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Factors Affecting Ballability of Mixture Iron Ore Concentrates and Iron Oxide Bearing Wastes in Metallurgical Processing

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ABSTRACT

Iron oxide bearing wastes (IOBS) are produced at every part of processing stage of sinter, molten iron and steel production. They are hard to handle and in many cases are stockpiled only to be a source of environmental pollution. However, they can be balled into pellets. Pellets characterized by good ballability values are transportable and recyclable as they can withstand stress without disintegrating back to dust. Yet, ballability is affected by certain factors like the grain sizes of the materials, the moisture and binder contents of the ball mix, wettability of the balled materials and the processing perimeters of the granulator. The objective of this research work is to investigate the factors affecting ballability of mixture of iron ore concentrates and iron oxide bearing wastes in metallurgical processing. The parameters under consideration were: grain size of materials, the moisture contents, speed of balling disc, IOBS and bentonite (binder) contents of the balled mix. The investigation was carried out by balling different volume fractions of mix containing iron oxide concentrate and IOBS using a balling disc and testing the resulting balls for green compressive strength using an universal testing machine. It was found that the ballability of the mixture of iron ore concentrate and IOBS increases as grain sizes of the materials reduce but increases as the moisture contents and IOBS content increase up to an optimum value of moisture content in the mix before it starts to reduce. The ballability also increases along with the speed of the granulator (balling disc) within the limit of this work. An increase in ballability with a slight raise in bentonite content in the mix was observed as well.

Keywords: ballabilty, bearing wastes, iron ore concentrates

INTRODUCTION

The processes of crude steel production, either in integrated steel plant or mini-plant, generate large volumes of by-products and wastes. Hitherto, most of these wastes were dumped or stockpiled, causing environmental hazard while few were recycled back into the production stream. Some of the stock-piled wastes are iron oxide bearing wastes (IOBS), in the form of dusts and sludge. They are most difficult to recycle because of their chemistry, granulametry and/or excessive moisture content [Afolalu et al. 2017]. The presence of fine particles of dust, causes dust explosion and also obstructs the permeability of air in the blast furnace and sintering machine, making it difficult to recycle them with conventional methods. On the other hand, these waste products contain high percentage of compounds, which are characterized by chemical compositions valuable to iron and steel production, such as, iron (Fe), iron oxide (FeO), carbon and slagging oxides in good quantity, similar to what is obtained in iron ore concentrates [Afolalu et al., 2015] (Table 1).

In order to solve the problem of granulametry, fine grained materials can have their grains bound into sizeable granules by an appropriate process of agglomeration [Abioye et al. 2017]. This process has been successfully applied in various fields, such as, in agriculture, pharmaceutics, metallurgy, etc., [Satry et al. 2008, Harun 2001]. The major types of agglomeration processes include: briquetting, nodulizing, sintering and pelletisation. Direct sintering of IOBS dust and sludge is not profitable because of the granulametry of these materials [Adetunji et al. 2016]. The fine grains will clog the bed of the sintering machine, thereby leading to low sinter production and this also may cause damage to the sintering machine [Ajayi et al. 2018]. Very high quantity of binder will be required if the fine grains present in IOBS dust are to be agglomerated by briquetting [Borowski and Kuczmaszewski 2005]. Pelletizing stands as the best method of agglomerating these fines [Esezobor et al. 2008]. Pelletisation consists in two major processes: i) balling and ii) induration. Balling is the process of forming nearly spherical balls by tumbling moist particulate (with or without binders) in such devices as drums, discs or cones. The balls formed this process should possess good drop and compressive strength values to be used for the purpose of recycling [Adetunji et al., 2015]. The ability of moist particulate material to form balls of high compressive strength is known as its ballability. Therefore, the ballability of materials can be evaluated based on the green compressive strength of balls formed from such materials [Dirisu et al., 2017]. The balls with high green compressive strength are said to have high ballability. The ballability of iron oxide concentrates is affected by factors like particles (grain) sizes, quantity of binder, moisture content in the mix and wettability of the materials as well as the processing parameters of the granulator [Harun 2001, Topiary and Topiary 2007, Satry et al. 2008].

This work examines the effect of some of the above-mentioned factors on the ballability of IOBS. The examined factors include: (i) grain sizes, (ii) moisture content, (iii) binder, (iv) content of iron oxide wastes in the mix, and (v) speed of the balling disc or granulator. A detailed study of the ballability of IOBS and various factors that affect it will enhance balling of these hard-to-handle materials and their subsequent recycling for an effective use in the metallurgical industry.

Table 1. Output and chemical composition of wastes [Esezobor et al. 2008]

Type of Waste	Composition, weight %										
	Kg/T	%	Fe	CaO	MgO	MnO	SiO_2	Al_2O_3	S	C	CO_2
A. Sinter plant											
1. Sludges, which include:											
- washing	71.0	7.68	50.7	10.0	0.6	1.5	8.6	0.1	0.1	2.6	6.2
- wet gas deduster	14.0	1.51	50.6	9.9	1.0	1.1	8.5	0.1	0.4	0.1	4.0
Total	**85.0**	**9.18**	**50.7**	**10.0**	**0.7**	**1.4**	**8.6**	**0.2**	**0.15**	**2.3**	**5.8**
2. Dust, inclusive											
(a) collector & particulate	170	18.38	50.8	9.8	1.0	1.0	7.9	1.50	0.08	0.5	4.0
(b) from control pollution control system	100	10.81	50.0	9.7	0.2	0.8	9.6	1.50	0.08	1.8	4.0
(c) cyclone	59.0	6.38	50.8	9.8	1.0	1.0	7.9	1.50	0.08	0.5	4.0
Total	**329**	**35.57**	**50.56**	**9.8**	**1.06**	**0.9**	**8.4**	**1.5**	**0.08**	**0.65**	**4.0**
3. Blast furnace, workshop sludges, which include:											
(a) under (bunker breeze	49.0	5.30	50.8	10.0	2.0	1.0	8.0	1.0	0.01	1.5	4.5
(b) semi-fine purification	28.0	3.03	47.0	7.5	1.4	0.3	8.6	1.6	0.2	11.0	12.5
(c) fine purification	13.0	1.40	50.2	7.0	1.2	0.2	8.4	1.5	0.1	6.0	8.0
(d) furnace top tap	8.0	0.86	46.1	8.10	0.5	0.4	9.1	1.1	0.4	11.6	16.5
(e) casting machines	5.0	0.50	0.6	27.4	4.9	0.6	9.4	22.0	0.6	14.2	22.4
Total	**103.0**	**11.13**	**47.3**	**9.6**	**8.76**	**0.6**	**8.4**	**2.2**	**0.43**	**6.0**	**3.0**
4. Dust, inclusive											
(a) flue dust	41.0	4.43	46.1	8.1	0.5	0.4	9.1	1.1	0.4	11.6	14.0
(b) casting house dust	2.0	0.22	35.0	3.5	2.5	1.2	5.2	1.2	0.5	30.0	34.0
Total	**43.0**	**4.65**	**45.6**	**7.9**	**0.6**	**0.4**	**8.9**	**1.1**	**0.4**	**12.5**	**14.9**
(c) Total sludge	188	40.2	48.8	9.8	1.3	1.0	8.5	1.3	0.14	4.3	7.6
(d) Total dust	372	20.32	50.0	9.6	1.2	0.8	8.5	1.4	0.1	2.0	5.3
(e) mixture of dust & sludge	560	60.54	49.6	9.7	1.1	0.9	8.5	1.4	0.1	2.7	6.0
5. Sinter return	365	39.46	52.8	12.2	1.8	1.3	9.4	0.8	0.05	0.071	0.30
Total waste	**925**	**100.0**	**50.9**	**10.7**	**1.4**	**1.1**	**8.9**	**1.2**	**0.03**	**1.7**	**3.7**

METHODOLOGY

The following materials were used for the work; (i) iron oxide concentrate from Itakpe Iron Co., Kogi State, Nigeria, (ii) Electric Arc Furnace (EAF) dust from Universal Steel Company, Ogba, Lagos, Nigeria, (iii) Pellet dust from Delta Steel Company, Aladja, Warri, Delta State, Nigeria and (iv) Lime and Bentonite sourced from the local market.

The chemical analysis of these materials was conducted using X-ray fluorescent (XRF), model XRF spectrophotometer Ex 310 from Jordan Valley AR Inc. Then, the materials were pulverized using a ball milling machine and sieved to the required grain sizes using a Dorr-Oliver apparatus with ten sizes, ranging from 63 μm to 1000 μm. This procedure was followed by mixing and vigorously stirring the iron oxide bearing wastes with iron oxide concentrates, lime, water and bentonite according to the factor that affects the investigated ballability. Various volume fractions of the materials were used in the carried out work, as shown in Table 2(a, b and c).

RESULTS AND DISCUSSION

The mixes used to investigate the effect of iron oxide bearing wastes were varied in terms of the percentage of moisture content, as shown in Table 3. After measuring out and mixing the materials, each of the volume fractions were taken through balling process using a Radicon balling disc of 40 cm diameter and 10 cm depth, inclined at 45°. The residence time for each balling operation was 5 minutes.

Wet compressive strength (ballability) test

Wet compressive strength tests were carried out on the newly formed green balls using a Universal Material Testing machine. This test is used to evaluate the ability of balls to retain their shape during handling, transportation, and in the furnaces. The first step in green compression strength test involved drying the balls under the atmospheric conditions for 12 hours. Then, the dried balls or green pellets were tested for green compressive strength using a Universal Material Testing machine. Twenty randomly sampled green pellets from each mix were tested for compression strength, and the average of their values was taken as the wet or green compression strength of the pellets made from such mix. A good pellet should possess the green compression strength of ≥ 9N/pellet.

The ballability test was conducted for each factor that affects the ballability and the results for each test were recorded separately. Table 4 shows the results pertaining to the chemical analysis of iron ore concentrate and IOBS, while Table 5

Table 2. Volume fraction for effect of moistrue content investigation (a), grain size investigation (b), bentonite investigation (c)

Moistrue content investigation					
Moisture content (%)	6	9	10	10.5	11
Iron oxide bearing wastes (%)	20	20	20	20	20
Iron ore concentrate (%)	70	67	66	65.5	65
Lime (%)	4	4	4	4	4
Grain size investigation					
Grain size (mm)	> 0.71	0.71 – 0.250	0.250 – 0.125	0.125 – 0.063	<0.063
Moisture content (%)	10	10	10	10	10
Iron oxide bearing wastes(%)	20	20	20	20	20
Iron ore concentrate (%)	66	66	66	66	66
Lime (%)	4	4	4	4	4
Bentonite investigation					
Bentonite content (%)	0.4	0.8	1.2	1.6	
Moisture content (%)	10	10	10	10	
Iron oxide bearing wastes(%)	20	20	20	20	
Iron ore concentrate (%)	65.6	65.2	64.8	64.4	
Lime (%)	4	4	4	4	

Table 3. Percentage by weight of various mixes for balling

Moisture content (wt %)	Concentrate (wt %)					
	Mix					
	A1	A2	A3	B1	B2	C
6	89.5	80	70	-	-	-
8	87.5	78	68	-	-	-
9	86.5	77	67	47	27	87
10	85.5	76	66	46	26	-
11	84.5	75	65	45	25	85
12	-	-	-	44	24	-
13	-	-	-	-	-	83
14	-	-	-	42	22	-
15	-	-	-	-	-	81
16	-	-	-	-	-	80

A1 – control Experiment with 4% lime and 5% bentonite, B1 – mix with 40% dust and 4% lime.
A2 – mix with 10% dust and 4% lime, B2 – mix with 60% dust and 4% lime.
A3 – mix with 20% dust and 4% lime, C – mix with 4% lime and dust.

Table 4. Chemical analysis of the iron ore concentrate and iron oxide bearing wastes
*FeO = 1.0, SO_3 = 0.01

S/N	Compound	Composition, wt %														
		Fe_T	Fe_20_3	L.O.I	Al_20_3	$Si0_2$	MgO	CaO	S	TiO_2	Na_2O	K_2O	P_2O_5	ZnO	MnO	C
1*	Itakpe Iron ore concentrate *	63.0	88.9	0.26	0.6	8.6	0.02	0.15	0.02	0.30	0.11	0.01	0.06	ND	ND	-
2	Universal steel eaf dust	35.73	51.09	7.08	0.02	3.2	0.25	1.28	0.39	0.31	0.39	0.94	0.10	29.50	2.17	2.6
4	Delta steel pellet dust	59.90	85.64	6.43	1.30	7.03	0.25	4.17	-	0.27	0.27	0.03	ND	ND	0.14	2.5
5	Burden (mix)	54.29	78.6	3.51	0.63	6.86	0.13	1.49	0.11	0.29	0.22	0.25	0.03	7.38	0.58	1.30
6	Iron oxide bearing wastes	47.3	68.3		0.66	5.1	6.76	0.25	2.73	0.39	.29	0.49	0.10	15.0	1.16	2.6

Table 5. Sieve analysis of iron concentrate and iron oxide bearing wastes

No.	Materials	Sieve size, µm									
		+1000	+710 -1000	+500 -710	+355 -500	+250 -355	+180 -250	+125 -180	+90 -125	+63 -90	-63
1	Itakpe iron ore concentrate	14.23	4.44	10.8	20.99	36.63	6.46	3.23	1.82	0.71	0.20
2	Universal steel eaf dust	10.30	10.30	12.16	10.98	10.64	16.89	18.24	8.45	1.86	0.17
3	Delta steel pellet dust	0.10	0.70	0.30	0.40	0.40	1.31	15.11	57.20	19.90	4.53
4	Lime	-	2.05	16.68	49.64	6.55	17.09	2.66	3.89	0.92	0.51
5	Ground concentate	-	-	-	0.31	0.61	4.18	14.29	45.71	26.43	8.47
6	Ground iron oxide bearing wastes	-	0.10	0.20	0.61	2.04	4.18	8.36	39.65	31.81	13.05

presents the results of sieve analysis carried on pulverized iron ore concentrate, IOBS and lime

Effect of grain size

Figure 1 shows the effect of grain size on ballability. The results indicate that the ballability of materials having IOBS is inversely proportional to the grain size of the mix components. That is, the greater the materials particle sizes, the lesser the ballability measured in terms of green or wet compression strength. This can be attributed to various factors.

As the size of the mix particles decreases, their Blaine specific surface area increases and as the Blaine specific surface area increases, the ballability is raised as well [Harun 2001, Kristensen and Schaefer 1987].

Additionally, pulverization of the mix materials in order to obtain decreased grain sizes leads to the transformation of the conventional cubic morphology of magnetite to plate and flakes morphology (Figures 2 and 3). This phenomenon also enhances the ballability [Deqing et al 2004]. Thus, pulverization could be recommended as a pre-treatment to materials to be balled, in order to enhance the ballability of materials. Furthermore, finer grained materials have the tendency of being better packed, and therefore are characterized by improved interlocking of particles than coarser and larger materials, for a given agitation force. Enhanced packing of the particles results in increment in compression strength or ballability because of better interlocking of particles.

Effect of moisture content

The results related to the effect of moisture content on the ballability of mix that contains IOBS is shown in Figure 4. The graph seems to fit well into the capillary theory put forth by Newitt and Conway-Jones [1958]. This theory is based on the saturation of pellets or balls with moisture.

At low liquid saturation of the pellet or ball, the particles of the ball are held together by liquid bridges known as pendular bonds. This stage is known as pendular stage and is characterized by very low green strength. This is the stage where the liquid and gaseous phases are clearly found in the pore structure.

At a higher liquid saturation level of the ball, funicular stage is reached. At this stage, the ball particles are held by both pendicular and capil-

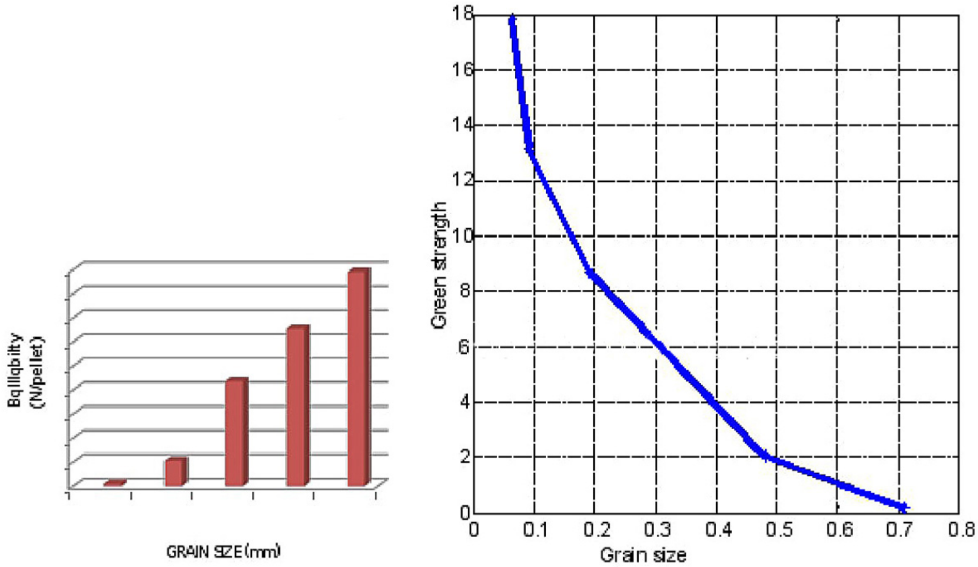

Figure 1. Effect of grain size on the ballability

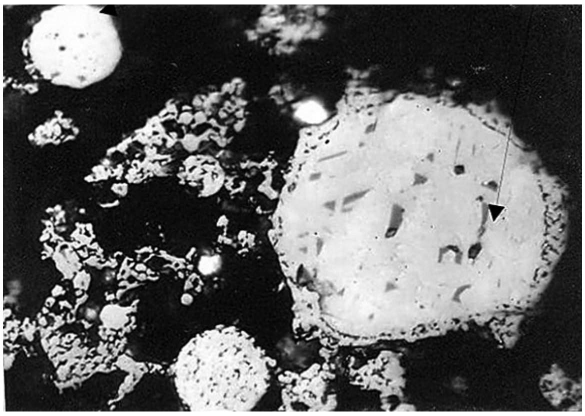

Figure 2. The morphology of unground iron oxide mix in pellet showing spherical morphology of magnetite (x200)

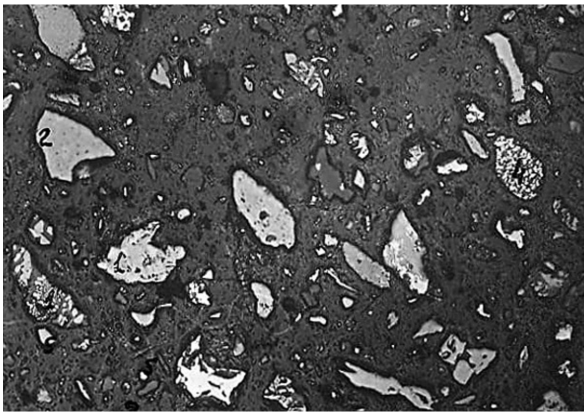

Figure 3. The morphology of ground iron oxide mix in pellet showing plate and flake morphology of the magnetite (x200)

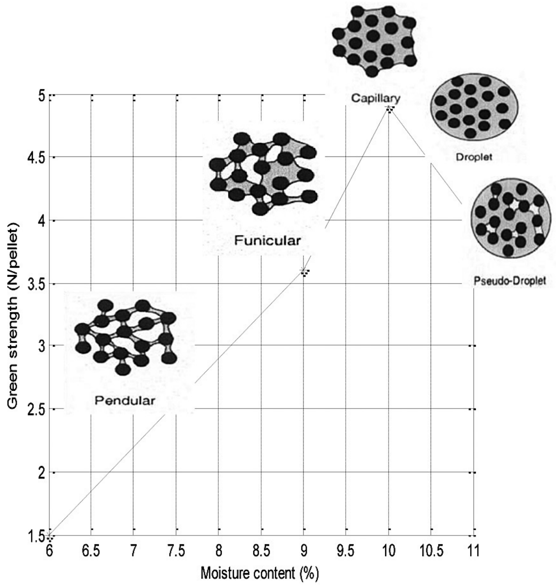

Figure 4. Effects of moisture content on ballability

lary forces. The presence of gaseous phase in the pore structure is lesser compared to the furnicular stage, making for greater green strength in the ball. However, the highest green strength is attained in the balls at the stage when all the capillaries in the ball are completely saturated with water and concave surfaces are formed in the opening of the capillary due to capillary forces tending to draw in the water on the ball's periphery. There is no gaseous phase at all in the pore structure. This stage is known as the capillary stage. The force that holds the pellet particles at this stage is known as capillary force.

There is yet another stage – known as the droplet stage – that is reached when the liquid saturation of the pellet is further increased. In this case, the pore structure is completely saturated with water and the surface of the capillary as well as the agglomerate is held together by the cohesive force of the liquid. This stage is characterized by lower green strength of the balls. The last stage, which has further reduced green strength of balls, is reached at a further increase of water saturation of the ball materials. It is known as the pseudo-droplet stage and is characterized by voids trapped in the liquid droplet. At this stage; the agglomerate deforms under its weight. This result indicates that with other factors kept constant, ballability will increase along with the percentage of moisture content up to a level, which is the capillary stage, and then begins to decline.

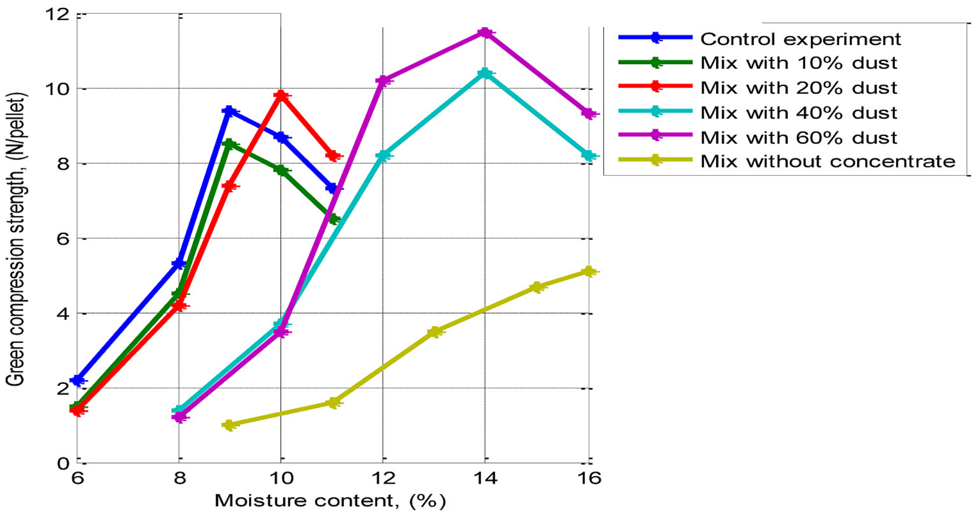

Figure 5. Effect of iron oxide bearing wastes content on ballability

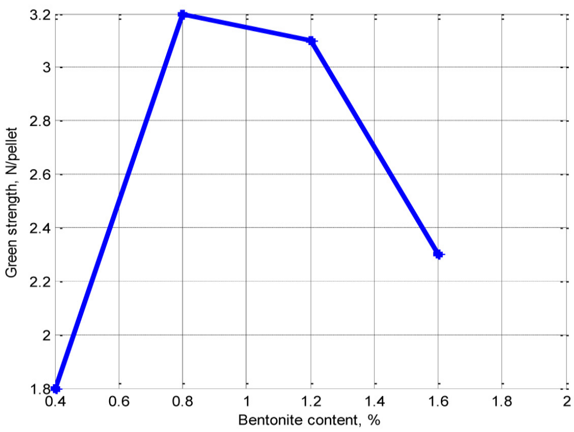

Figure 6. Effect of bentonite on ballability

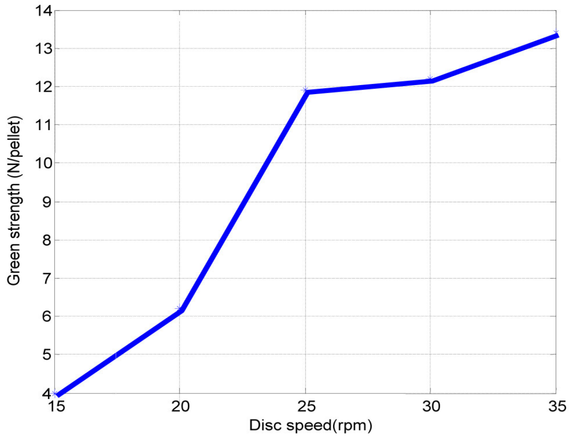

Figure 7. Effect of disc speed on ballability

Effect of iron oxide bearing wastes

The effect of percentage of IOBS on the ballability is shown in Figure 5. Here, the green strength or ballability of balls increases along with the percentage in IOBS. This trend can be attributed to the presence of slaked lime (CaO) in favourable percentage (1.25–2.25%) in the IOBS (Table 4). This forms calcium hydroxide [$Ca(OH)_2$] when reacted with water and acts as a good binder. However, for effective ballability and enhanced ball strength, the moisture content in the mix should be increased proportionally with the IOBS. The strength index of iron oxide pellet is directly proportional to the shrinkage that takes place in the pellet. This shrinkage increases as the quantity of CaO increases in the pellet [Ahmed et al. 2005].

Effect of bentonite

The green pellet compressive strength increases with the percentage of bentonite, up to 0.8% of bentonite. Further increase in bentonite results in a decrease of this property (Figure 6). This is because the high volume of the binder reduces the moisture receptability of the mix, thereby reducing the capillary force in the formed pellet.

This result implies that the quantity of bentonite required for production of pellets from mix with iron oxide bearing waste is minimal. Consequently, a greater quantity of iron would be produced per tonnage of pellets in the balls that contain IOBS than in that which contains only bentonite, because bentonite yields gangue when pellets are reduced to metallic iron. Therefore, the more bentonite in the pellet, the more gangue and less iron is produced. Additionally, the iron ore concentrate mixed with IOBS will require lesser quantity of binder for an effective balling than the mix that does not contain iron oxide bearing wastes.

Effect of balling disc speed

The ballability of pellets produced from mix with iron oxide bearing wastes increase along with the rotational speed of the balling disc within the limit of this work, as can be seen from the results presented in Figure 7. This is because the rotational speed, combined with angle of inclination of the balling disc, gives the tumbling force which brings the individual liquid wetted particle into proximity and compaction. The higher the balling disc rotational speed, the greater the tumbling force generated for better compaction. However, excessive speed of the disc will lead to breakage of balls due to impact.

CONCLUSION

From the foregoing research work, it can be concluded that a mixture of iron ore concentrate and iron oxide bearing wastes can be balled and iron oxide bearing wastes be a good material for iron and steel production when pelletized with iron oxide concentrate. It can also be concluded that the ballability of mix that contains IOBS increases along with the percentage of moisture content until the capillary stage (where optimum moisture content is reached). Ballability is also found to be proportional to IOBS content in a mix and the speed of the granulator (balling disc) but inversely proportional to the grain size. It was also observed that iron oxide bearing wastes has a good binding property.

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