Innovative Systems Design and Engineering
ISSN 2222-1727 (Paper) ISSN 2222-2871 (Online)
Vol.6, No.7, 2015

Design of Comminution Circuit for Optimum Performance of the Gravity Separation Unit at Itakpe Iron Ore Processing Plant, Nigeria

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Abstract
Designing an efficient and economic mineral processing plant begins with the choice of the best and most economic comminution circuit based on ore properties and concentrate end-user's specifications. This is because crushing and grinding for preparation of suitable feed for the downstream processes are cost intensive. The Itakpe iron ore processing plant presently produces a taiing material containing up to 22% iron minerals mostly fines produced inevitably during comminution. This article analyzed the existing circuit and ore properties, and presents specific comminution tests that were undertaken in order to recommend an alternate and more effective circuit. Sieve analyses of the various products of the existing circuit were carried out. The results show that fines exist in the circuit as a result of the brittleness of some portions of the ore which leads to crumbling and sloughing of the material during crushing and handling. It is revealed that mechanical stacking and reclamation also contributes to the generation of fines in the circuit. One possibility to a solution is to screen the product of secondary crusher ahead of grinding with a +2mm coarse screen between the reclaimer and the primary autogenous mills to prevent further production of fines during crushing unless the downstream recovery process is entirely designed for flotation. This option however still allows much fine material to the concentration lines. It is therefore recommended that materials less than 2mm be screened off the products of primary and secondary crushers and treated separately in gravity or magnetic unit without grinding. A +2mm screen is also recommended for installation as control for the product of primary autogenous mills which should be treated for concentration in the gravity unit. If flotation is to be employed, a regrind mill will be installed on either or both of the concentration lines or to a blend of the two.
Keywords: sloughing, crumbling, user's specifications, hardness, dropping impact, iron-rich, brittleness

1.0 Introduction

The iron ore deposit of Itakpe Hill is located in the northern part of Kogi state, Nigeria on latitude 7^0 36' 20" North and longitude 6^0 18' 35" East. (Onyemaobi, 1990a; Sofremines, 1978). The deposit which has an estimated reserve of about 182.5 million tones consists mainly of quartzite with magnetite and hematite situated in a series of migmatites and gneiss belonging to the basement complex of precambrian age (Sofremines, 1978).

The Itakpe Iron deposit is important for the successful development of iron and steel industry in Nigeria though on the national scale there are other silico-ferruginous formations which are of interest from commercial and economic viewpoint especially Ajabonoko Hill and Choko-Choko deposits (Figure 1). The Itakpe deposit has been developed to supply iron ore concentrates to the Ajaokuta Steel Plant and the Delta Steel plant, Aladja. The plant processing the ore presently produces tailing products having iron mineral content of between 20 and 22% (Ajaka, 2009) which is considered a significant loss of value. The iron minerals in the tailings are generally fine grained materials thought to have been produced partly in the process of comminution and partly as the natural fine content of the ore. The loss of value in the plant by the assessment of our researchers was mainly from the gravity unit. One of the objectives of the project from which this article is derived was to reduce the fine grained iron minerals in the comminution circuit with a view to improve iron mineral recovery by designing an alternate circuit that will eliminate the problem of loss of this fine iron minerals.

Although the geology of the deposit and information from NIOMCO plant suggest that the values are liberated at about 1.6mm; so this value (i.e. 1.6mm) is set as control for the comminution circuit in the plant. However, results from the bench scale comminution tests carried out in the course of this work show that recovery can be improved if the control size for comminution for the gravity unit is increased to about 2mm so that coarser particles are presented for gravity concentration which can be upgraded to a super concentrate by the flotation process or well controlled hindered settling regrinding.

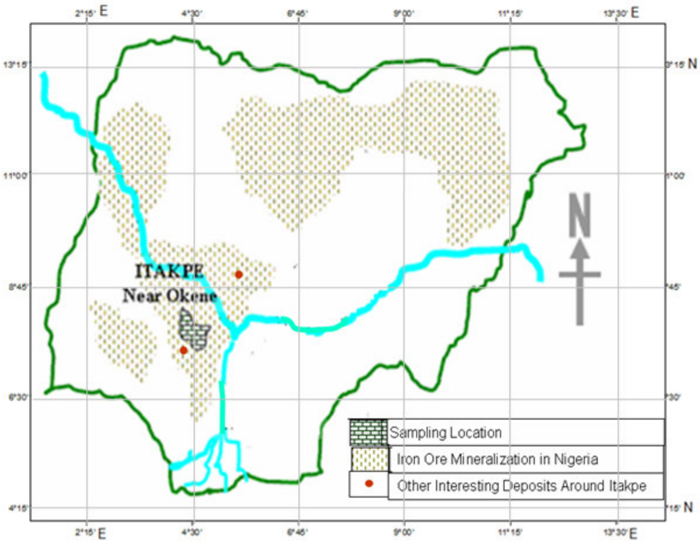

Figure 1: Map of Nigeria Showing Iron Mineral Formation in the Country and Itakpe Deposit (Onyemaobi, 2001)

The existing crushing circuit of the plant (shown in Figure 2) is equipped with a primary crusher of the gyratory type and a double toggle secondary jaw crusher. It is intended to produce a granulometry that represents a compromise between the necessity of blending the ore and the requirements of autogenous grinding. For this purpose, the granulometry of the run-of-mine (ROM) ore after primary crushing must be 98% less than 200mm, which means a closed side setting (CSS) of the crusher at about 150mm (Ajaka, 2010). The product of secondary crusher which forms stockpile in the blending yard has average size of 20mm. The blending yard composition is expected to be same with that of the repartition bins. A stacker and reclaimer are attached to the blending yard for homogenization.

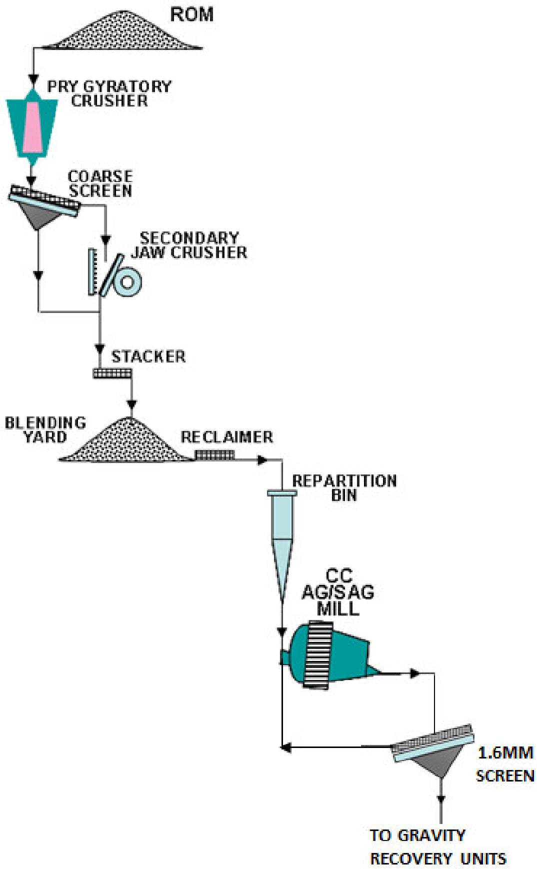

Figure 2: Existing Comminution Circuit of the Itakpe Iron Ore Processing Plant (Soframine, 1978)

The autogenous grinding is intended to produce materials of size not more than 1.6mm in size for production of concentrate as feed for the Ajaokuta steel plant blast furnace as contained in the original design of the plant (Ajaka, 2009). Thus, a screen of 1.6mm is set as control for product of the grinding unit. This control may have contributed to the production of fines during comminution which in turn contributes to loss of value in the plant. Ideally, all crushing products should be about 80% finer than the crusher's "set". However, in most cases, products of sizes far smaller than the set value are produced. Sometimes, large quantity of rock dust is produced also (Major, 2002; Callow and Moon, 2002). Dust or large quantity of below-set product is produced for some reasons. First, the progressive impact on materials as they slide down the crusher chamber results in further crushing of already crushed materials. Similarly, the relative movement of the crushing components of the machine and feed material results in attrition which tends to produce grinding effect rather than crushing. These are equipment performance factors whose adverse effects can only be corrected through equipment design or careful selection of equipment (Burt, 2002; Callow and Moon, 2002).

A second and very important factor in the production of "below set value products" is the degree of brittleness of the ore sample. This property is controlled by a number of other properties which are internal to the ore material (Will,2006; Maurice and Kenneth, 2003; Kelly and Spottistwood, 1982). Among properties that control this factor are texture, grain size, clay content, moisture content and others. Brittleness determines the breaking characteristics of the ore on impact and thus helps in selecting the crusher types that will be most efficient, the number of crushing stages and the overall crushing circuits.

Materials and Methods

Materials

The materials used in the course of this project included the flowsheet of the existing iron ore processing plant, iron ore samples taken from the west pit of the Itakpe iron ore mine, the products of the primary gyratory crusher, material from the blending yard, repartition bin and tailings dump. Various laboratory equipments ranging from crusher, ball mill, set of sieves with sieve shaker and SPSS 11.5 statistical analysis software were used for analysis of the results.

Methods

The flowsheet of the existing plant was analyzed with a view to identifying the sources and causes of excessive fine grains in the comminution circuits. Sieve analyses of the various samples (products of the secondary jaw crusher, blending yard, repartition bin and the waste) were carried out. It was not possible however to do a size distribution analysis of samples from the crusher, blending yard and repartition bin directly in the laboratory because a high percentage of these samples were large lumps of about 20mm and 150mm. So the large lumps were removed from the samples and the remaining analyzed for size distribution. The large quantity of material (2kg) used in the size analysis was chosen to ensure that the samples were fairly representative since we were dealing with large quantity of ore in stockpiles and bins. The actual behaviour of the ore under crushing impact was investigated through series of crushing and grinding tests. The crushing tests were carried out with a well sized feed of about 50mm and crusher setting (CSS) of 5mm. The grinding runs were in form of grindability tests carried out at 212microns to compare autogenous and media assisted grindability of the ore (Venkatathanan and Degaleesan, 1982). Details of the grindability tests are contained in another article but the effects are summarized in Tables 7 and 8. Three runs of each experimental test were made and the sieve size distribution analysis done with a measured quantity of the products. The results obtained were analyzed with the statistical tool to determine their actual trends. The mean values were thereafter plotted and their trend lines used to make some deductions about the behaviour of this ore during comminution.

Results and Discussion

Tables 1, 3 and 5 contain the size distribution of crushing tests results and those of samples from the blending stockpile and repartition bin respectively. The values generated from statistical analysis of these results shown in column 2 of Tables 2, 4 and 6 were used for the sieve analysis of the results. The trend lines of the cumulative percent weight retained are plotted as shown in Figures 6, 7 and 8 while the results of grindability tests summarized in Tables 7 and 8 are plotted in Figures 9 and 10.

Table 1: Results of Laboratory Crushing Tests

Nominal Aperture (µ)	**Tests**			**Aveg**
	1ST	**2ND**	**3RD**	
	Weight	**Weight**	**Weight**	
4750	325	297.2	312.3	311.5
2000	35	46.5	38.6	40.03
1700	10	34.8	36.3	27.03
1180	30	23.3	26	26.43
850	25	22.4	22.9	23.43
600	20	20.8	17.9	19.57
425	15	16.5	15.3	15.6
212	18	12.5	13.8	14.77
150	3.1	3.8	1.7	2.87
75	1.9	2.5	1.1	1.83
-75	0.47	0.72	0.23	0.47

Table 2: Sieve Size Analyzed of Crushing Test Results

Sieve Size (µ)	**Weight Retd**	**Cum. Weight Retd**	**Cum. Weight Passing**	**% Cum. Weight Retd**
4750	311.50	311.50	172.03	64.42
2000	40.03	351.53	132.00	72.70
1700	27.03	378.56	104.97	78.29
1180	26.43	404.99	78.54	83.75
850	23.43	428.42	55.11	88.60
600	19.57	447.99	35.54	92.65
425	15.60	463.59	19.94	95.88
212	14.77	478.36	5.17	98.93
150	2.87	481.23	2.30	99.52
75	1.83	483.06	0.47	99.90
Pan	0.47	483.53	0	100.00

Table 3: Size Distribution of Samples from the Blending yard

Nominal Aperture (µ)	**Tests**			Aveg
	1ST	**2ND**	**3RD**	
	Weight	**Weight**	**Weight**	
4750	1103	1017	1003	1041
2000	105	103	122	110
1700	154	171	166	491
1180	103	100	108	103.67
850	92	102	111	101.67
600	83	97	100	280
425	120	117	129	122
-425	**193**	**234**	**227**	218

Table 4: Sieve Size Analysis of Samples from the Blending Yard

Nominal Aperture (µ)	**Weight Retained**	**Cum. Weight Retained**	**% Cum. Weight Retained**
4750	1041	1041	53.28
2000	110	1151	58.91
1700	164	1315	67.30
1180	104	1419	72.62
850	102	1521	77.84
600	93	1614	82.60
425	122	1736	88.84
-425	218	1954	100.00

Table 5: Size Distribution of Samples from the Repartition Bin

Nominal Aperture (µ)	Tests			Aveg
	1ST	2ND	3RD	
	Weight	Weight	Weight	
4750	952	877	978	935.67
2000	191	177	161	176.33
1700	203	206	191	200
1180	132	167	131	143.33
850	87	132	96	105
600	90	87	93	90
425	123	113	123	119.67
	197	**193**	**200**	196.67

Table 6: Sieve Size Analysis of Samples from the Repartition Bin

Nominal Aperture (µ)	Weight Retained	Cum. Weight Retained	% Cum. Weight Retained
4750	935.67	935.67	47.57
2000	176.33	1112.00	56.54
1700	200.00	1312.00	66.71
1180	143.33	1455.33	73.99
850	105.00	1560.33	79.33
600	90.00	1650.33	83.91
425	119.67	1770.00	89.99
Pan	196.67	1966.67	100.00

Crushing Circuit

A closer examination of Table 2 reveals that although the crusher set was adjusted to 5mm yet crushing result produced a cumulative below 4.750mm (approximately 5mm) set size (i.e. cumulative weight passing) of 172g representing about 35.6% of the crushed product. The largest sieve size that was available is about 0.25mm less than the set value (i.e. 5mm - 4.75mm = 0.25mm). This also implies that if a sieve size of exactly 5mm were used the percentage of undersize products would have increased.

Of course the aim of crushing was to produce material of below crusher set value. However, the quantity of such undersize material present in the crushed product partly shows the breaking characteristics of the ore. For example, leaving the sieve size of 4750µ which is the size just below the set value of the crusher, the next nominal aperture is 2000µ, and a good look at Table 2 shows that over 27% of the crushed products is below this sieve size.

It is therefore obvious that although the ore is hard, it is also brittle. The coarse–grained variety especially crumbles on impact, producing even dust. Materials of size below 2000microns are to be treated as dust in primary ore crushing (though this size may be higher in quarrying or aggregate production). The crushing test however produced over 40% of this size range for a crusher close side setting (CSS) of 5mm.

According to Soframine (1978), the Itakpe iron ore plant was initially designed to produce iron concentrate for Ajaokuta steel plant, which requires coarse material for its blast furnace. This means that the concentrate produced at Itakpe iron ore processing plant must contain iron minerals of coarse grains otherwise there will be need for pelletization by sintering which will increase beneficiation cost significantly. But the first stage of comminution (i.e.. primary and secondary crushing) produces about 30% of below control size {1.6mm material} Tables 4 and 6 and Figure7. The existing crushing circuit must therefore be well controlled so as to ensure that minimum values of these undersize materials are produced at the crushing stage so as to minimize production of extra-fine material during grinding and thus prevent loss of much valuable iron minerals in the plant.

A number of crushing circuit options can make this possible. First, the set (i.e. CSS) of the secondary crusher may be adjusted such that the product is fairly large thus preventing production of fines at the initial stages, though this may necessitate tertiary crushing if not carefully controlled. Another possible option is to screen the products of the primary crusher in order to remove materials far below secondary crusher set value so as to prevent further reduction of already sized materials in the secondary crusher before they get to the mills where there is expected to be controlled size reduction process. This will in turn ensure that the production of fines is controlled at the crushing stages, will minimize loss of iron minerals during storage in extensive stockpile or blending yard and prevent undesirable segregation of materials which may impose a difficulty of providing a closely sized feed to the concentration processes (Scott, 2002).

Normally, material in the blending yard should have the same size distribution as that of the repartition bin (i.e. mills feed) since there is no comminution stage between them. But a comparison of the size distribution analyses of materials in the blending yard and repartition bin shown in Tables 4 and 6 and plotted in Figure 7 shows a shift, meaning that the reparation bin contains finer material than the blending yard indicating that more fines have been produced in moving the material between the blending yard and repartition bin. The only cause that can reasonably be adduced to this is the sloughing nature of the ore (especially the hematitic ore) which enables grains to be easily removed from new edges by attrition and other minor forces such as the impact of the reclaimer buckets and minor collisions between crushed materials during movement from the blending yard to the bin. It is also obvious that the same trend will be followed between crushing and blending because material from the crushing unit are dropped from a height of about 10 meters from the boom of the stacker and this will inevitably produce some fines due to dropping impact.

Since most of the valuable iron minerals lost to the waste are fine grained minerals, it follows that production of this fine fractions should be minimized as much as possible at the early comminution stages. A potential hindrance to eliminating fines completely from the circuit is the fact that the ore itself consists of about 18% primary fine grained iron minerals which are said to be predominantly hematite (Soframine, 1978). The first stage of the crushing circuit therefore should be such that a screen is installed to size the product of the primary crusher so as to remove materials of sizes below the "set" of the secondary crusher.

If no fines were produced between the blending yard and repartition bin, it would only have been necessary to screen the crushed products with +2mm vibrating screen before stockpiling in the blending yard such that only the coarse fractions go to the stockpile while the undersize is stored in bins or another storage point and processed directly as shown in Figure 3. This treatment is expected to have some advantages. First, it will prevent lost of the fine fraction during reclamation from the blending stockpile. It will help to separate most of the clay impurities (dust) leaving a substantially iron-rich material as feed to the primary mills.

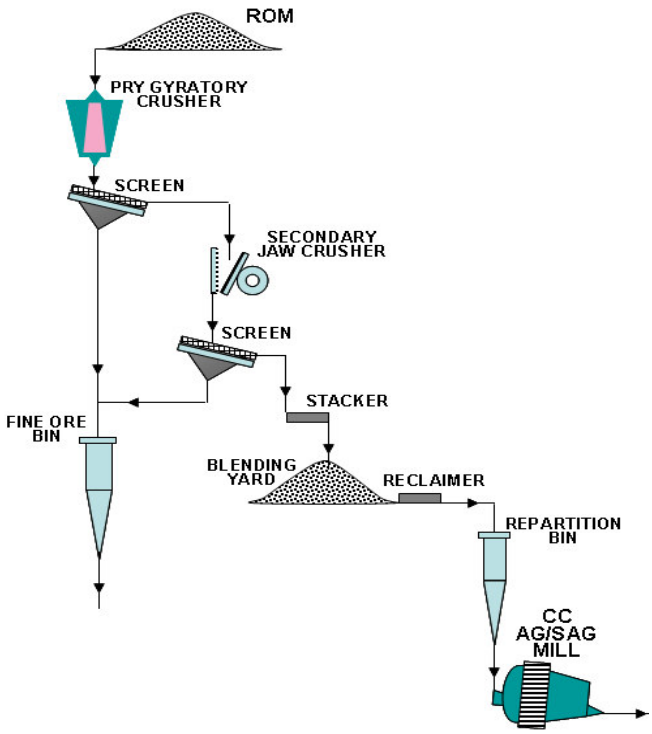

Figure 3: A Possible Comminution Circuit for the Iron Ore Plant

Since the receiving Ajaokuta blast furnace requires coarse concentrate for efficient operation, the fine ore material stored in bins may be concentrated directly in a multi-stage gravity unit without prior grinding provided the iron minerals are sufficiently liberated (Figure 4). The first stage of this concentration unit should preferably be a simple hindered settling option such as the use of density separators which will eliminate most of the clay impurities by clarification producing a rougher product for a more efficient gravity method. Thus, as a result of the sloughing nature of the ore, the significant percentage of primary fine valuables and end–user's requirements, the crushing circuit should produce two products (1) a coarse product stored in stock pile after blending for mill treatment, and (2) a relatively fine product for direct concentration (Figures 4 and 5).

From the sieve analysis of crushed products, the fines constitute about 25% of the entire products. Since a high percentage of the clay and other slime material will be contained in the fine product fraction, this product may first be subjected to clarification to reject these materials before concentration (Figure 5).

Grinding Requirement

Although there is wide difference between autogenous grinding performance and that of the media assisted as shown in Figures 8 and 9 the plant performance indicated that autogenous or semi-autogenous grinding is suitable for application to this ore based on the present choice of gravity and magnetic concentration techniques. If flotation is considered however, a full media assisted grinding (with complete ball load) would be required to meet the production requirement. Since the mineral components of this ore are well liberated at coarse grain size, and density differences of the various components favours application of gravity separation technique, an autogenous/semi-autogenous (AG/SAG) grinding system is suitable for a plant processing this ore. Another factor that favours the choice of an autogenous grinding for this ore is its natural sloughing and crumbling of some of its components. Details of the experimental procedures and results of grindability tests on this ore are described in another article.

Table 7: Results of Autogenous Grindability test at 212 microns for reducing mass by difference for a 5kg charge per run

No. of Rev.	Weight Ground		Grindability (G) g/rev		Average (G_{AV}) g/rev
	1ST Run	2ND Run	1ST Run	2ND Run	
100	55	35	0.55	0.35	0.45
200	75	82	0.38	0.41	0.40
300	100	138	0.30	0.46	0.38
400	150	141	0.38	0.35	0.37
Average					0.40

Table 8: Results of Media Assisted Grindability Test for a Ball Charge of 200% Weight of Ore at 212μ for reducing mass charge by difference

No. of Rev.	Weight Ground		Grindability (G) g/rev		Average (G_{AV}) g/rev
	1ST Run	2ND Run	1ST Run	2ND Run	
100	50	52	0.50	0.52	0.51
200	100	103	0.50	0.51	0.51
300	150	150	0.50	0.51	0.51
400	201	200	0.51	0.51	0.51
Average					0.51

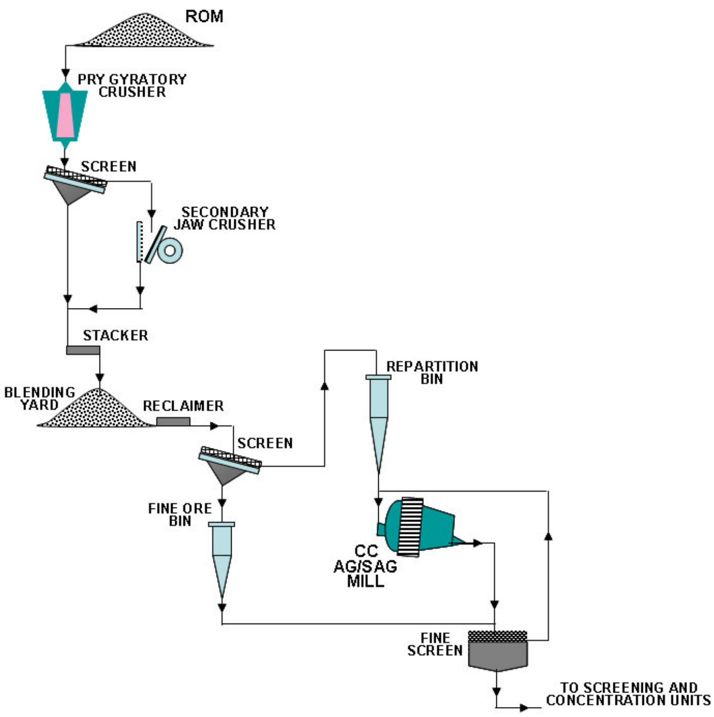

Figure 4: Preferred Comminution Circuit for the Iron Ore

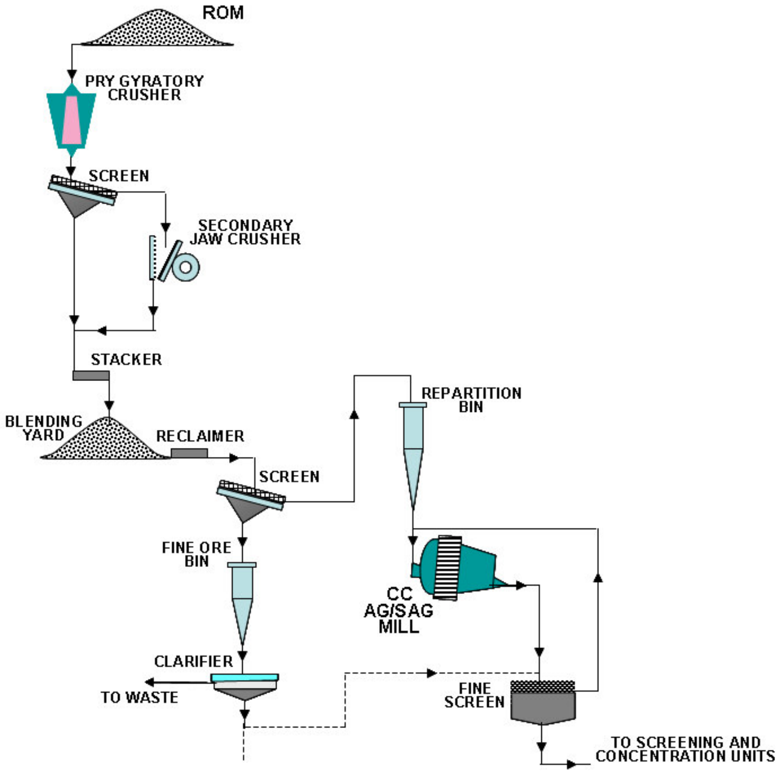

Figure 5: Preferred Comminution Circuit for the Iron Ore

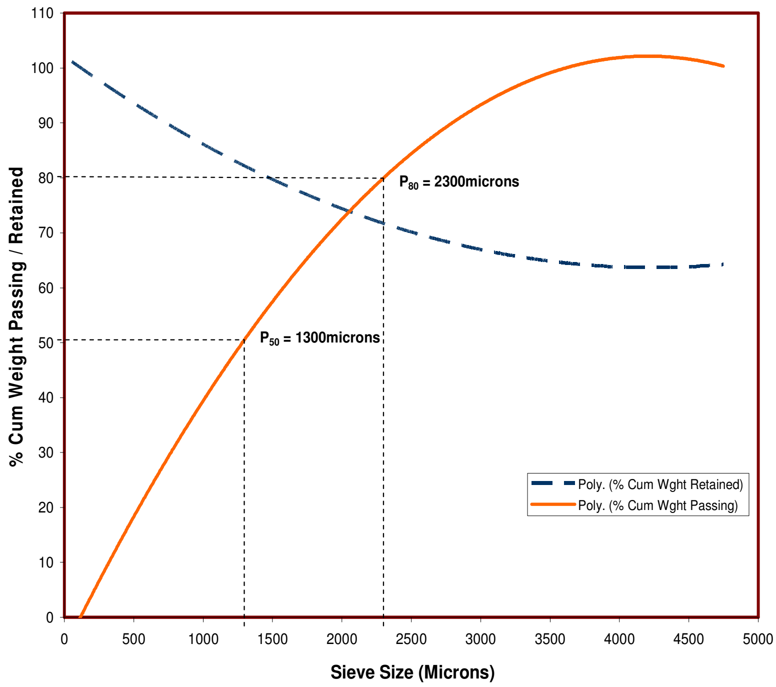

Figure 6: Results of Size Distribution Analysis of Laboratory Crushing Test

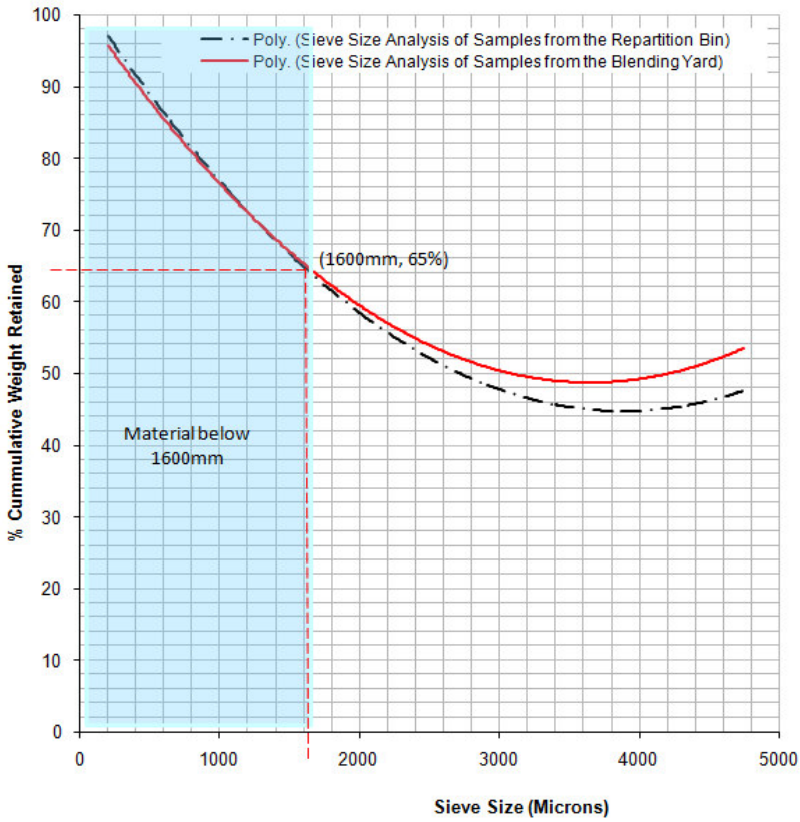

Figure 7: Comparison of Size Distribution of Materials in the Blending Yard and Repartition Bin.

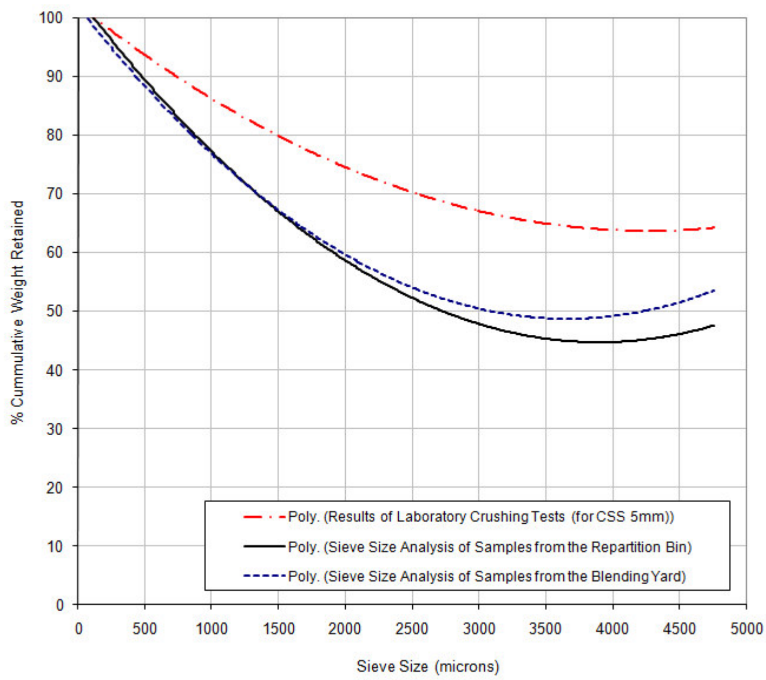

Figure 8: Comparision of Size Distribution of Material in the Blending Yard and Repartition Bin with Crushing Tests

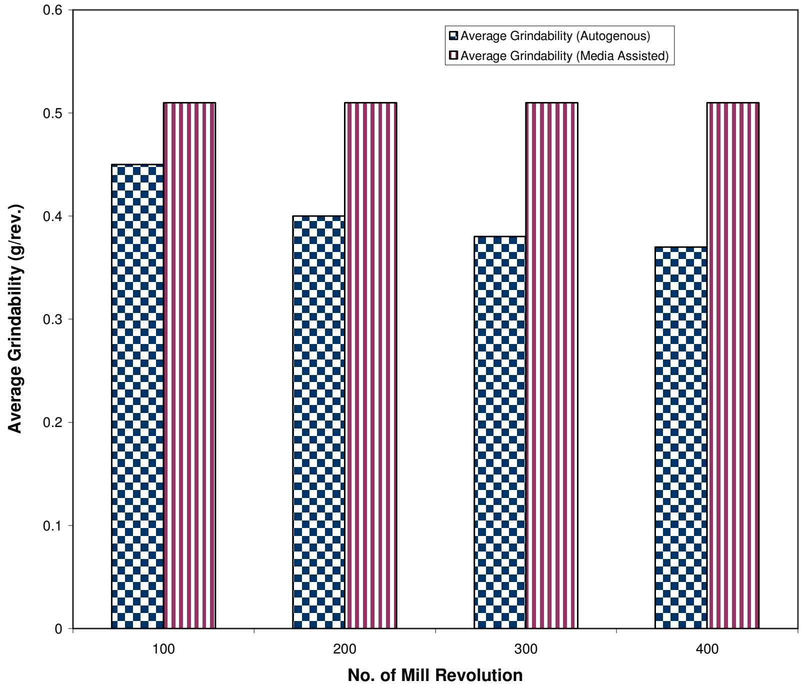

Figure 9: Comparison of results of Autogenous and Media Assisted Grindability Tests

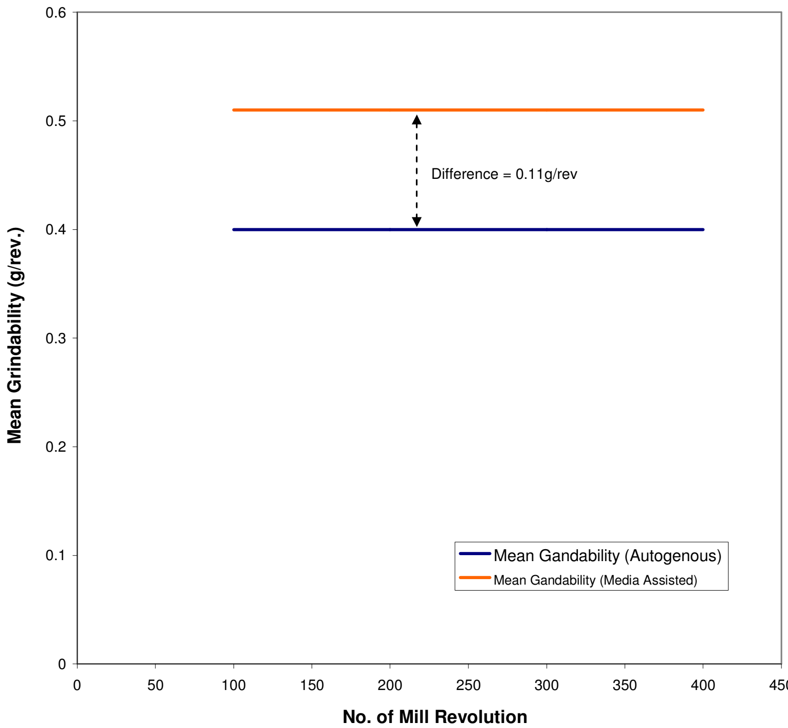

Figure 10: Comparison of results of Autogenous and Media assisted grindability tests

Conclusion

It can be reasonably concluded from the foregoing that the presence of fine iron minerals in the concentration lines reduces the recovery since such fine valuable minerals are likely to be loss to waste stream if the recovery techniques are not carefully selected to handle such fines. It has also been shown that screening the products of the crushing unit as reclaimed from the blending yard before milling will reduce the amount of fines reporting to the concentration units and thus minimize loss in the plant. It is therefore recommended that the products of the primary and secondary crushers be screened in the course of size reduction to prevent production of fines during crushing unless the downstream process is entirely designed for flotation. One way is to install a +2mm coarse screen between the reclaimer and the primary autogenous mills. This option however will still leave fine material to the entire concentration line (Figure 5). To avoid this the products of both primary and secondary crushers should be screened off separately of material less than 2mm and this fraction treated in a separate recovery line (Figure 11).

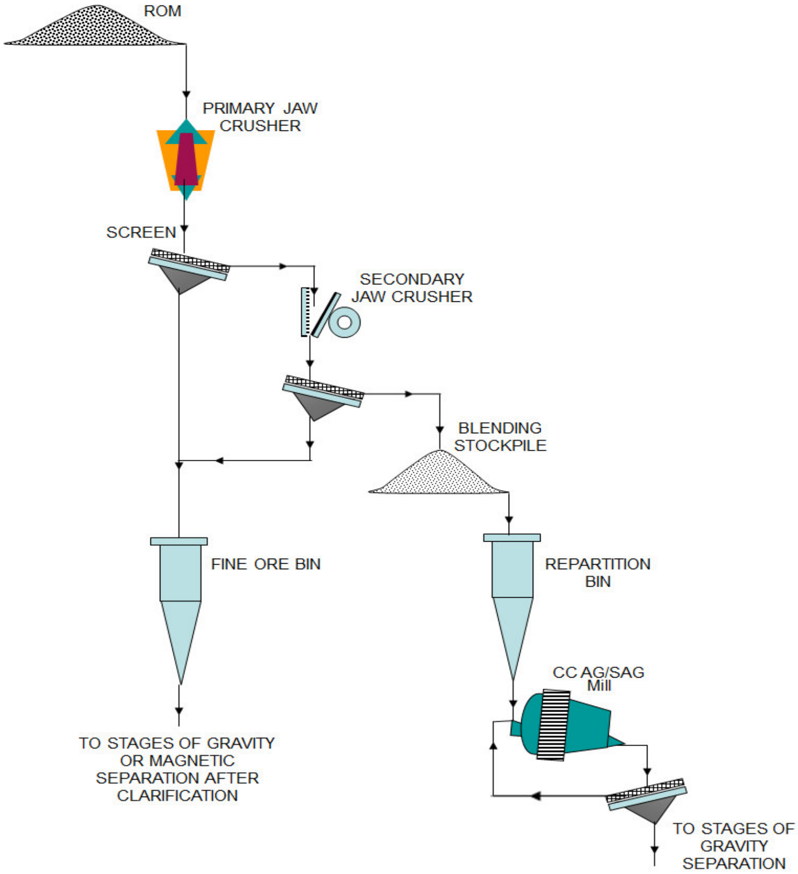

Figure 11: Preferred Comminution Circuit for Effective Performance of the Gravity Separation.

Recommendations

Based on the existing configuration of the plant nd the foregoing analysis, the plant will definitely be improved and loss of valuable minimized if the comminuted materials are maintained in two lines of fine and coarse fractions such that the fine fraction is treated by low intensity magnetic separation after clarification to remove the slime; and the coarse fraction concentrated by gravity methods (Figure 11). This treatment will ensure that the gravity unit which is expected to treat over 75% of the feed incurs little or no loss of value during concentration.

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