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Recycling of Solid Wastes from Integrated Steelmaking Plant: A Sustainable Alternative

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Worldwide, the iron and steelmaking industry generates around 30 million tons of the recyclable wastes per year. They are generated at different phases of the production with different types and characteristics. Within these are: sludge of the Blast Furnace; coke fines; fine and coarse fractions from oxygen converters; sludge from water treatment at rolling mill unit; and others. In this paper the above dusts and sludges were physically and chemically characterized. The obtained results allowed defining self-reducing pellets using these materials. The high temperature behaviors of the pellets were evaluated. Good results, with no decrepitation and swelling, and high yield of reduction, show that it is feasible to recycle them, as self-reducing pellets, in oxygen steelmaking converter, with a net benefit of US$ 20 per ton of these dusts.

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1. Introduction

The ironmaking and steelmaking processes generate, annually in the world, almost 30 to 40 million tons[1] of recyclable dusts and 140–150 million tons of slag. This paper discusses and presents experimental results obtained when wastes containing more than 20% of iron, from integrated steel plant, were treated as self-reducing agglomerates. In the integrated steel making plant around 80% of dusts, sludge, mill scales generated at steel making (BOF), blast furnace and rolling mills (containing iron unit) are recycled as a raw material for the sintering plant. Since most of these residues are very fine the use of them affect the permeability of the charge, therefore decreasing the productivity of sinter plants. Furthermore ultra fine materials such as sludges are not possible to be recycled in this way, therefore an alternative way for recycling part of them charging directly into the BOF as a substitute for scrap is proposed.

The Table 1 shows the generation of the main recycled wastes. BOF and Blast Furnace generate most of the recyclable iron containing wastes. Most of them are very fine and proper for pelletizing with exception of mill scale from rolling mills, from scarfing and from continuous casting. The sludge from BOF bears high iron; most of it is present as metallic iron. BOF sludge presents also very high basicity. Blast Furnace sludge contains low iron and shows low basicity and high carbon content. The data from the literature do not match well but the estimated generation rate of these wastes are in the range of 40 to 60 kg/t of steel, depending on the production scale and operational procedures.

Table 1 Generation of ironmaking and steelmaking solid wastes. Estimated data.

	World		Brazil
	kg/t steel	Million, *t*	Million, *t*
Recyclable	43[1]	30[1]	1.2
B.F. dust	1 to 2[2]	0.5 to 1.0	0.02 to 0.04
B.F. sludge	< 1[2]	~ 0.2	~ 0.001
Sintering dust	15[2] ?	7	0.3
Coke fines	?	?	?
BOF sludge coarse fraction	5–6[2]	2.5	0.1
BOF sludge, fine fraction	17[2]	8	0.34
Scales	10–20[2]	7	0.3
Electric arc furnace dust	15[2]	4.6	0.07
B.F. Slag	150 to 350 (300)[2]	140	6.0
B.O.F. slag	100[2]	47 (*)	2.0 (**)
Cont. casting slag	30–35	17 (*)	0.7 (**)
Electric arc furnace slag	15[2]	5 (*)	0.075

(*) 60% by BOF and 40% by EAF and (**) 80 e 20% respectively.

Tables 2 shows the present destination for these wastes and alternatives for recycling. Most of these iron-bearing wastes are presently recycled at sinter plant. The critical are BOF sludge and BF sludge, due to fineness and large volume generated. With higher demand for galvanized steel for automobile industry the scraps used in BOF generate sludge with more zinc content. The maximum content of zinc in the Blast Furnace is limited. This limit constraints the use of these sludge in the sinter plant, therefore alternative destinations are demanding. One is the FASTMET process for DRI production. Another one is the use of it as substitute for scrap, charging directly the self-reducing agglomerate into BOF. The last one is the object of this paper, which is a part of a broader program and more detailed technical results are published elsewhere.[3–6]

2. Experimental

Eight types of the iron bearing wastes, representing most of the important ones, were composed taking into account iron content, carbon content, fineness, basicity and residual elements (mainly sulfur) to produce the 10 different types of self-reducing pellets and 6 types of briquettes. The behaviors of these agglomerates were evaluated at room temperature and at high temperature for a given thermal route.

Table 2 Destination of the main recyclable ironmaking and steelmaking solid wastes.[3)]

	Destination	Obs.	mass%	Recycling alternative
BF dust	100% sintering	< Permeability	41%Fe and 26%C	Reductant in pellets
BF sludge	50% sintering	Function of %Zn	37%Fe and 30%C	Reductant in pellets
Sintering dust	100% sintering	< Permeability		Scrap substitute
Coke fine	Sintering			
BOF sludge coarse fraction	15% recycled 11% Comercializ.,	Function of %Zn	87%Fe where 85% metal	Scrap substitute
BOF sludge fine fraction	42% landfill		60%Fe where 32% metal	Scrap substitute
Rolling mill sludge			65%Fe	
Mill scale	83% recycled	Oil should be < 2%	74%Fe	Scrap substitute
EAF dust	25% comercializ.	Heavy metals (dangerous waste)	30–50%Zn	Zn recover

Table 3 Chemical composition of materials (mass%).

Waste	C	MnO	SiO_2	MgO	Al_2O_3	Fe(t)	Fe°/ Fet	K_2O	Na_2O	CaO	S	Fe_2O_3	FeO
I	1.11	1.76	1.80	1.90	0.14	59.24	31.9	0.14	0.13	8.70	0.087	—	59.23
II	0.62	0.26	1.79	0.93	0.14	86.42	85.4	0.068	0.037	4.33	0.009	—	27.91
III	30.25	0.33	6.95	0.65	2.60	36.55	—	0.113	0.17	1.67	0.325	49.12	2.19
IV	26.63	0.38	6.89	0.83	1.97	40.67	—	0.07	0.153	2.43	0.25	50.77	5.16
V	7.99	0.47	2.39	0.46	1.69	64.2	—	—	—	0.87	0.14	—	79.14
VI	22.58	0.36	6.97	1.08	2.05	35.29	—	—	—	3.07	0.37	—	3.47
VII	0.26	0.89	2.5	0.11	0.85	71.20	—	—	—	1.7	0.033	—	—
VIII	0.1	0.82	4.9	0.11	1.21	75.8	—	0.033	—	2.93	0.007	—	—

2.1 Sludge, dusts and mill scale

Table 3 shows the chemical analysis of the sludge, dusts and mill scale used. These wastes were supplied by an integrated steelmaking and the designations are: a) I: BOF sludge, fine fraction; II: BOF sludge, coarse fraction; III: BF sludge, fine fraction; IV: BF sludge, coarse fraction; V: sludge from rolling mill (water treatment); VI: BF dust; VII: scale from continuous casting; VIII: scale from slab's scarfing.

The particle size distributions of the 2 most critical wastes, within the 8 above listed, are presented in the Fig. 1 (BOF sludge, fine fraction) and in the Fig. 2 (BOF sludge, coarse fraction).

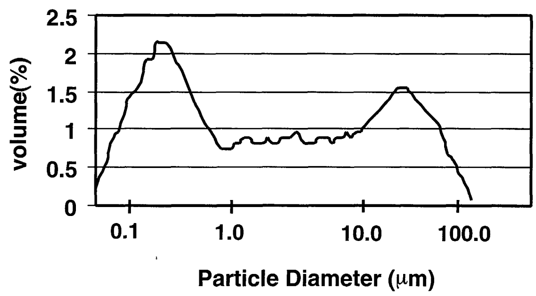

Fig. 1 Particle size distribution of the fine fraction of the BOF sludge.

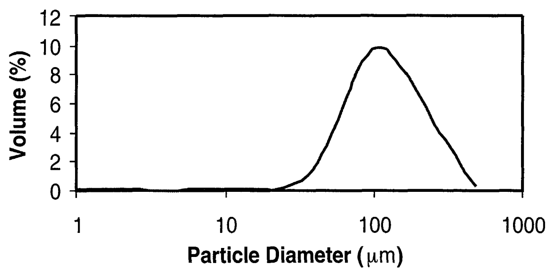

Fig. 2 Particle size distribution of the coarse fraction of the BOF sludge.

2.2 Reductant

When used, the reductant was coke fine, containing: $C_{fix} = 85$ mass%, ash = 13 mass%, and volatile matter = 2 mass%; and with particle size 90% less than 150 μm.

2.3 Binder

The binder used for cold bond agglomeration was Portland cement with high initial strength (68 mass%CaO) and particle size 100% less than 100 μm.

2.4 Composition of agglomerates

Table 4 shows the composition of the agglomerates evaluated. Pellets are designated by Pi and Briquettes by Bi.

2.5 Pelletizing

Self-Reducing pellets with diameter within 12 mm and 18 mm were produced using a laboratory disc with 800 mm diameter.

Table 4 Composition (mass%) of the agglomerates employed in this work.

Material	I	II	III	IV	V	VI	VII	VIII	Coke	Cement
P1	65.8	11.6	—	—	—	—	—	—	12.6	10
P2	68.3	12.1	—	—	—	—	—	—	13.1	6.5
P3	69.4	12.3	—	—	—	—	—	—	13.3	5.0
P4	70.1	12.4	—	—	—	—	—	—	13.5	4.0
P5	70.8	12.5	—	—	—	—	—	—	13.6	3.0
P6	84.8	—	—	—	—	—	—	—	8.7	6.5
P7	36.5	12.0	17.0	8.0	—	—	—	—	20.0	6.5
P8	—	60.9	1.7	14.6	—	—	—	—	16.3	6.5
P9	—	50.6	—	—	25.0	—	—	—	17.9	6.5
P10	60.6	7.5	—	—	2.2	—	—	—	23.3	6.5
B1	—	54.9	—	—	—	—	23.8	—	21.3	—
B2	—	30.8	—	3.9	—	—	—	51.2	14.1	—
B3	—	70.1	—	—	4.9	—	9.2	—	15.8	—
B4	—	33.9	—	—	22.2	10.9	19.2	—	13.8	—
B5	—	42.1	—	—	—	—	36.5	—	21.4	—
B6	—	20.7	—	14.6	8.2	—	38.5	—	17.9	—

Table 5 Thermal Route C_1.

Temp. (°C)	690	1190	1220	1260
Time (min)	3	4	5	10

Obs.: The pellets were taken directly to 690°C, keeping them during 3 min; then quickly brought to 1190°C and kept during 1 min at this temperature, and so on, such that after exposing 5 min to 1260°C the total time of the experiment was 10 min.

Table 6 Thermal Route C_2.

Temp. (°C)	700	800	900	1000	1100	1200	1350
Time (min)	3	4	5	6	7	8	10

Obs.: The same procedure described in Table 5.

2.6 Briquettes

The briquettes were produced using a cylindrical matrix with 10 mm diameter and height of the briquettes was within 10 and 16 mm. The pressures were 30–60 kN/cm^2.

2.7 Decrepitation and swelling tests

Two thermal routes (Tables 5 and 6) were used for testing the decrepitating and swelling behavior of the agglomerates. The apparatus and procedures are described elsewhere.[5)]

2.8 Other characterization techniques

Additional information about the dusts and sludge were obtained employing Scanning Electron Microscopy, EDS microanalysis and X-ray diffraction analysis.

3. Results and Discussion

3.1 Analysis of the wastes

The chemical analysis of the BOF sludge (Table 3) shows that its main components are CaO, SiO_2, MgO, MnO, Al_2O_3 and also high content of metallic iron, which come from ejection of slag and steel during CO generation, forming small particles that are carried out by the gases.

The high content of carbon and hematite of BF sludge, as determined by X-ray, are due to dust generation by fluidization of small particles of the charge.

The main conclusions from the observations of microstructure, X-ray diffraction analysis and microanalysis of BOF sludge were: (a) BOF sludge fine fraction (I) contains calcium ferrites (Fe, Ca)O besides "FeO" and metallic iron; and (b) BOF sludge coarse fraction (II) contain complex solid solution such as (Ca, Mg, Fe, Si)O, (Ca, Si, Fe)O and (Fe, Ca)O, besides "FeO" and metallic iron.

The observation of the Blast Furnace sludge fine and coarse fractions (III and IV) showed that: a) the main components of the BF sludge fine fraction are hematite and carbon from coke; and b) these fine particles contain also micro-regions with the following elements, in decreasing order, Fe, C (or O) together with the presence of Na, Al, Si, S, Ca, Mn.

The analysis and observations performed with the sludge from rolling mill (V) confirmed that the main component of this sludge is "FeO". The presence of carbon is due to the oil.

3.2 Cold compression strength of self-reducing pellets after 28 days of curing

Table 7 shows the results of the compression strength of the pellets after 28 days of curing at room temperature. The strength of 300 N/pellet was achieved with 10% cement. When 6.5% cement was used as the binder the strength was in the range of 70–270 N/pellet. This strength, when extrapolated for industrial units, should double, therefore these values are acceptable for handling. With the binder content lower than 6.5% (P3, P4 e P5) the results of strength were very low.

3.3 Decrepitation and swelling tests of the pellets

The pellets P1 through P6 were submitted to the thermal route C1 and the pellets P2 through P10 to the thermal route C2. No decrepitating or abnormal swelling were observed regardless of the cold strength of these pellets.

3.4 Thermal processing of the self-reducing briquettes

Dusts not suitable for pelletizing due to coarse particle size (mill scale, scale from continuous casting and residues from scarfing) were agglomerated as self-reducing briquettes (B1

Table 7 Cold Compression Strength of the pellets after 28 days of curing. (Newton/pellet)

Type	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
N/pel	300	115	25	16	12	98	110	277	68	100

Table 8 Metallic recover yield after smelting of self-reducing pellets.

Pellet	Sludge	Metallic yield (%)
P6	BOF	95
P10	BOF + Rolling mills	96

Table 9 Data used for economic estimate.

Scrap price	US$ 80/t	
Wastes disposing in landfill	US$ 20/t[1)]	
Agglomeration capacity	100,000 t/year	In house
Investment cost	US$ 45/t.year	Depends on the scale
Binder's cost	US$ 70/t	
Operational cost (labor, utilities, logistic, *etc.*) for drying, mixing and agglomeration	US$ 1.0 million/year	Brazilian conditions

through B6). These briquettes were submitted to the thermal route C2 to test the degradation behavior.

The briquettes B1 and B3 through B6, containing scale from continuous casting (VII), after submitted to thermal route C2, presented total disintegration, forming a metallic button covered by fine magnetic particles. This result could be a consequence of a liquid phase formation at the final stage of the thermal cycle.

The briquettes B2, containing scales from scarfing machine (VIII) did not present degradation, after thermal path C2.

3.5 Smelting tests

The aim of these tests was to evaluate the behavior, mainly metallic recover yield, of the self-reducing agglomerates when charged directly to metallic bath. The agglomerates (around 1000 g, each charge of 250 g) were charged directly to the ~2800 g liquid Fe–C alloy melted by induction and kept at ~1500°C. To keep the slag fluid enough some silica was also added. The metallic yield was measured by weighting the metal after solidification in a cast iron ingot. The results are shown in Table 8, and they confirm[1)] the high yield of metallic units. These results indicated the benefit of recycling this sludge as the substitute for scrap in the BOF.

3.6 Industrial feasibility

Acceptable behavior of the self-reducing agglomerates, including very good recover yield of the metallic unit (95%) during smelting tests indicated that alternative of recycling them charging the agglomerates directly to BOF, as a partial substitute for scrap, should be considered. Therefore some preliminary economic analysis was also made.

The alternative of partial substitution for scrap, in the initial charge of BOF was chosen among others because the following reasons:

1. The rate of reduction for recovering the iron units from self-reducing agglomerates is very fast (few minutes) when submitted at high temperatures. It was estimated that the reduction starts as soon as the agglomerates are charged into the hot BOF and almost all the reduction is finished before the end of pouring of the pig iron. This would give good reduction and an incorporation of iron unit into the bath before starting the oxygen blowing.
2. The agglomerates have high content of iron, including part of them as metallic iron.
3. The recover yield of iron from the agglomerate to the bath of 95% was obtained in the laboratory tests.
4. Deleterious elements mainly sulfur, contained in the agglomerates showed to be acceptable for this operation.
5. When charged 2–3 mass% of the total charge of the BOF almost no influence is shown in the thermal balance and slag volume of the BOF.
6. Recycling at BOF means that it is done in the nearest operation for final product production. When recycled at sintering plant the material is processed previously by sintering and reduction in the Blast Furnace before reaching the BOF.
7. The scrap is one of the highest unitary economic values of the BOF charge.

Therefore, the main advantages of this way of recycling should be: the re-use of these critical fines in an integrated steel plant; some zinc content in the dusts should be acceptable; minimize to dispose in the landfill; and avoid the use of these fines in the sintering machine.

3.7 Economic considerations

The Tables 9 and 10 show the boundary conditions used for estimating the benefits of this substitution. Since it is a preliminary estimate neither all cost and all benefits were considered but only the main ones. The analysis shows, with good confidence, that recycling these wastes containing iron units, by self-reducing agglomerates, charging directly into the BOF as a partial scrap substitute is an economically feasible procedure. It is estimated a net benefit, after capital recovery, of around US$ 20 per ton of the recycled waste. The net benefit of around US$ 15/ton of agglomerate is equivalent to US$ 20/ton of the waste.

4. Conclusions

(1) It is economically feasible to recycle integrated steelplant wastes containing iron, by agglomerating as self-reducing pellets or briquettes and charging them into BOF as partial substitute for scrap.

(2) It is roughly estimated, for such procedure, a net benefit of US$ 20 per ton of recycled waste or equivalent to US$ 15/t of agglomerate.

Table 10 An economic estimate: Wastes containing iron as substitutes for scrap in BOF.

Benefits: = cost of the wastes(cost of disposing in the landfill (US$/t)) + average Fe content in the agglomerate x yield x scrap cost(US$/t) + benefits at the sintering plant.
Costs = capital cost(return on investment(roi) = 10%, 20 years life) + binder's cost(US$/t) + cost for agglomeration(drying, mixing, agglomeration)

	Technical coefficient	US$/t	US$/t agglomerate	Obs.
BENEFITS				
Cost of wastes disposed in landfill	0.2 t.waste* 0.8 waste/t agg = 0.16	20.00	3.2	Only 20% of generated wastes go to landfill
Scrap (substituted)	0.42 t of Fe/ t.agglomerate* 95% yield = 0.4	80.00	32	Average Fe content of 40% in the agglomerate
Improvement in sintering plant			Not computed	
Total			**35.2**	
COSTS				
Capital	r.o.i = 10% and life of 20 years on US$ 4.5 millions invest.		5.3	Annual interest rate of 10%, without residual value after 20 years.
Binder	0.065 t.agglomerate	70.00	4.6	6.5% of binder
Other cost for agglomeration	US$ 1.0 millions/year		10	labor + utilities+ overhead *etc.*
Total			**19.9**	
BENEFITS (-) COSTS			**15.3**	

(3) The economic benefit is a consequence of the high content of total iron: 85 mass% (coarse fraction of the BOF sludge) and 60 mass% (fine fraction of the BOF sludge).

(4) Blast Furnace sludge due to high content of carbon (around 30 mass%) is an alternative as reductant for self-reducing agglomerates, but care should be taken because high content of sulfur (around 0.25 mass%).

(5) The cold bonded self-reducing pellets made from wastes presented mechanical strength enough for handling and therefore feasible for the operational procedure.

(6) Smelting of the self-reducing pellets and briquettes presented, at laboratory scale, a yield recovery of iron of 95%, confirming the results reported in the literature.

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