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Research article

The effect of machine parameters and the composition of additives in the pelletization process on the physical and mechanical properties of pellets in Se Chahoon Pelletization, Bafgh

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Abstract

Pelletization is a technique in which fine particles of iron ore concentrate are gradually mixed with lime and an adhesive (bentonite or fondue cement). These products are called raw pellets. These pellets must have standard metallurgical properties. Also, to prevent crushing during transportation, it must have sufficient physical and mechanical properties. In this research, the parameters affecting the pelletizing process, including the speed and rotation angle of the balling disc, the moisture content, the type and combination of the adhesive used, and the optimal conditions for the production of pellets with the desired dimensional characteristics and mechanical properties were determined. Bentonite and a combination of bentonite and Cement Fondu were used as an adhesive. The falling number and fracture strength tests were carried out on raw and dried pellets. Based on the results of the conducted experiments, the best pelletizing efficiency was recorded for a rotation angle of 40 degrees relative to the horizon, a rotation speed of 30 rpm, and a pelletizing duration of 60 minutes in the balling disc. The optimal moisture level in the moisture testing was around 9%. The increased bentonite content in the pellet showed an increasing/decreasing trend for the strength and falling number, and the highest strength was recorded for 3-4% bentonite content. The maximum compressive strength of dry pellets increased about six times compared to wet pellets with 9% moisture content. Using a mixture of Cement Fondu and bentonite in the pellets increases the strength. Still, after baking at high temperatures, lower strength was obtained compared to that of the pellet containing bentonite. Also, according to the results, the positive effect of increased fracture strength at high temperatures for the pellets made with a combination of 2% bentonite and 2% Cement Fondu is far less than pellets made with 3% bentonite and 1% Cement Fondu, while the same pellet showed an opposite result at ambient temperature.

1. INTRODUCTION

Iron and steel industries are mainly the driving forces of development in any country, and this industry has a great influence on the country's economic status. The pelletizing process consists of three essential steps, namely raw material preparation, green pellet formation, and pellet strength. The Raw material preparation includes the grinding and mixing of pellet feed materials [1]. Iron ore pellets are widely used in downstream reduction processes, namely Blast Furnace, Direct Reduced Ironmaking (DRI), and Midrex, due to their incomparable advantages for maintaining uniform size, excellent metallurgical performance, and high physical strength [2]. The pellet production quality is mainly influenced by the chemical, physical, thermal, and mineralogical properties of the pellet feed materials. The feed material consists of iron ore with additives such as anthracite coal/coke breeze, fluxes, and a suitable binder [3]. The addition of a binder, either organic or inorganic, provides adhesion to feed particles and increases the pellet strength. Sometimes, the increase in the binder's dosage may affect the green pellet growth rate by producing smaller pellets [4]. The study of the physical and mechanical characteristics of the pellets is important because the pellets must be strong and resistant enough to withstand physical pressures and crushing during transportation [5]. Additives affect the properties of pellets. Depending on the materials used in pelletizing, these properties may change [6]. Bentonite causes a severe decrease in total iron grades (TFe) of pellets, requiring effective organic binders urgently to reduce its dosage in pelletizing [7]. Many investigations have been carried out to study the binding mechanism and the effect of adhesive material on the physical properties of iron pellets, among which we may refer to the studies by Kawatra et al. [8], Sivrikaya et al. [9, 10], and Forsmo et al. [11] which are mostly focused on the effect of bentonite and other adhesives on the physical properties of pellets. In addition, in the same context, one may refer to the study by Mr. Fallahi et al. [12], which was carried out in 2018.

Bentonite is commonly used as a binder in iron ore pelletizing. Its primary phase is montmorillonite, characterized by a layered crystal structure capable of absorbing a lot of water. Consequently, bentonite exhibits favorable water absorption and high thixotropy [13,14]. However, an increase of 1% of weight in the $SiO2$ and $Al2O3$ content of bentonite can decrease the TFe grade of the pellet by 0.4%-0.6% of weight. Thus, substituting bentonite with binders that are more compatible with pellets presents an urgent challenge in both industrial and scientific contexts [15,16]. The processes applied to the pellets used in the blast furnace and direct regeneration methods may cause them to crumble and disintegrate. As a result, it is important to investigate the mechanical and physical characteristics of pellets and their regenerability. Thus, it is necessary to carry out several tests under standard conditions to determine the pellet characteristics [17]. The disc angle of the balling disc and its rotational speed, moisture level, and furnace temperature are among the parameters that affect the mechanical and physical characteristics of the produced pellets [18]. Considering that pelletizing projects are being developed in Iran, it is necessary to achieve optimal efficiency in the pelletizing process to use the pellets characterized by desirable physical and mechanical features in the production process. Achieving such properties has been investigated by adjusting the pelletizing conditions in the balling disc machine and by using two adhesive materials, i.e., bentonite and Cement Fondu. The mechanical characteristics of these pellets have been investigated by using the standard mechanical characteristics tests and reported. The laboratory samples used in this research were prepared from Se Chahoon Pelletization. Therefore, the research results can be used in other industrial projects.

2. RESEARCH MATERIALS AND METHODS

2.1. Specifications Of Raw Materials And Concentrates Used

In this research iron concentrate prepared from the Choghart mine was used as the main material for making pellets. The chemical analysis of this concentrate is presented in Table 1.

Table 1. Chemical analysis of iron concentrate

Composition	Fe	FeO	SiO2	Other elements
Weight percentage	66.58	23	3.34	7.08

Using laboratory sieves, sieving analysis has been carried out to determine the grain size distribution of the concentrate according to the ASTM standard. Bentonite and Cement Fondu adhesives were used to bind concentrate particles and form pellets. This product is purchased from Iran Refractory Cements Company (IRC Co.) which has been producing calcium aluminate cement since 1997 starting with producing IRC40 cement .Chemical analysis of bentonite and Cement Fondu adhesives are shown in Tables 2 and 3, respectively. Furthermore, the size distribution of bentonite and Cement Fondu particles is presented in Table 4 via the sieving analysis method.

Table 2. Chemical analysis of bentonite

Composition	P_2O_3	LOI	MnO	S
Weight percentage	0.22	12.52	0.31	0.38
Composition	CaO	K_2O	Na_2O	TiO_2
Weight percentage	1.32	0.30	2.95	0.51
Composition	MgO	Fe_2O_3	Al_2O_3	SiO_2
Weight percentage	2.98	3.53	11.96	63.20

Table 3. Chemical analysis of Cement Fondu

Composition	Weight percentage
CaO	37-39
TiO_2	<4
MgO	<1
Fe_2O_3	15-18
Al_2O_3	37-40
SiO_2	4-5

Table 4. Sieving analysis for bentonite and Cement Fondu

Additives	Grain size (μm)	Weight percentage
Bentonite	-50+20	12.6
	-100+50	74.5
	+100	12.9
Cement Fondu	-50+20	23.1
	-100+50	65.8
	+100	11.1

2.2. Preliminary Tests

Pellets were produced in a laboratory-scale balling disc machine (featuring a disc diameter of 50 cm and the height of the band around the disc of 10 cm), with the possibility of changing the speed and rotation angle (Fig. 2). To determine the optimal rotation speed, angle, and duration of the device, first 120 grams of the concentrate was mixed with 5 grams of bentonite. Then, some water was sprayed at certain intervals to form the pellets. To determine the optimal rotation speed and angle, the primary rotation time was considered to be 30 minutes. After completing the experiment, the pellets bigger than 5 mm were collected, and the weight of the pellets was measured in wet and dry states. The initial test conditions to determine the optimal conditions of the pelletizing device are shown in Table 5.

Based on the results obtained in different scenarios, the efficiency of the device was calculated using Eq. (1), and the optimal conditions for the rotation angle and speed were determined [19].

$$p_p = \frac{w_1}{w_2} \times 100 \qquad (1)$$

where Pp stands for the efficiency percentage of the balling disc device, W1 is the weight of dry pellets in grams, and W2 represents the weight of the material fed to the pelletizing device in grams.

Fig. 1. The laboratory-scale balling disc device.

After determining the optimal conditions for the balling device, the pellets were made in suitable conditions using two types of adhesives, bentonite and its mixture with Cement Fondu with different percentages and fixed and certain moisture contents. The pellets were dried in a dryer (oven) for 24 hours at 105°C. Eq. (2) was used to calculate the pellet moisture in percentage.

$$\text{The moisture content} = 100 \times \frac{m_2 - m_1}{m_2} \qquad (2)$$

Where:

m_1: weight of dry pellets and m_2: weight of wet pellets

Table 5. Test conditions used to determine the optimal speed and rotation angle of the device

The angle of rotation of the plate relative to the horizon (°)	Rotational speeds (rpm)
30, 40, 45	15, 20, 25, 30, 35, 40, 45

2.3. Conducted Tests

2.3.1. The falling number:

To perform this test, 30 pellets of the same size and composition are selected, and each is dropped from a distance of 46 cm so that the pellets fall on a thick steel plate. The number of times a pellet can withstand cracking or damage is regarded as the drop number of the pellet [20]. The obtained results are presented in the next section, and the dispersion and error of the results are given according to the minimum and maximum values of the mean in all reports.

2.3.2. Failure test:

The strength of the pellets made in three states, i.e., raw, dry, and after regeneration, was determined using a Cold Crushing Strength (CCS) device according to the associated standard. This means that the average breaking strength of 30 pellets was regarded as the final strength of the pellets [21].

2.3.3. Fracture strength in baked pellets:

To perform this test, a number of pellets of the same size and composition were placed in a furnace (temperature of 1100 Celsius degrees) for 20 minutes. Then, the removed pellets were placed at ambient temperature to determine the average fracture strength of pellets with different adhesive content percentages at high temperatures. Thus, the average fracture strength of healthy pellets was regarded as the pellet strength at high temperatures [22].

3. RESULTS AND DISCUSSION:

3.1. The effect of the speed, angle, and duration of disk rotation on the efficiency of the device

This research investigated the effect of disk rotation speed (within the range of 15-45 revolutions per minute) and changing the angle (30,40,45 degrees) to the horizon on the efficiency of the pelletizing machine to determine the optimal working conditions of the same machine (Table 5).

Figs. 2 and 3 show the results of this investigation as well as the effect of pelletizing duration on efficiency by keeping other variables constant. It can be seen that the best results were obtained at a rotation speed of 30 rpm and an angle of 40 degrees to the horizon, where the efficiency of the device exceeds 85%, and the size of the resulting pellets is within the 5-25 mm range.

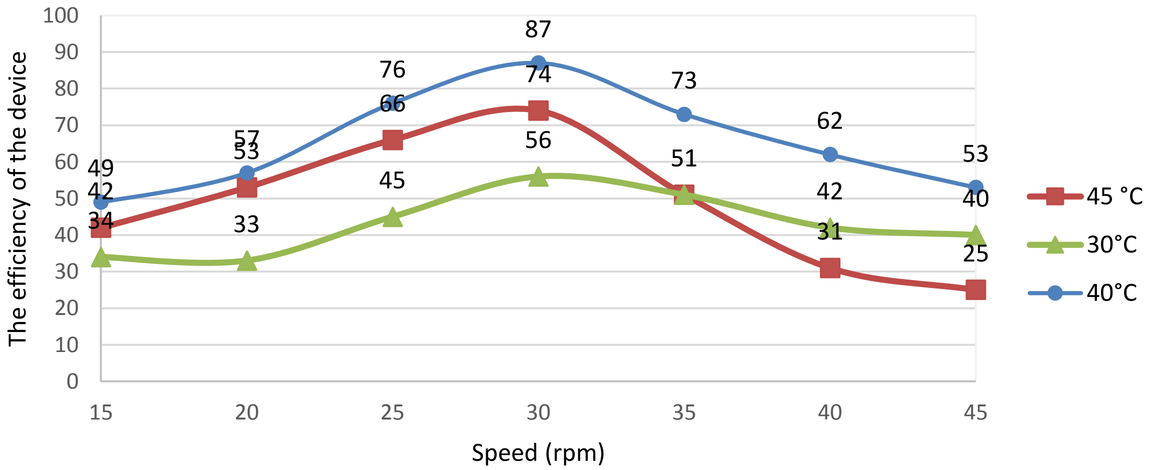

Fig. 2. The efficiency of the device at different speeds with the disc at angles of 45, 40, and 30 degrees to the horizon.

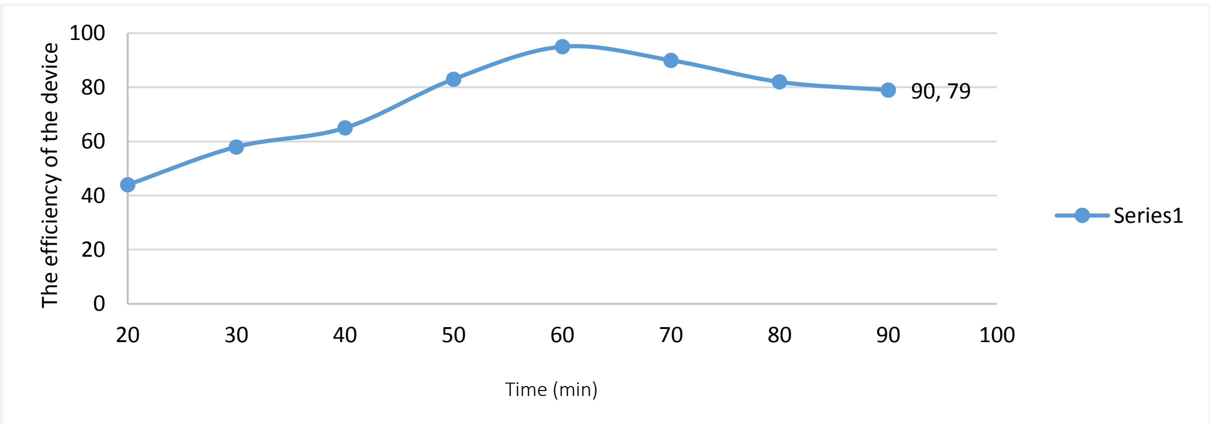

Fig. 3. Efficiency of the device versus time while keeping other variables constant.

After determining the best angle for the disk, the efficiency test was performed for the device at different times. The results showed that the efficiency of the device increases with increasing time up to 60 minutes and then decreases. The best pelletizing time is 60 minutes. During shorter times, although pellets usually begin to grow in size, there is not enough opportunity and time for their growth to reach the desired dimensions. It seems that during times longer than 60 minutes, the water inside the pellets will partially escape, and the resulting pellets will fail.

To determine the optimal duration, according to the conditions listed in Table 6, the optimal time was determined for producing pellets at the optimal rotation speed and angle.

Table 6. Test conditions to determine the appropriate duration for the pellets at the optimal rotation angle and speed.

Pelletization duration	The angle of rotation of the plate to the horizon (degrees)	Rotation speed (rpm)
20, 30, 40, 50, 60, 70, 80, 90	40	30

3.2. The Effect Of Moisture On The Physical Characteristics Of Pellets

The moisture content is one of the important factors in the production and growth of pellets. First, a thin layer of water is formed on the surface of the particles, which causes the particles to stick to each other, resulting in the formation and growth of pellets. By spraying water on the surface of the concentrated particles, the surface of the particles is moistened, and a layer of water is formed on their surface. Due to the surface tension of water, after wet particles come into contact with each other, some liquid bridges are formed between them, and the particles are connected. The first particles are formed due to the combined effect of the movement of the pelletizing machine and the added moisture. Adding moisture after this stage increases the density of pellets. If the water of a typical pellet is less than a certain limit, an incomplete water film will be formed on the surface of the particles, which will not be sufficient to bond the particles together. As a result, germination and growth will not progress completely and correctly, and given the non-uniform distribution of moisture, the pellet will perform poorly in terms of its properties. If the moisture percentage and the charge exceed the optimal amount, then the charged particles will not have the necessary binding force between them, and, although the dimensions of the pellets will grow, due to the increased plasticity, the pellets will easily change shape. The formation of sprouts will have a suitable speed only at a critical moisture level. Thus, it is necessary to optimize the amount of the consumed water [23].

The exact amount of water content for pellet production is an empirical parameter that is determined by testing. The results of pellet moisture optimization are presented in Fig. 4 and Fig. 5. As is clearly shown in Fig. 4, with the increase in the moisture content of the pellets, the efficiency of the device may increase/decrease. For pellets with a higher amount of consumed water, since the pellet is not completely formed or due to its high deformability, and the formed pellet turns into a muddy lump, the efficiency of the device declines. In lower moisture contents, the initial pellets start to germinate; however, to continue the process and make the pellets featuring the right dimensions, lower moisture causes the pellet not to form appropriately. The results of the falling number test for raw pellets with different moisture contents are shown in Fig. 5. Therefore, considering the efficiency of the device and also given the desired strength for the concentrate, the optimal amount of moisture for the pellets in this research is 9% by weight.

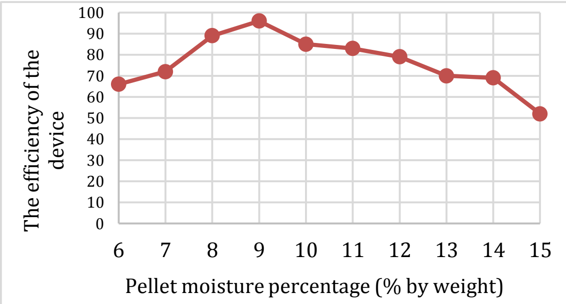

Fig. 4. The efficiency of the device versus different moisture contents.

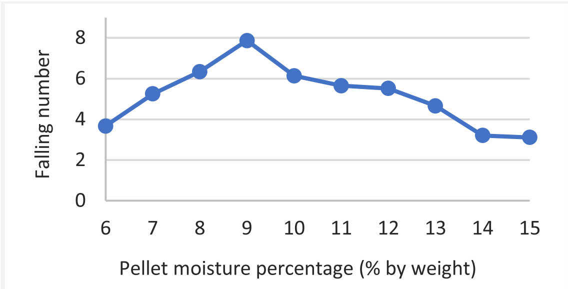

Fig. 5. The average falling number of pellets with different moisture percentages.

In the experiment conducted at this stage, the angle of the disc to the horizon is 40 degrees, the speed is 30 rpm, the pellet production time is 60 minutes, and the amount of bentonite is 2%. An average was calculated for a number of 10 pellets with different moisture contents.

3.3. The Effect Of Bentonite On The Physical Characteristics Of Pellets

It is evident that by increasing the adhesive material used in the pellet, the average falling number for the manufactured pellets shows an increasing/decreasing trend. Also, it can be seen that for 3 to 4 percent of bentonite content, the highest falling number is obtained for different percentages of moisture, the finding which is also confirmed in Fig. 5-b. The results of the falling number for dried pellets with 9% moisture by weight are shown in Fig. 6.

The results of fracture strength of raw and dry pellets are shown in Figs. 7 and 8, respectively, that the highest strength value of dry pellets occurs for 3% bentonite content, but for raw pellets, the highest fracture strength is related to a bentonite content of 3.5%. The reason for the increased strength in raw and dry pellets with the increase of this adhesive material is that the strength of the pellet depends on the distribution of bentonite particles and the shape of the created bed. By increasing the bentonite content in the pellets, the strength of the wet and dry pellets increases, and since the strength of a pellet against free fall and fracture strength depends on the strength of its bonds, the falling number and fracture strength increase. By absorbing water and moisture into its molecular structure, bentonite reduces the water required for the aggregation of particles, promoting the growth of sprouts and initial pellets. Many studies conducted on bentonite as an adhesive material have approved its effect in keeping particles together by forming hardened gels that form bridges between particles and increased van der Waals forces between particles. The increasing/decreasing trend observed for strength and falling number is due to the fact that by increasing the percentage of bentonite from an optimal value, adhesion increases due to the presence of excess bentonite, and the production of pellets becomes difficult. In fact, pellets with a large amount of bentonite are not produced homogeneously, and during pelletizing, micropellets, and primary sprouts join together and form pellets with irregular and uneven surfaces. The results of the strength of pellets made by using bentonite (contents of 1, 3, and 5%) at different temperatures are depicted in Fig. 9. The strength of the pellet increases as the temperature increases. The effect of increased bentonite content is more significant at high temperatures compared to low temperatures. During baking and regeneration to produce high-strength pellets, sodium, and calcium ions in bentonite act as lubricants, and by lowering the melting point of some minerals found in the pellet, they melt at a lower temperature and increase the strength of the pellets even in the preheating stage. This process reduces the failure and loss of pellets during their transportation in the final baking stage.

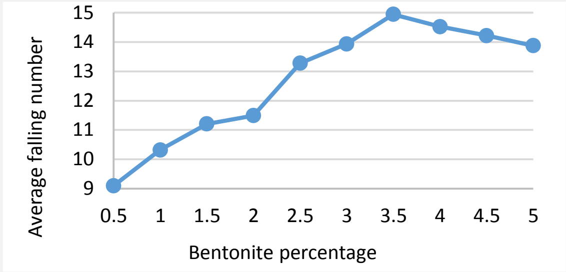

Fig. 6. The average pellet falling number for dry pellets with an initial moisture content of 9%

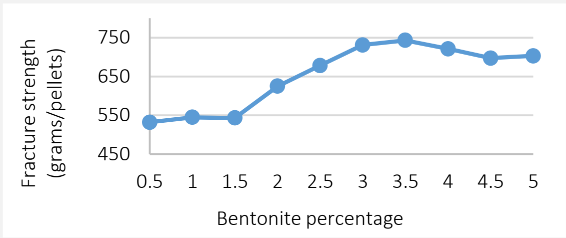

Fig. 7. The average fracture strength for wet pellets with an initial moisture content of 9%

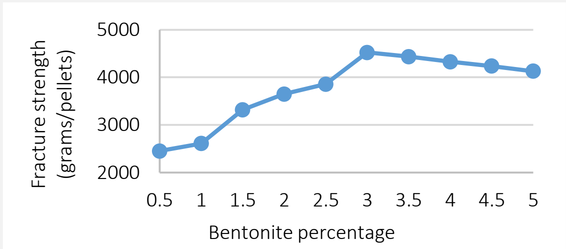

Fig. 8. The average fracture strength for dry pellets with an initial moisture content of 9%

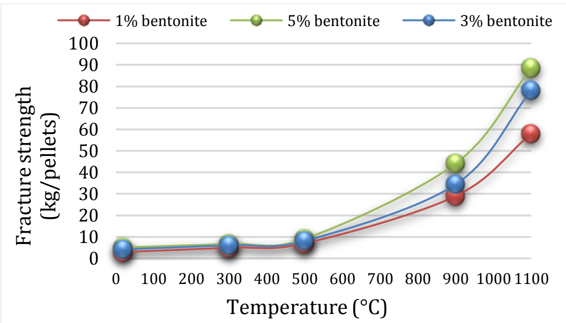

Fig. 9. Results of fracture strength of pellets with different percentages of bentonite at different temperatures.

3.4. The Effect Of Bentonite Mixture And Fondue On The Physical Characteristics Of Pellets

Figs. 10 and 11 show the results of the falling number test for pellets containing a mixture of bentonite and Cement Fondu for the wet and dry conditions, respectively. Adding bentonite to a certain percentage of Cement Fondu results in an increasing trend. According to the results of Figs. 10 and 11, it can be said that in the raw state, the strength is predominantly affected by the hydraulic bonds between the concentrate particles. Cement with concentrated particles forms a film of the same compounds, and adding water leads to the formation of hydrated crystals, and the particles are placed in the vicinity of one another in a completely resistant manner. Therefore, the addition of Cement Fondu with a certain percentage of bentonite with concentrated particles causes the formation of a thin layer of these compounds, and the addition of water leads to the formation of hydrated crystals which increase the strength. Then, as the samples dry, the hydraulic bond between the particles is replaced by a stronger chemical bond. For this reason, the strength and falling number in the dry state show a favorable and significant increase compared to those of the raw state [23].

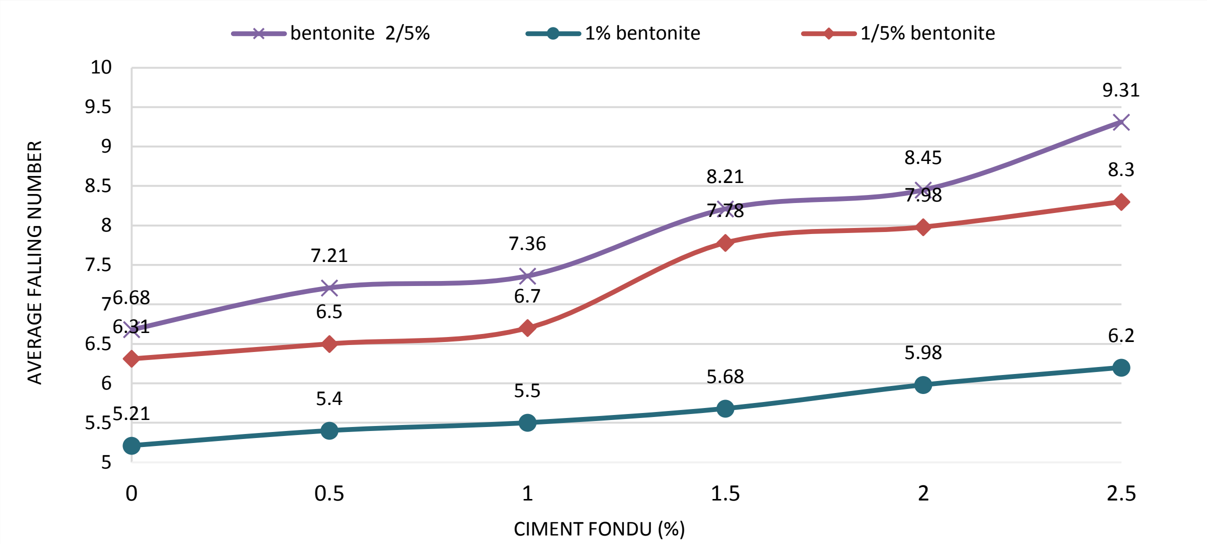

Fig. 10. The average falling number for the wet pellets with a mixture of Cement Fondu and bentonite with different percentages.

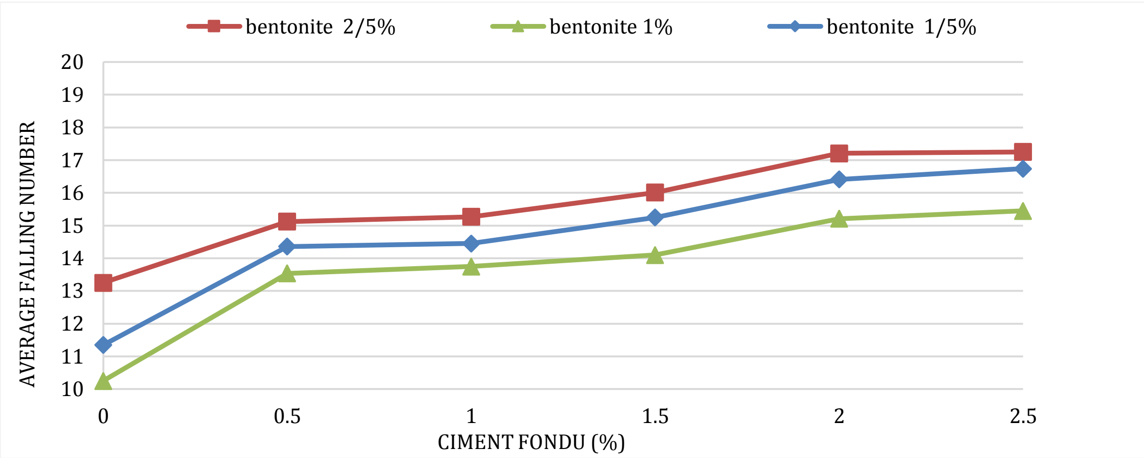

Fig. 11. The average fall number for dried pellets with a mixture of Cement Fondu and bentonite with different percentages.

Figs. 12 and 13 show the fracture strength results for wet and dry pellets created using a mixture of bentonite and Cement Fondu, respectively. Also, Fig. 14 presents the results of pellet fracture strength with different percentages of bentonite and Cement Fondu at different temperatures. According to the obtained results, it is clear that at high temperatures, the pellets with higher cement content have lower strength than the pellets with more bentonite content. In addition, the positive effect of increased fracture strength at high temperatures for the pellets made by combining 2% bentonite and 2% Fondu is far less than the pellet made by 3% bentonite and 1% Fondu. However, the same pellet shows the opposite result at ambient temperature, and the increased content of Cement Fondu in the pellet increases the fracture strength of the pellet. For example, for pellets made using 1% bentonite, the pellets with a higher percentage of cement have higher fracture strength at lower temperatures. However, as the temperature increases, increasing the cement content has a negative effect, and bentonite serves as the factor leading to increased strength.

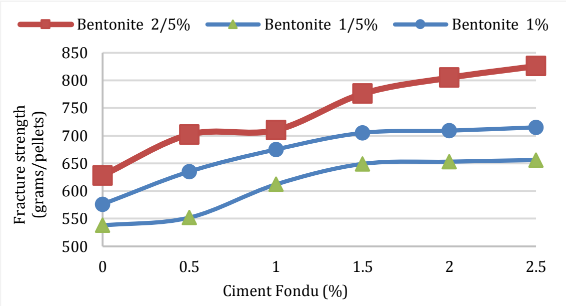

Fig. 12. Fracture strength for the wet pellets with a mixture of Cement Fondu and Bentonite with different percentages.

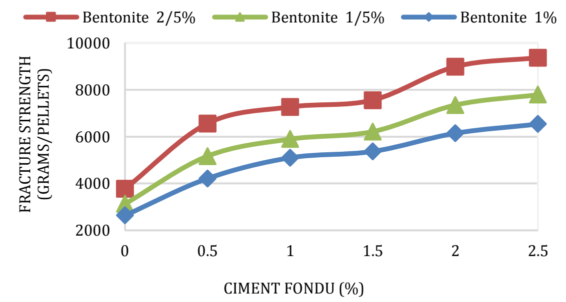

Fig. 13. Fracture strength for the dry pellets with a mixture of Cement Fondu and Bentonite with different percentages.

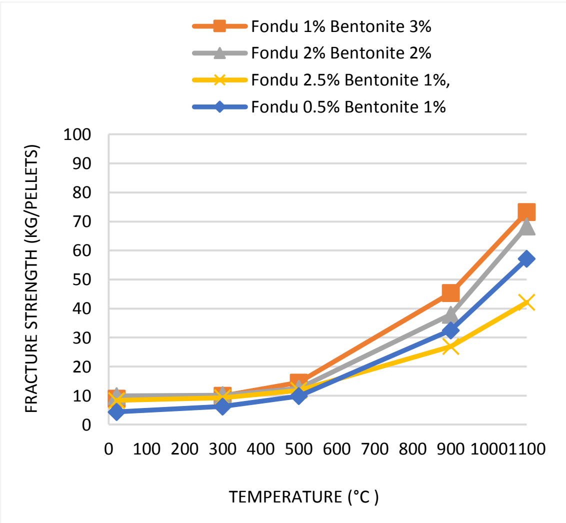

Fig. 14. Fracture results for pellets with different percentages of Fondu and bentonite at different temperatures.

4. CONCLUSIONS

The present study investigated the production of pellets from the iron concentrate procured from the Se Chahoon mine in Bafgh using a laboratory balling disc machine. While determining the working conditions of the device to achieve maximum efficiency, the effect of added moisture and also the use of bentonite and bentonite-cement Fondu mixture as an adhesive on the strength of pellets at ambient temperature and high temperature were investigated according to standard tests. According to the results:

a) In the laboratory balling disc machine used with a disc diameter of 50 cm and a strip height of 10 cm, a rotation angle of 40 degrees to the horizon, a rotation speed of 30 revolutions per minute, and a pelleting time of 60 minutes led to the best pelleting efficiency.

b) The optimal moisture content for pelletizing (1-5% bentonite content) was found to be around 9% according to the falling number index.

c) Increasing the bentonite consumed in pellets within the 1-5% range showed an increasing/decreasing trend for the falling number and strength in such a way that for a bentonite content of 3-4%, the highest falling number and strength were obtained for raw and dry pellets. Bentonite showed an increasing trend in strength at high temperatures.

d) The use of bentonite for pelletizing is suitable to increase the strength, but it adversely affects the next processing stages. The use of Cement Fondu as a consumable adhesive along with bentonite in pelletizing showed an increasing trend for the strength at ambient temperature and the falling number of raw and dry pellets. At high temperatures, adding Cement Fondu to bentonite reduces the fracture strength of the pellet compared to the state of pure bentonite due to the phase change in cement binding reaction products.

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