The Effect of Binder Dosage and Sintering Temperature on the Strength Of Chromite Pellets Using Various Sodium Bentonite Binders

C. Silent [1,2], H.P. van Schalkwyk [2], F. B. Waanders [2]

***Abstract*—** Sodium bentonite is an essential binder in the pelletising of chromite ores for ferrochrome production, owing to its unique swelling and cation-exchange properties. Nevertheless, the understanding of how its mineralogical, chemical and physicochemical characteristics influence pellet performance under varying processing conditions remains limited. The present study aimed to characterise sodium bentonite and determine the effects of binder dosage and sintering temperature on the mechanical integrity of chromite pellets.

Comprehensive characterisation of various sodium bentonites was conducted employing X-ray diffraction (XRD) for phase identification, X-ray fluorescence (XRF) for bulk chemical composition, standard swell index, plate water absorption (PWA) and cation exchange capacity (CEC) measurements to evaluate their hydration and exchange properties. Pelletisation trials were subsequently performed with varying binder dosages, and the green pellets were subjected to controlled sintering at multiple temperatures to investigate strength development. Fired pellet strengths were quantified to establish relationships between the properties of the bentonite, its dosage, and sintering regime.

Results show that both bentonite dosage and sintering temperature significantly influence pellet strength development. Correlation analyses reveal that bentonite CEC and swelling capacity are strong predictors of green ball plasticity and final fired strength. These findings enhance the understanding of bentonite–chromite interactions during pelletising and offer a scientific basis for selecting binders and optimising processes in ferrochrome production.

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***Keywords*—** Binder Dosage, Ferrochrome Production, Sodium Bentonite, Swell Index

I. INTRODUCTION

The global demand for ferrochrome, a critical alloying element in stainless steel production, continues to increase in response to industrial growth and infrastructure development [1]. Chromite ores, the primary source of chromium, are typically beneficiated and agglomerated prior to smelting to enhance furnace efficiency, reduce dust losses, and improve feed permeability [2-3]. Pelletisation has emerged as one of the most efficient agglomeration techniques, producing uniform, mechanically strong, and thermally stable feed materials suitable for both pre-reduction and smelting operations [4].

Bentonite is the most widely used inorganic binder in the pelletisation of fine ores due to its excellent water absorption, swelling, and cation exchange properties [5][6]. In the ferrochrome industry, sodium bentonite plays a vital role in imparting plasticity and cohesiveness to the moist ore mixture, facilitating the formation of spherical green pellets that maintain integrity during drying and sintering [6]. Upon firing, the binder contributes to the development of solid bridges between chromite particles, enhancing fired pellet strength and reducibility [7]. Despite its widespread use, the effectiveness of bentonite as a binder is highly dependent on its mineralogical composition, exchangeable cation type, and physicochemical behaviour under thermal treatment.

Most existing studies on pelletisation have focused primarily on iron ore systems, with relatively limited investigations dedicated to chromite–bentonite interactions. Chromite ores differ substantially from iron ores in terms of mineralogy, surface chemistry, and reduction behaviour, which influence the binder's performance during both green balling and firing [8]. Furthermore, industrial experience indicates that the optimal binder dosage and sintering temperature are highly process specific, suggesting that a more fundamental understanding of the interplay between bentonite properties and pellet performance is required.

The present study aims to systematically characterise three sodium bentonites used for chromite pelletisation and to determine the influence of binder dosage and sintering temperature on the mechanical integrity of chromite pellets. The objectives are to:

1. Determine the mineralogical and chemical composition of the sodium bentonite using XRD and XRF analyses;

C Silent[1,2] is with OMV, Potchefstroom, 2531, South Africa and a master's student at the NWU, Potchefstroom, South Africa.

HP van Schalkwyk[2] and FB Waanders[2], Centre of Excellence in Carbon-based Fuels, Faculty of Engineering, North-West University, Private Bag X6001, Potchefstroom, 2520, South Africa

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2. Evaluate its hydration and exchange properties through swell index, plate water absorption (PWA), and cation exchange capacity (CEC) measurements; and
3. Assess the effects of binder dosage and sintering temperature on fired pellet strength.

This work contributes to the scientific understanding of binder–ore interactions in the ferrochrome pelletisation process and provides a foundation for optimising binder selection and processing conditions to achieve superior pellet quality and process efficiency.

II. Materials and Methods

A. Raw Materials

1. Chromite filter cake

The chromite filter cake used in this study was sourced from a South African ferrochrome operation.

The mineralogical composition of the chromite filter cake was determined using X-ray diffraction (XRD) to identify crystalline phases, while X-ray fluorescence (XRF) analysis provided the bulk chemical composition (Table 1) and revealed chromite ($FeCr_2O_4$) as the dominant phase, with silicate impurities.

TABLE I: CHROMITE FILTER CAKE MINERAL AND CHEMICAL COMPOSITION

Chemical composition	(%)
Na_2O	1.073
MgO	9.498
Al_2O_3	14.375
SiO_2	4.07
SO_3	0.074
K_2O	0.499
CaO	0.563
TiO_2	1.292
V_2O_5	0.324
Cr_2O_3	35.848
Fe_2O_3	28.746
Mineral composition	(%)
Chromite	86.9
Talc	2.6
Enstatite	10.5

2. Sodium Bentonite

Three commercially sourced sodium bentonites, named bentonite A, bentonite B, and bentonite C were evaluated to assess the influence of their mineralogical and physicochemical variability on fired pellet strength.

Physicochemical properties, including swelling capacity, plate water absorption (PWA), and cation exchange capacity (CEC) were measured following standardised procedures (Table 2).

TABLE II: STANDARD METHODS USED TO DETERMINE THE PROPERTIES SHOWN OF THE BENTONITES A-C

Property	**Unit**	**Method**	**Bentonite A**	**Bentonite B**	**Bentonite C**
Swell Index	mL / 2 g	ASTM D5890-19	25	21	32
Plate Water Absorption (PWA)	%	ASTM D5891-20	367	370	430
Cation Exchange Capacity (CEC)	meq / 100 g	ASTM C837-09	61.53	65.18	57.78

X-ray diffraction (XRD) was used for phase identification and to quantify the smectite content (Table 3). X-ray fluorescence (XRF) analysis was used to determine the bulk oxide composition (Table 4).

TABLE III: QUANTITATIVE MINERALOGICAL COMPOSITION OF SODIUM BENTONITES.

Mineral Phase	Bentonite A (%)	Bentonite B (%)	Bentonite C (%)
Quartz	4.3	12.6	22.7
Plagioclase	0.9	0.8	1.0
Calcite	0.6	0.8	1.1
Kaolinite	22.4	3.9	3.9
Muscovite	1.7	23.1	23.1
Smectite	70.0	65.1	48.2

TABLE IV: XRF ANALYSIS RESULTS OF THE THREE INVESTIGATED BENTONITES

Chemical composition (%)	Bentonite A	Bentonite B	Bentonite C
Na_2O	0.93	1.03	4.36
MgO	2.18	2.50	2.82
Al_2O_3	16.2	15.37	13.94
SiO_2	44.53	52.26	58.25
P_2O_5	0.01	0.00	0.00
SO_3	0.16	0.46	0.17
K_2O	0.33	1.22	1.29
CaO	0.84	1.78	1.03
TiO_2	2.14	0.61	0.40
V_2O_5	0.09	0.02	0.01
Cr_2O_3	0.04	0.01	0.01
MnO	0.13	0.08	0.1
Fe_2O_3	13.25	5.44	4.66

B Pelletising procedure

Chromite filter cake was blended separately with each bentonite type at three binder dosages: 0.8 wt. %, 1.2 wt. %, and 2.0 wt. %. Moisture content was adjusted to 9–11 %, and the mixture homogenised in a pan pelletiser operating at 30 rpm and 60° tilt until pellets of 9–12 mm diameter was obtained.

Green pellets were air-dried for 48h. Dried pellets were sintered in a muffle furnace at 200, 400, 800 and 1200 °C with a 2-hour holding time.

B. Strength testing

The fired pellet strength was evaluated using a universal testing machine fitted with a 5 kN load cell. Each value represents the average of six pellets per condition.

III. Results and Discussion

A. Material characterisation

1. Mineral characterisation

X-ray diffraction (XRD) patterns for all three bentonites confirmed that the smectite mineral group is the principal phase (Table 3). Quartz was detected as a common impurity in all samples, while minor plagioclase and calcite quanitites were observed in bentonite A and bentonite B. Traces of kaolinite and muscovite were also present.

The relatively sharper and more intense basal reflection of bentonite C indicated higher crystallinity and layer ordering, supporting its superior chemical purity and sodium character inferred from XRF results.

2. Elemental characterisation

X-ray fluorescence (XRF) analysis revealed compositional variations among the three sodium bentonites (Table 4), reflecting differences in their sodium content and parent deposit characteristics. All samples were dominated by silica and alumina, consistent with the aluminosilicate framework of the smectite group minerals. However, clear contrasts in Na_2O, Fe_2O_3, and TiO_2 contents suggest differing extents of cation exchange and impurity mineral inclusion.

Bentonite C contained the highest SiO_2 (58.25 %) and Na_2O (4.36 %), accompanied by relatively low Fe_2O_3 (4.66 %) and TiO_2 (0.40 %). The elevated Na_2O concentration and high Si/Al ratio are consistent with Na-bentonite and associated with higher swelling capacity [9]. Bentonite B displayed intermediate chemistry, characterised by moderate Na_2O (1.03 %), higher SiO_2 (52.26 %), and lower Fe_2O_3 (5.44 %) relative to bentonite A.

The variation in CaO (0.84–1.78 %) among the samples reflects differing levels of residual divalent cations in the interlayer sites.

Overall, bentonite C appears to possess the most chemically favourable composition for binder performance, combining high Na_2O and low Fe_2O_3 with minimal divalent contamination.

3. Plate Water absorption

The plate water absorption (PWA) test quantifies the amount of water bentonite can absorb and retain under standardised conditions, providing insight into its overall hydration capacity and the surface area available for water adsorption. This property is crucial during the wetting and nucleation stages of pelletisation, where adequate water uptake enables proper dispersion and binding of fine chromite particles.

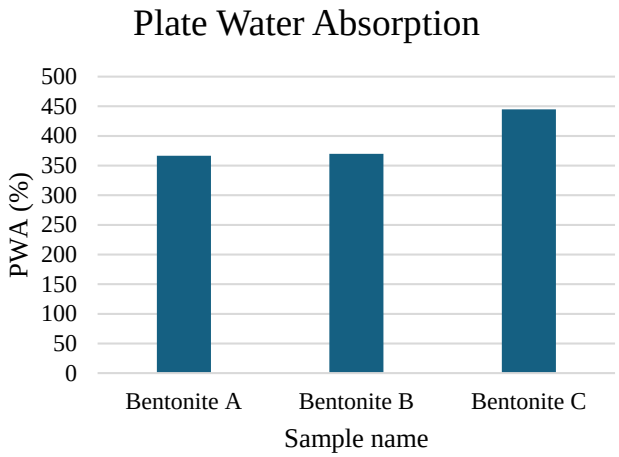

Fig. 1: Plate water absorption results of the bentonites

Among the tested samples, bentonite C exhibited the highest PWA, followed by bentonite B and bentonite A (Figure 1). The elevated PWA value of bentonite C reflects its superior swelling and interlayer hydration behaviour, as also indicated by its high Na_2O content (4.36). This composition promotes the formation of a stable gel structure capable of uniformly coating ore particles and sustaining plasticity during pellet growth.

In contrast, bentonite A and B absorbed substantially less water, suggesting a reduced smectite content and more limited interlayer expansion. The marginally higher PWA of bentonite B relative to bentonite A, despite its lower swell index, may result from microstructural differences such as finer particle size distribution, which increases surface adsorption without necessarily improving gel strength.

Overall, PWA results correlate strongly with the swell index trends and provide complementary information regarding bentonite functionality. High PWA values (> 400 %) generally indicate robust hydration behaviour and effective binder dispersion, both of which enhance pellet plasticity and green ball strength. Thus, the superior PWA performance of bentonite C supports its classification as the most suitable binder among the three samples for chromite pelletisation [6] [10].

4. Swell Index

The swell index test provides a rapid assessment of the hydration and expansion capacity of bentonite when dispersed in water, reflecting the degree of sodium saturation and layer charge density of the smectite structure. The results obtained for the three samples show clear variability: Bentonite C exhibited the highest swell index, followed by bentonite A and bentonite B (Figure 2).

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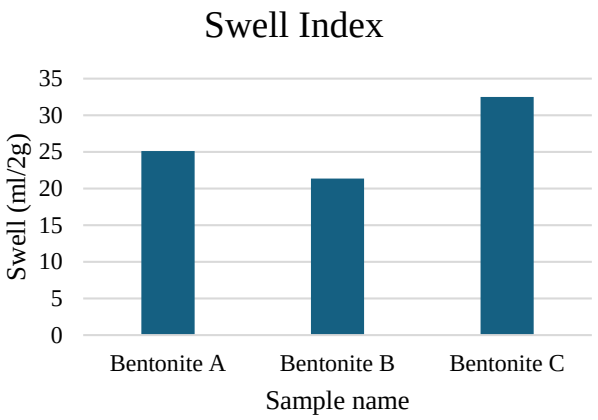

Figure 2: Swell indices of the bentonites investigated

The superior swelling behaviour of bentonite C is consistent with its high Na_2O content (4.36 %) and relatively low Fe_2O_3 concentration (4.66 %), suggesting a highly sodium-exchanged montmorillonite with minimal structural substitution by iron or calcium. The expansion of the interlayer spacing during hydration enables the formation of a viscous gel that enhances particle adhesion and plasticity during pellet formation. Conversely, bentonite B's limited swelling corresponds to its lower Na_2O (1.03 %) and higher CaO (1.78 %), indicative of incomplete Na activation and the presence of divalent cations that restrict interlayer expansion.

Bentonite A displayed intermediate swelling behaviour, likely moderated by its elevated Fe_2O_3 (13.25 %) and TiO_2 (2.14 %) contents, which may occupy octahedral sites within the smectite structure and reduce layer flexibility. These findings confirm that swell index is a reliable indicator of bentonite activity, directly influencing the binder's ability to distribute water uniformly and generate cohesive green pellets.

5. Cation Exchange capacity

Cation exchange capacity (CEC) is a critical parameter that governs the hydration behaviour, swelling potential, and electrostatic binding of smectite clays. It quantifies the total number of exchangeable cations associated with the negatively charged layers of montmorillonite, and therefore strongly influences the strength and plasticity of green pellets.

The measured CEC values for the three sodium bentonites were 61.53, 65.18, and 57.78 meq/100 g for bentonite A, bentonite B, and bentonite C, respectively (Table 2). Although bentonite B exhibited the highest CEC, it simultaneously showed the lowest swelling index (21 mL/2 g) and moderate water absorption (370 %). This combination suggests that while Bentonite B possesses abundant exchange sites, many may be occupied by divalent cations such as Ca^{2+} (3.18 %), which restricts layer expansion and hydration.

Bentonite A, with a CEC of 61.53 meq/100 g and higher smectite content (70 %), demonstrated balanced behaviour, corresponding to a partially sodium-activated system. The moderate Ca^{2+} content (1.33 %) allows for adequate layer expansion while maintaining structural integrity during pellet drying and firing.

In contrast, bentonite C recorded the lowest CEC (57.78 meq/100 g) and lowest smectite content (48.2 %) yet achieved the highest swelling (32 mL/2 g) and water absorption (430 %). This may be attributed to its cleaner chemical composition, particularly low Fe_2O_3 (4.66 %) and CaO (1.03 %), which promote greater interlayer flexibility and hydration efficiency per unit charge.

Overall, the results confirm that CEC alone does not fully predict binder performance. The most effective pelletisation binders exhibit a synergistic balance between CEC, swelling ability, and smectite content. Bentonite B's high CEC but low swelling reflects limited sodium activation, whereas bentonite C, despite lower CEC, demonstrates superior hydration efficiency - favourable for producing green pellets and uniform microstructures during sintering.

B. Pellet strengths

1. Effect of Sintering Temperature on Fired Pellet Strength

The compressive strength of fired chromite pellets increased markedly with rising sintering temperature for all three sodium bentonites (Figure 3). This behaviour reflects progressive solid-state diffusion, the onset of liquid-phase sintering, and microstructural densification as temperature increased from 200 °C to 1200 °C.

At low temperatures (≤ 400 °C), pellet strength remained negligible, corresponding to the dehydration stage of the bentonite binder where only weak van der Waals and electrostatic forces contribute to interparticle adhesion. Between 800 °C and 1000 °C, a sharp increase in strength occurred due to the formation of incipient necks between chromite grains and the partial vitrification of bentonite components.

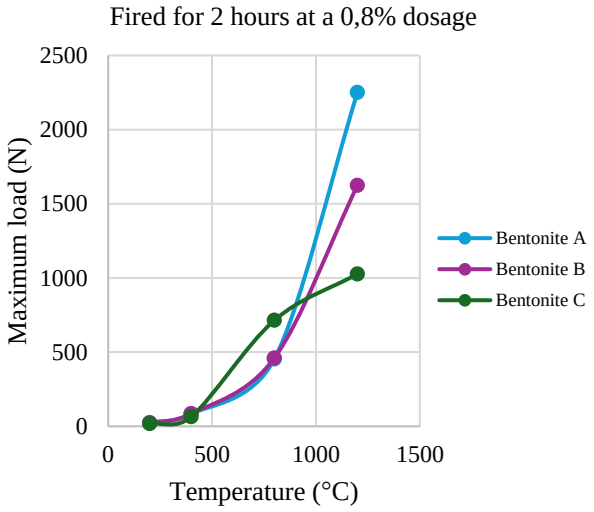

Figure 3: Pellet strengths at various temperatures

At 1200 °C, all samples reached their highest mechanical strength; however, the extent of improvement differed notably among binder types. Bentonite A achieved the highest maximum load (~2300 N), followed by bentonite B (~1600 N) and bentonite C (~1050 N). The superior fired strength of

bentonite A may be attributed to its higher Fe_2O_3 (13.25 %) and TiO_2 (2.14 %) contents, which promote the formation of iron–titanate and silicate bonding phases during high-temperature sintering. These compounds enhance intergranular neck growth and contribute to improved mechanical stability.

Conversely, bentonite C, despite its superior swelling and hydration characteristics, produced the weakest fired pellets at elevated temperature. Its relatively high SiO_2 (58.25 %) and low Fe_2O_3 (4.66 %) composition result in limited formation of low-melting eutectics and fewer solid bridges, leading to lower densification. This finding highlights the inverse relationship that can arise between hydration behaviour (beneficial for green strength) and thermal reactivity (governing fired strength).

Bentonite B displayed intermediate performance, consistent with its moderate Fe and Ca contents, suggesting balanced but not optimal thermal bonding characteristics. Overall, these results indicate that chemical composition exerts a dominant influence on high-temperature pellet strength, with Fe- and Ti-bearing bentonites favouring stronger sintered bonds, whereas highly siliceous sodium bentonites tend to produce more porous fired structures.

IV. Conclusion

The results confirm that the mineralogical composition and cation exchange capacity of sodium bentonite critically affect its function as a binder in chromite pelletisation. Bentonite C, characterised by high sodium content, exhibited superior hydration and swelling, while Bentonite A achieved the greatest fired strength.

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References

[1] E. Kleynhans et al., "Chemical beneficiation of chromite ore to improve the chromium-to-iron ratio for ferrochrome production," *Minerals Engineering*, vol. 201, pp. 108196, 2023. Available: https://doi.org/10.1016/j.mineng.2023.108196.

[2] Marius VASILESCU, and Mircea DOBRESCU, "Chromite. Processing and Applications,", vol. 42, no. 1, pp. 12-18, 2019. Available: https://doi.org/10.35219/mms.2019.1.02.

[3] E. Kleynhans et al., "Unique challenges of clay binders in a pelletised chromite pre-reduction process," *Minerals Engineering*, vol. 34, pp. 55-62, 2012. Available: https://doi.org/10.1016/j.mineng.2012.03.021.

[4] J. I. Verdeja González, D. Fernández González, and L. F. Verdeja González, "Pelletizing," *Topics in Mining, Metallurgy and Materials Engineering*, pp. 65-92, 2020. Available: https://doi.org/10.1007/978-3-030-54606-9_3 .

[5] H. Liu, B. Xie, and Y.-L. Qin, *"Effect of Bentonite on the Pelleting Properties of Iron Concentrate," Journal of Chemistry, vol. 2017,* Article ID 7639326, 6 pages, 2017. *doi: 10.1155/2017/7639326*

[6] T. C. Eisele, and S. K. Kawatra, "A review of binders in iron ore pelletization," *Mineral Processing and Extractive Metallurgy Review*, vol. 24, no. 1, pp. 1-90, 2003. Available: https://doi.org/10.1080/08827500306896.

[7] C. Tang et al., "Oxidation Behavior of High FeO Ferrous Spinels and Its Impacts on the Induration Characteristics of Oxidized Pellets," *Metallurgical and Materials Transactions B*, vol. 55, no. 5, pp. 3072-3086, 2024. Available: https://doi.org/10.1007/s11663-024-03230-y.

[8] V. Singh, and S. M. Rao, "Study the effect of chromite ore properties on pelletisation process," *International Journal of Mineral Processing*, vol. 88, no. 1-2, pp. 13-17, 2008. Available: https://doi.org/10.1016/j.minpro.2008.04.003.

[9] M. Ç. Karakaya, N. Karakaya, and S. Bakır, "Some properties and potential applications of the Na- and Ca-bentonites of ordu (N.E. Turkey)," *Applied Clay Science*, vol. 54, no. 2, pp. 159-165, 2011. Available: https://doi.org/10.1016/j.clay.2011.08.003.

[10] T. Karidakis, "Plate water absorption method for bentonite evaluation and its relevance to iron pelletizing performance," in *38º Seminário de Redução de Minério de Ferro e Matérias-Primas e 9º Simpósio Brasileiro de Minério de Ferro*, São Luís, Brazil, 2008, pp. 440–450, doi: 10.5151/2594-357x-0045.