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## IMPROVEMENT OF MECHANICAL STRENGTH OF IRON ORE PELLETS USING RAW AND ACTIVATED BENTONITES AS BINDERS

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**Abstract:** In this study, sodium, calcium, and mixed bentonite samples were used as binders in the pelletizing fine iron ore concentrate obtained from the Divrigi Iron Ore Concentration Plant in Turkey. In the pelletizing tests, sodium bentonite sample was used as received and after upgrading process. Additionally, the calcium bentonite sample required activation by sodium bicarbonate while the mixed bentonites sample was used untreated and as well as activated. The pellets produced were tested for compressive strengths, drop number, and porosity in order to characterize the pellets. The results showed that untreated and upgraded sodium bentonite samples provided relatively stronger pellets compared to calcium and the mixed type bentonite samples needed activation with sodium bicarbonate to increase the strength of the pellets. Based on the results of the drop number, compressive strengths, and porosity, it is possible to make pellets which meet the standards by adequate addition of type and amount of bentonite.

**Keywords:** bentonite, pelletizing, iron ore concentrate, binder, sodium bicarbonate

### Introduction

Major raw material in iron and steel industry is iron ore which can be classified as high grade and low grade in terms of its Fe content. High grade iron ores, which can directly be used in a blast furnace, are not abundant in earth's crust to supply the need of iron and steel industry. The exploitation of low grade iron ores is possible after enrichment. Low grade iron ores contain considerable amounts of impurities including compounds of silica, alumina, calcium, and magnesium. Hence the concentration process is required based on crushing, grinding for adequate liberation before the implementation of separation techniques. Liberation can mostly be achieved at considerable fine particle sizes. For this reason, the concentrate obtained is not suitable to be charged directly into the blast furnace or the direct reduction plant

without converting it into suitably sized agglomerates. The most commonly employed agglomeration technique is pelletizing by which a mixture of iron ore, water, and binder is rolled up in a mechanical disc or drum to produce agglomerates (green or wet pellets) (Sivrikaya and Arol, 2010).

A narrow size distribution in green pellets is an important criterion for the pellet quality because high permeability in the pellet bed is beneficial for reduction process in steelmaking. In practice, variations may occur in the incoming pellet feed properties (like moisture content, fineness and wettability) which result in variations in the green pellet growth rate and size distribution. Pellet size is controlled either mechanically, by adjusting the screen opening or “chemically” by slightly varying the moisture content or the binder dosage. Increasing the binder dosage is known to decrease the green pellet growth rate, making pellets smaller, while increasing the water content results in an opposite effect (Forsmo et al., 2006; Sastry and Fuerstenau, 1972). Eketorp (1962) found that the surface area of particles affects the moisture retaining capacity of pellets. Moisture content in green pellets is critical where the optimum amount is the case at which all open pores are filled by water. Insufficient moisture causes air inclusions which reduce the capillary effect. However, an excess amount forms a coherent film of water which neutralizes the capillary effect.

Green pellet strength and plasticity are important parameters for the productivity of an iron ore pelletizing plant. Green pellet strength is described by two test values, that is by drop number and compression strength. The drop number describes the green pellet strength during a fast impact such as the impact that occurs during unloading from a conveyor belt. The drop number must be high enough for the green pellets to survive the transportation from the balling circuits to the pelletizing machine. The drop number is, however, influenced by changes in both plasticity and elasticity, and it increases with increasing moisture content and bentonite dosage. The green pellet strength under static load, e.g., in the pellet bed in the drying zones, is described by the wet compression strength. It needs to be high enough to assure minimum deformation and breakage. Plastic deformation and green pellet breakage decrease the permeability of the pellet bed in the drying and oxidation zones of the pelletizing machine, resulting in negative consequences for both pelletizing capacity and pellet quality (Forsmo et al., 2008).

Bentonite is primarily used for improving dry compressive strength of iron concentrate pellets so that they go through the processes such as smelting without much damage. Ball et al. (1973) indicated that bentonite clay has the following effects.

- Bentonite absorbs moisture, allowing for higher moisture concentrate feeds to be pelletized. Moisture variations can be overcome by altering bentonite dosages.
- As bentonite is mixed into the iron ore concentrate it becomes wet so that clay layers expand and disperse by the hydration of exchangeable interlayer cations, transforming into a matrix that bonds the ore particles together.
- During tumbling, the pellets are formed by particles adhering to each other in layers, which are compacted by the weight of the other pellets into a spherical

shape. Bentonite is well dispersed and retains an even distribution of moisture throughout the wet pellet as it grows.

- During drying, bentonite increases the drying rate by providing a pathway for the moisture to be removed.

The binding of iron oxide grains by bentonite clay to form pellets is a complex process, with a large number of variables, many of which have never been adequately studied. Current practice for pelletizing iron ore concentrates was developed in 1950's during which bentonite clay was practiced as a binder and since then it has remained the most acceptable binder because of its effectiveness and relatively low cost. The minimum industrially acceptable dry pellet compressive strength is typically 22 N. A typical dosage of bentonite is 0.66% of the moist (typically 10% moisture) iron ore concentrate filter cake (Ripke and Kawatra, 2000). The dosage of sodium bentonite needs to be kept as low as possible because pellets containing more bentonite cost more to produce and contain higher silica content. This gives the industry an incentive to use bentonites in ways that produce adequate strengths at lower dosages. However, in the case of mixed or calcium bentonite usage as binder, the dosages can be higher because of their low binding properties. In pelletizing process, Na bentonite is generally used as a binding material which is more expensive than calcium and mixed types bentonites. Calcium bentonite and mixed type bentonite are cheaper, however, they must be activated with sodium bicarbonate or Na-CMC (sodium carboxyl methyl cellulose) before they can be used as binding materials (Ripke and Kawatra, 2003).

It is well known that sodium carbonate (soda ash) improves the capability of bentonite to bind iron ore into pellets and reduce the total amount of bentonite required for a given quantity of iron ore fines. Sodium in soda ash replaces some of the calcium and magnesium in the bentonite lattice and thereby improves the binding efficiency of Ca-bentonite. However, it was believed that bentonite would not combine with sodium carbonate except when sodium carbonate solution is employed to make the ion replacement (Erickson and Palusky, 1973). In this context, the aim of this study is to investigate the use of sodium, calcium, and mixed type of bentonite samples as a binder in the pelletizing of fine iron ore concentrate.

## **Experimental**

### **Materials**

#### **Magnetite and bentonite samples**

Magnetite concentrate ( $\text{Fe}_3\text{O}_4$ ) used in the studies was obtained from the Divrigi Iron Ore Concentration & Pelletizing Plant (Turkey). The chemical analysis of magnetite sample is presented in Table 1 (Arslan et al., 2007). Three different bentonite samples were used for the experiments. Na- bentonite was brought from Resadiye district. Ca-bentonite and mixed bentonite were obtained from Somas and Canbensan Company, respectively. The chemical analyses of the bentonite samples are presented in Table 2.

Original bentonite samples were first dried at 60°C and then dry screened to determine the particle size distribution of the particles. In the case of wet screen analysis, bentonite samples were soaked overnight where the solids ratio was 6% by weight. The stainless steel screens were used for the dry and wet particle size analysis. The results of the particle size distributions of the samples are shown in Fig. 1.

Table 1. Chemical analysis of magnetite sample (Arslan et al., 2007)

Compound	Fe	S	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	Ni
Content (%)	69.0	0.30	1.50	0.78	0.65	0.55	0.04	0.08	0.23

Table 2. Chemical analyses of bentonite samples

Compound (%)	Resadiye	Somas	Canbensan
SiO <sub>2</sub>	57.09	51.76	54.74
Al <sub>2</sub> O <sub>3</sub>	16.73	14.77	15.53
Fe <sub>2</sub> O <sub>3</sub>	3.24	5.48	5.06
MgO	2.03	3.31	3.11
CaO	3.18	3.56	2.51
Na <sub>2</sub> O	2.51	0.47	1.70
K <sub>2</sub> O	0.97	0.94	1.51
TiO <sub>2</sub>	0.3	0.54	0.71
P <sub>2</sub> O <sub>5</sub>	0.15	0.16	0.09
MnO	0.08	0.11	0.04
LOI	13.4	18.7	14.8

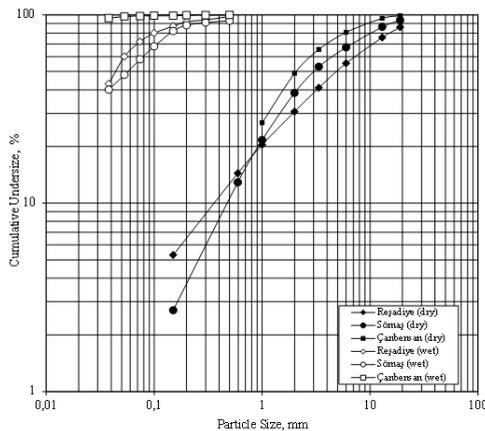


Fig. 1. Particle size distributions of bentonite samples

## Methods

### Upgrading bentonite sample

Upgrading of Na-bentonite sample was carried out employing a 50.8 mm (2 inch) lab scale Mozley hydrocyclone with apex diameters of 4.3 and 6.5 mm. Prior to concentration the run-of-mine bentonite sample was first crushed below 3–4 mm to avoid excessive size reduction of non clayey minerals, and then soaked for 24 hr after which agitated for 24 hr. This method was also explained in detail in a previous study (Boylu et al., 2010). Material balance on upgrading was not taken into consideration since the effect of upgrading on binding properties of bentonites was of primary interest.

### Activation procedures of bentonites

Prior to the soda activation, the bentonite samples were initially water sprayed to adjust the desired moisture content of 35–40% as already done in industrial application. The effect of specific cations on the process was eliminated by using membrane filtered water with 30–35 ppm TDS (total dissolved solids) as the moisturizing agent. The homogenized bentonite samples with the desired moisture and soda powder were mixed to form bentonite dough as in industrial applications, and it was needed until all the soda was absorbed in the entire sample. The activated bentonite samples, approximately 3–4 mm in size, were then left to dry and/or to be cured in room temperature ( $23 \pm 1$  °C). Following the drying, the activated bentonite samples were ground below 150  $\mu\text{m}$  using a mortar and pestle.

The cation exchange capacities (CEC) (based on the methylene blue test standard of ASTM 837 C) and swelling indexes (Boylu et al., 2010) of as received or upgraded bentonite samples were given in Table 3.

Table 3. CEC and swelling indexes of bentonite samples

Bentonite Type	Activation	CEC (meq/100 g)	Swelling Index ( $\text{cm}^3$ )
Na-bentonite (as received)	–	78.0	20.5
Na-bentonite (upgraded)	–	94.0	32.0
Mixed bentonites	Activated with 0.5% soda	64.5	14.0
	Activated with 1.0% soda		16.0
	Activated with 2.0% soda		20.0
	Activated with 3.0% soda		22.0
Ca-bentonites (as received)	Activated with 0.5% soda	60.0	8.0
	Activated with 1.0% soda		14.5
	Activated with 3.0% soda		20.0
Ca-bentonites (upgraded)	Activated with 0.5% soda	78.5	11.0
	Activated with 1.0% soda		14.0

### Pelletizing tests

In the initial tests, different amounts of bentonite were added to the magnetite concentrate to determine the optimum binder ratio and moisture content and then pellets were prepared by rolling them carefully in hand. The compressive strength and drop tests were performed on green pellets. After determination of binder ratio and moisture content of the samples, further experiments were carried out at a laboratory-scale pelletizing disc under optimum test parameters and different types of green pellets were produced. The compressive strength, drop number, and porosity tests were applied to the pellets where following numbers were taken into consideration for the evaluation of the results (Meyer, 1980).

- Compressive strength: 1 kg/pellet for green, 1 kg/pellet for dried pellets and 200 kg/pellet for fired pellets,
- Drop number: 4 for green and dried pellets,
- Porosity: 25–32% for fired pellets.

A 60 cm diameter pelletizing disc was used in the experiments. The slope and rotation speed were 45° and 40 rpm, respectively. Previously mixed magnetite concentrate and bentonite (2 kg in dry basis) samples were fed to the disc. After the sample was introduced a little amount of water was added and nuclei generation started. The nuclei were moistened with water spray to retain moisture content while adding additional material to enlarge them into pellets. These products are called green pellets. The green pellets were immediately dried at 105 °C and held at this temperature for 20–24 hr to ensure that they were completely dried. The dry pellets were fired at 1200 °C for 30 min (Fig. 2). Finally, compressive strength, drop and porosity tests were applied on the respective samples.



Fig. 2. (a) Green, (b) dry, (c) fired pellets

### Compressive strength tests

Compressive strength of dry pellets is a crucial factor. It is measured to find the required value for handling, drying, and firing processes. When pellets are fed to rotary furnaces they are exposed to high pressure. To prevent possible size reduction of pellets, they must be strong enough. Compressive strength of the pellets were

measured by compressing individual pellets between two plates where the speed of the moving plate was 10 mm/min. Tests were performed on 5 pellets, and the average compressive strength values were calculated.

### **Drop strength tests**

The drop number describes the strength of green and dry pellets under impact. This test measures the ability of pellets to remain intact during handling. The type of bentonite, ore moisture, surface area, pelletizing conditions and mixing are the factors affecting the drop strength. In tests, green and dry pellets are allowed to fall from a height of 46 cm to a steel plate and the breakage is visually detected. The drop number gives the average number of drops before a fracture is observed. Tests were run for 5 pellets and the average value was calculated. Pellets are expected to remain unbroken after 4 drops.

### **Porosity tests**

Porosity is a very important property of pellets. Lower porosity leads to a better particle-particle contact, but obstructs the diffusion of oxygen through the green pellet during oxidation. High porosity causes material loss. Therefore, it is very essential to test the porosity value of pellets. Porosity values were calculated using the following formula where  $D$  and  $d$  are actual and apparent specific gravities respectively:

$$\text{Porosity} = \frac{D-d}{D} \cdot 100. \quad (1)$$

## **Results and discussions**

### **Results**

#### **Effect of sodium bentonite addition on specification of pellets**

A series of pelletizing experiments were carried out to determine the effect of sodium bentonite addition on the formation of pellets. The binder ratio was chosen between 1% and 4% by weight of magnetite concentrate and the moisture content was adjusted as 8, 9, 10, and 12% for all binder ratios. When compared to industrial applications higher dosages of bentonite addition were tested in the case of bentonite samples other than enriched Na-bentonite. It is obvious that the dosages should be higher when mixed or calcium types were used because of their low binding properties. Regardless of the bentonite amount added, the increase in the dosage of water improves the strength of green pellets. This might be attributed to the colloidal nature of bentonite having high surface area. Hence, the plasticity of green pellets is increased (Dor et al., 1970). The results of drop number tests showed that the optimum binder ratio was 2.5% and the moisture content was 12% for both green pellets. Compressive strength tests were carried on dry and fired pellets obtained. Furthermore, the effect of

concentrated sodium bentonite was also investigated. The results of the tests are given Table 4.

Table 4 clearly shows that Na-bentonite addition leads to a substantial improvement in the pellet strength. The optimum test results were attained when 2.5% bentonite (as received) was added. An increase in bentonite addition causes an enhancement in drop number, compressive strength and porosity but compressive strength values tend to decrease with further addition of as received bentonite amount. In the case of upgraded bentonite addition, the compressive strength values increased with the increasing amount of bentonite. However, drop numbers of green and dry pellets were found to be low.

Table 4. Effect of sodium bentonite on crushing and drop strength of pellets

Bentonite Type	As received Na-bentonite			Upgraded Na-bentonite		
	2	2.5	3	0.7	1	1.5
Bentonite Amount (%)	2	2.5	3	0.7	1	1.5
Compressive Strength (kg/dry pellet)	10	7	6	5	6	9
Compressive Strength (kg/fired pellet)	510	328	318	250	407	447
Porosity (%) (fired pellet)	24	28	30	25	29	32
Drop Number (times/green pellet)	5	7	10	2	2	7

#### **Effect of calcium bentonite addition on specification of pellets**

Sodium bentonites are more absorbent than calcium bentonites because the divalent calcium ions hold the clay platelets more strongly together than monovalent sodium ions, letting less water in between the platelets (Kawatra and Ripke, 2003). It is a fact that Turkey has more calcium bentonite reserves than sodium bentonite. On the other hand, the prices of sodium bentonites are more expensive compared to calcium bentonites. Therefore, Ca bentonite was used for the following tests.

Similar procedure was repeated with calcium bentonite. The binder ratio was adjusted between 1% and 4% by weight of magnetite concentrate and the moisture content was adjusted as 8, 9, 10 and 12% for all binder dosages. Preliminary test results showed that increasing the amount of bentonite results in an increase in the average drop number of green pellets. However, these values are still under the standard value which is 4.

In the initial tests, best results were obtained when sodium bicarbonate ratio was 0.5% of solids added. At this ratio drop number of both green and dry pellets had the standard drop number of 4. Secondary tests were accomplished using laboratory-scale pelletizing disc at 0.5, 1 and 3% soda addition and then crushing and drop strength tests were applied to the pellets produced. The results given in Table 4 show that increasing the dosage of sodium bicarbonate activated bentonite provided an increase in the compressive strength, drop number and porosity of pellets. The best results were

obtained when bentonite activated with 3% sodium bicarbonate was added at an amount of 4%.

The effects of sodium bicarbonate on the activation of upgraded calcium bentonite were tested individually. In the initial tests optimum binder ratio was found to be 4% for both raw and dry pellets. Further tests were carried out with pelletizing disc at 3% and 4% binder ratios. In the activation processes, sodium bicarbonate ratio was 0.5% and 1% by weight of solids (Table 5). The average drop number of pellets increases with the addition of 4% activated calcium bentonite binder. The same trend is reported for the compressive strength for raw and dry pellets. However, compressive strength of fired pellets is seen to be under standard values. Furthermore, the required porosity value could not be attained with the addition of either activator.

#### **Effect of mixed type bentonite addition on specification of pellets**

In these tests mixed type bentonite was added to magnetite concentrate at different dosages (1, 2, 3, and 4%). The moisture content was adjusted to 8, 9, 10, and 12% for all binder additions. The higher the binder addition the higher the average drop number for green pellets was noted.

In the case of sodium bicarbonate activation the ratios were 0.5, 1, and 3%. Best results with sodium bicarbonate activation were obtained when the binder ratio was 3%. Proceeding tests were accomplished using a laboratory-scale pelletizing disc at 0.5, 1, 2, and 3% sodium bicarbonate addition and then the pellets were tested for compressive and drop strengths. The results are given Table 5. As it is seen in Table 5, the addition of 1% sodium bicarbonate is enough to meet standard values. When activated bentonite ratio is increased the values of compressive strength, average drop number and porosity rise.

#### **Discussion**

It is well known that Na-bentonites are mostly preferred for pelletizing iron ore concentrates due to their high binding capacities. Binding capacities of Na-bentonites may possibly be related to the swelling index. It is obvious that possible replacement of alkaline activated mixed or Ca-bentonites as binding agents will be more economic since Na-bentonite reserves in the world are limited. The prices of Na-bentonites in pelletizing agent grade are also relatively high when compared to other bentonites. Therefore, the way to activate the mixed or Ca-bentonites into sodium form can be advantageous. In this study, the pelletizing characteristics of Na, mixed, and Ca-bentonites were investigated, and the results are summarized in Figs. 3–7.

As seen in Fig. 3, upgrading of Na-bentonites resulted in lower bentonite addition for standard dry pellets. Additionally, the required bentonite addition (minimum 2%) for original Na-bentonites (as received) was reduced to the levels of 0.7% after the upgrading process. Similar behavior was also obtained for the compressive strengths and porosity of fired pellets (Figs. 4 and 5). The higher swelling index or CEC, the better pellet properties are. When drop numbers of pellets are evaluated, it can be said

that bentonite addition in pellets increased the drop number of green pellets and the addition of bentonite can be reduced to lower levels with the soda activation of Ca or mixed bentonites and upgrading of Na-bentonites (Fig. 6). This can be attributed to increased binding characteristics of bentonite through soda activation or upgrading.

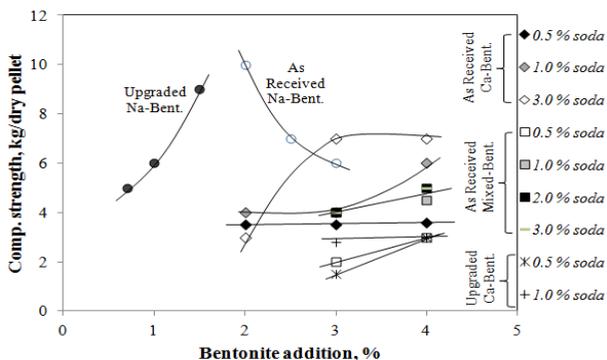


Fig. 3. Compressive strengths of dry pellets with different types of bentonites

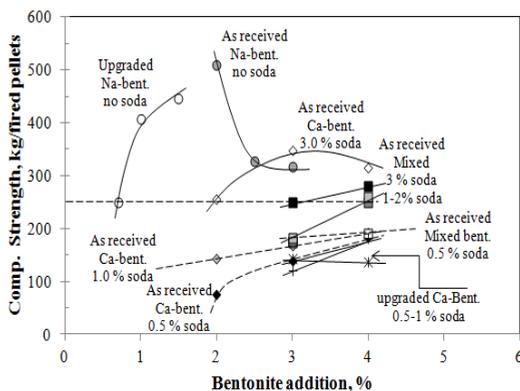


Fig. 4. Compressive strengths of fired pellets with different types of bentonites

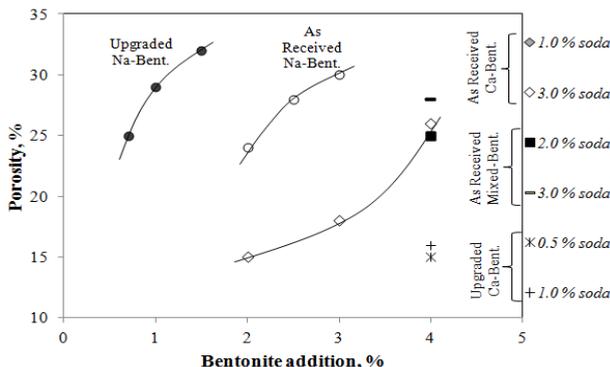


Fig. 5. Porosity of fired pellets with different types of bentonites

Table 5. Effect of activated Ca and mixed bentonite on compressive strength, porosity, and drop strength of pellets

	Ca-bentonite (as received)			Ca-bentonite (upgraded)			Mixed-Bentonite (As received)														
	Sodium bicarbonate amount (%)			Sodium bicarbonate amount (%)			Sodium Bicarbonate Amount (%)														
	0.5	1	3	0.5	1	0.5	1	2	3												
Bentonite Amount (%)	2	3	4	2	3	4	3	4	3	4	3	4									
Compressive Strength (kg/green pellet)	1	1.2	1	1.5	2	1	2	2.2	0.8	1.1	0.9	1	1.5	1.3	2	1.5	1.5	1.6	2		
Compressive Strength (kg/dry pellet)	3.5	3.5	3.6	4	4	6	3	7	7	1.5	3	2.8	3	2	3	4	4.5	4	5	4	5
Compressive Strength (kg/fired pellet)	75	140	184	144	167	192	255	348	314	143	137	120	183	173	190	176	250	182	260	250	280
Porosity (%) (fired pellet)	-	-	-	-	-	15	18	26	-	15	-	16	-	-	-	-	25	-	25	-	28
Drop Number (times/green pellet)	2	4	7	3	5	7	3	5	8	3	7	3	8	4	7	5	8	7	10	8	10

Activation of mixed bentonites with soda in the amounts of higher than 1% also enhanced the compressive strengths (dry and fired pellets). On the other hand, soda dosages less than 1% on the activation yielded bentonite which did not meet the pellet standards (Figs. 3-4). Similar behavior was also observed for the drop number of green pellets (Fig. 6). For the required porosity of pellets in compliance with pellet standards, the optimum dosage of mixed bentonites after the soda activation was found to be in the amounts of higher than 2% (Fig. 5).

The most interesting finding on the pelletizing tests was about the usage of Ca-bentonite. It is known that Ca-bentonite cannot be used in practice because of its low binding characteristics. The test results showed that Ca-bentonite could be well considered as an additive for the pelletizing of fine magnetite concentrates when it is activated with soda (Figs. 3-6). The dosages of bentonites providing the pellet standard requirements with respect to CEC and swelling characteristics of bentonites are summarized in Fig. 7 where the confined regions depict pellets conforming with the standards. As seen in Fig. 7, Na-bentonites as received meet the standards for pelletizing agents, and should be added to magnetite concentrate in amounts of  $>2\%$ . In Turkey, approximately 1% sodium bentonite addition is required for pelletizing fine iron ore concentrates. The use of higher dosages required in this study may be attributed to the quality of the bentonite samples used. Therefore, upgrading of as received bentonite was carried out. Upgrading Na-bentonites resulted in lower dosages down to 0.7% for the required standards. Mixed bentonites meet the standards after the activation. When the bentonite is activated with 2% soda, the required bentonite amounts in the pelletizing should be higher than 4%. On the other hand, in the case of activation process with 3% soda, the amount of bentonite addition should be reduced down to 3%. Similarly, to prepare the pellets complying with the standard Ca-bentonite, addition should be higher than 4%, provided that the activation was achieved with minimum 3% soda addition. The results also showed that the amount of bentonite to be used for the pellets is related to the swelling capacities and CEC of the bentonite. Hence higher soda dosages in the activation process result in lesser addition of bentonite for binding.

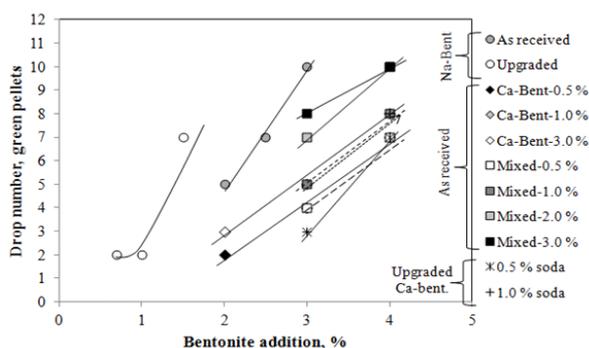


Fig. 6. Drop number of green pellets with different types of bentonites

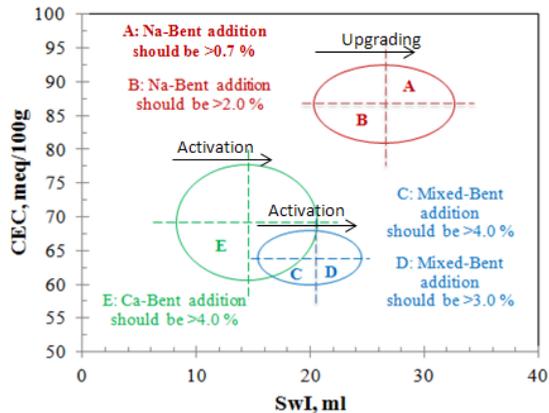


Fig. 7. Bentonite requirement in relation to swelling index and CEC

## Conclusions

In pelletizing of fine magnetite concentrates, pellets with required mechanical strength could be produced when as received and upgraded Na-bentonites were used in the amounts of  $>0.7\%$  and  $>2\%$ , respectively. On the other hand, in the case of calcium and mixed type bentonites much higher additions were needed, that is  $>3\%$  and  $>4\%$ , respectively. When the activated bentonites were used to produce pellets with adequate mechanical strength, best results were obtained with calcium bentonite activated using 3% sodium bicarbonate and mixed type bentonite activated using 2% sodium bicarbonate. Finally, the overall results proved that the compressive strength, drop, and porosity values of pellets meet the specifications.

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