt & Kawatra, 2014). It is for this reason that pellet induration using in this was carried out at 1110°C instead of the conventional 1200 °C.

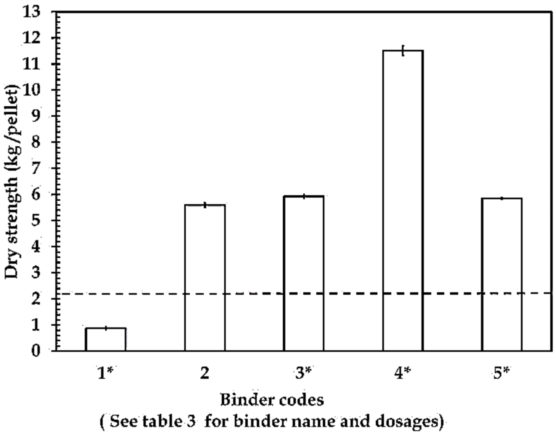

Fig. 6. Dry strength of pellets made by the different binders used in this study. Asterisks indicate statistically significant results

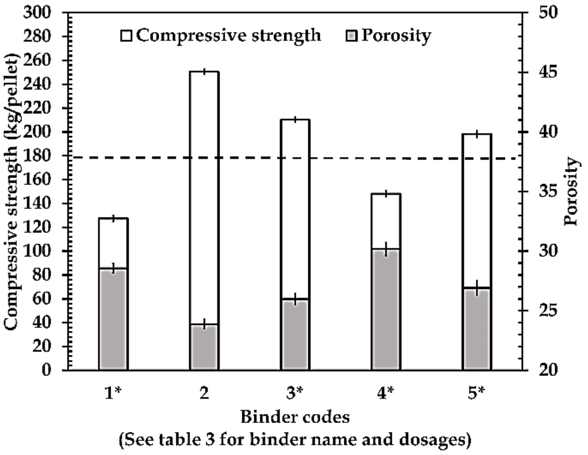

Fig. 7. Indurated strength and porosity of the iron oxide pellets. Asterisks indicate statistically signficant results

The CMC + boron oxide additive pellets had a porosity of 24.2 ± 0.37% which was slightly higher than bentonite's 23.7 ± 0.38% but within the recommended 18-32% porosity threshold as outlined by Sivrikaya & Arol, (2013a). This is an example of a binder getting correct the delicate balance between pellet strength and porosity. The organic portion of the binder getting eliminated helps increase pellet porosity whilst the small amount of inorganic boron oxide additive left boosts strength of the indurated pellets.

Table 4. Properties of pellets made with CMC organic binder and boron additive

Property	Value	Recommended minimum value
Wet drop number	5.80 ± 0.84	3
Wet compressive strength	1.89 ± 0.08 kg/pellet	1 kg/pellet
Dry compressive strength	2.93 ± 0.15 kg/pellet	2.2 kg/pellet
Indurated strength	252.63 ± 1.32 kg/pellet	181.4 kg/pellet
Porosity	24.2 ± 0.37%	18-32 %

4. Conclusions

CMC, corn starch and sodium lignosulfonate organic binders produced green with average compressive strengths of 2.05, 1.98 and 2.00 kg/pellet respectively, whilst bentonite pellets averaged 1.70 kg/pellet. Therefore, the three organic binders can possibly be used as effective alternatives to bentonite in synthesizing green pellets. For dry pellets, the CMC, sodium lignosulfonate and corn starch pellets averaged 5.93, 5.86 and 11.52 kg/pellet compressive strength respectively. Bentonite dry pellets had an average compressive strength of 5.60 kg/pellet. Evidently the three organic binders can possibly be used as capable alternative binders to bentonite in synthesizing dry pellets. The CMC (210.2 kg/pellet) and sodium lignosulfonate (198.1 kg/pellet) produced indurated pellets weaker than those of bentonite (250.4 kg/pellet) but still satisfied the industrial standard of 181.4kg/pellet. Therefore, CMC and sodium lignosulfonate can still possibly be used as capable binders in synthesizing indurated pellets. A boron oxide additive can be used to boost the strength of CMC indurated pellets (252.6 kg/pellet) so that they are stronger than those of bentonite (250.4 kg/pellet). Given that CMC and sodium lignosulfonate are synthesized from sugar cane bagasse and sawdust respectively, there is potential for local manufacture of these products for iron ore pelletization to replace bentonite which is scarce and often accompanied by significant shipping costs. This helps meet the ever growing market demand for iron against a backdrop of declining reserves of easy to process, high grade iron ores like magnetite.

Acknowledgments

This research received no external funding.

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Supplementary Information

Drop number

Binder	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
No binder	2	3	3	2	3
Bentonite	5	4	5	5	6
CMC	7	7	8	6	8
Corn starch	7	5	6	5	7
Sodium lignosulfonate	6	5	5	7	5
CMC and Boron	5	7	5	6	6

Wet compressive strength

Binder	**Run 1 (kg/pellet)**	**Run 2 (kg/pellet)**	**Run 3 (kg/pellet)**	**Run 4 (kg/pellet)**	**Run 5 (kg/pellet)**
No binder	0.30	0.27	0.28	0.26	0.25
Bentonite	1.76	1.80	1.55	1.67	1.73
CMC	2.05	2.01	1.94	2.22	2.04
Corn starch	1.91	1.96	1.89	2.07	2.10
Sodium lignosulfonate	2.07	1.96	2.03	2.13	2.01
CMC and Boron	1.77	1.89	1.95	1.88	1.98

Dry compressive strength

Binder	Run 1 (kg/pellet)	Run 2 (kg/pellet)	Run 3 (kg/pellet)	Run 4 (kg/pellet)	Run 5 (kg/pellet)
No binder	0.97	0.87	0.84	0.84	0.86
Bentonite	5.64	5.48	5.56	5.62	5.68
CMC	5.83	5.86	6.01	5.95	6.02
Corn starch	11.44	11.34	11.39	11.66	11.76
Sodium lignosulfonate	5.89	5.89	5.84	5.85	5.81
CMC and Boron	2.97	2.89	2.98	3.10	2.70

Indurated compressive strength

Binder	Run 1 (kg/pellet)	Run 2 (kg/pellet)	Run 3 (kg/pellet)	Run 4 (kg/pellet)	Run 5 (kg/pellet)
No binder	127.0	125.6	126.5	131.5	127.3
Bentonite	249.9	251.9	253.0	247.9	249.3
CMC	207.7	211.8	208.6	211.5	211.3
Corn starch	150.6	148.8	148.8	144.4	147.7
Sodium lignosulfonate	196.7	201.3	195.4	200.2	197.1
CMC n Boron	252.82	251.78	254.17	250.87	253.50

Porosity

Binder	Run 1 (%)	Run 2 (%)	Run 3 (%)	Run 4 (%)	Run 5 (%)
No Binder	28.3	29.1	28.1	28.5	28.8
Bentonite	23.4	24.1	23.7	23.8	24.4
CMC	26.7	25.4	25.8	26.1	25.9
Corn starch	30.6	29.5	29.7	30.6	30.5
Sodium Lignosulfonate	27.4	27.3	26.3	26.2	27.4
CMC and Boron	24.40	24.10	23.80	24.70	23.90