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Original Article

Agglomeration behaviour of steel plants solid waste and its effect on sintering performance

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ABSTRACT

Recycling has been the fascinating topic among the researchers for all times. The present study shows the recycling of steel plant's solid wastes as blast furnace flue dust and sludge towards agglomeration and their use in the production of sinter. These wastes consist of metal oxides and coke fines as a valuable material with some alkali oxides. Using these wastes as it is in the form of fines exacerbate the further processing. Pellets of these wastes are prepared with three types of binders as molasses, dextrin and bentonite. The result reveals that properties as compressive strength, shatter strength, are better in the case of bentonite binder having the productivity of the disc pelletizer machine as 75. After that, these macro pellets used for sintering with iron ore and other ingredients in pot type, down draft laboratory grade sintering machine, which shows very high productivity and good mechanical properties of the sinter as well. The microstructural analysis reveals the presence of re-oxidized hematite and a little bit of a magnetite phase with some slag phases, which confirmed later by XRD analysis. Results also show the decrease in coke rate, i.e. coke consumption to produce sinter and at the same time, this process is highly eco-friendly.

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1. Introduction

Blast furnace sludge and blast furnace flue dust are the hazardous metallurgical waste generated in the iron making plants [1]. The flue dust and sludge is a mixture of oxides expelled, whose major components are iron oxides and coke fines. It also contains silicon, calcium, magnesium and other minor elemental oxides in lesser amounts. The recovery of these valuable metals and carbon from this flue dust and sludge becomes very important, due to the increase in the price of coke breeze and the decrease of the primary resources of the raw materials. Moreover, it makes the environment safer by decreasing pollution.

The fact that it is not possible to recycle this dust and sludge directly or to reject it as landfill because it will contaminate the soil badly, so it is necessary to consider the recovery of the valuable elements contained in it and to obtain a non-hazardous residue that can be stored without problem or can be used in agglomeration units in iron-making industries [2,3].

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Although utilization of these wastes as it is from the plant for the production of sinters is a recirculation technique [4] but at the same time, it adversely affects the property of sinter, which is not up to the mark for use in blast furnace. In this study, we made the pellets [5–8] from the blast furnace waste and then used these pellets for preparing of sinter, which results in sintering properties such as sinter strength increases with using the waste made pellets, at the same time the productivity of the sinter machine also increases [9–11]. It also decreases the fuel rate in the sintering process [12]. The results were found that the presence of bentonite binder up to 4% provides the shatter index of the pellets less than 20, whereas molasses and dextrin gave the significantly high shatter index means very low strength. Hence, the 4% bentonite binder gave the optimum condition for the pelletizing machine. Thereafter, these pellets are used for sintering results in a decrease of coke consumption from 60 to 30 kg/ton of sinter, utilizes 25% of waste. At the same time, this much of waste addition also decreases the lime addition to maintaining the basicity. The productivity of sintering machine was found to increase up to 5.2 at 27% waste for the basicity of the sinter as 2.2.

2. Materials and methods

2.1. *Material used for pelletization*

The raw materials (blast furnace flue dust and sludge) were used for pelletization, obtained from the Durgapur Steel Plant (India). The chemical composition and sieve analysis are shown in Tables 1–3.

The waste sample shows the abnormal accumulation of iron as well as very fine carbon. At the same time, these also contain a high percentage of alkali, so it cannot be reused directly in the sintering process. The optical emission spectroscopy studies (OES) of these samples indicated that iron is present in very high amounts in comparison with the other elements. The X-ray diffraction (XRD) study shows the associated phases of iron metal, gehlenite ($Ca_2Al_2SiO_7$), magnetite, hematite, quartz and wustite in order of abundance. The XRD pattern of flue dust and sludge is shown in Figs. 1 and 2.

A number of organic and inorganic binder materials used as an additive in agglomeration technique are being reported in the literature. Here bentonite an inorganic, whereas molasses and dextrin (organic binders) are used for pelletization. The chemical compositions of bentonite and molasses binder are listed in Tables 4 and 5.

Table 1 – Chemical composition of blast furnace sludge.

Element	Weight %, by mass
Fe	30.82
CaO	8.95
SiO_2	11.59
MgO	3.83
Al_2O_3	3.6
Na_2O	0.09
K_2O	0.29

Table 2 – Chemical composition of blast furnace flue dust.

Element	Weight %, by mass
Fe	39.92
CaO	6.28
SiO_2	6.95
MgO	2.01
Al_2O_3	4.0
Na_2O	0.51
K_2O	0.29

Table 3 – Sieve analysis of blast furnace ferruginous waste material.

Sieve size (μm)	Weight % of flue dust	Weight % of sludge
1000	20	30
500	10	25
300	20	25
150	30	20
75	10	–

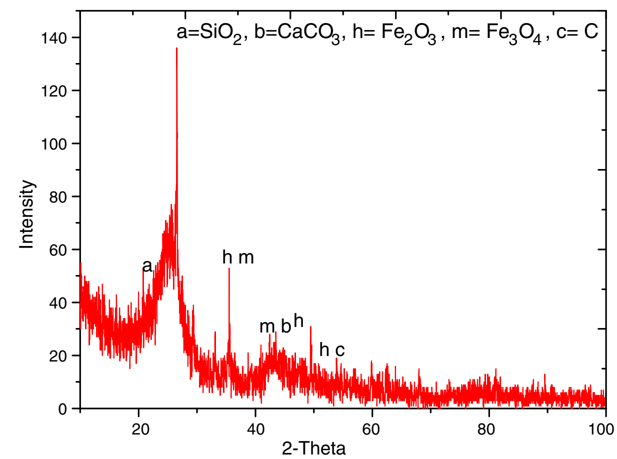

Fig. 1 – X-ray diffraction pattern of blast furnace flue dust.

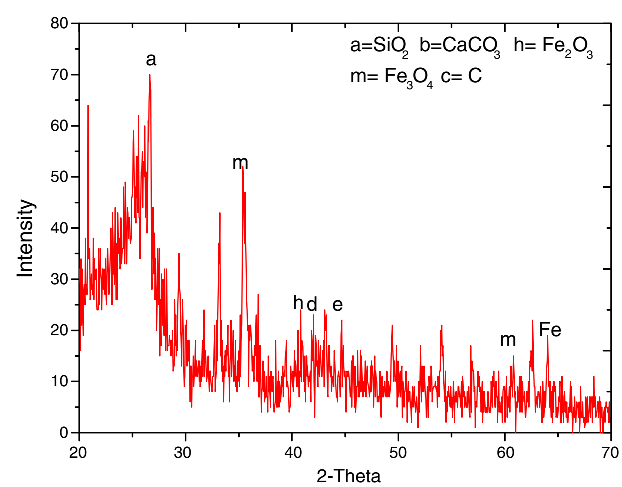

Fig. 2 – X-ray diffraction pattern of blast furnace sludge.

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Table 4 – Chemical composition of bentonite binder.

Element	Weight %, by mass
Al_2O_3	20.27
Fe_2O_3	9.08
TiO_2	0.78
SiO_2	54.82
CaO	2.10
MgO	3.02
Na_2O	1.31
K_2O	0.06

Table 5 – Chemical composition of molasses.

Constituent	Weight %, by mass
Organic material	72.7
Crude protein	0.06
Saccharose	49.3
Nitrogen	1.6
Water	20
Ash	7.3

2.1.1. *Dextrin*

Dextrin is a family of polysaccharides, which are obtained as an intermediate by-product of the breakdown of starches.

2.2. *Experimental set up and methods*

A detailed flow sheet of recycling of blast furnace sludge and flue dust is given in Fig. 14. A disc pelletizer was used in the formation of pellets having 56 cm diameter. The angle of inclination of disc pelletizer was set to 37.10° and the rotating speed of the disc was 28 rpm with the residence time of 10 min. The pelletization was carried out by taking the aforesaid binders in different proportions. Three categories of pellets were prepared: (i) flue dust only, (ii) sludge only, and (iii) mixture of both.

Raw materials mixed with the binder were fed to the pelletizing machine. The predetermined amount of water was spread onto the rolling bed of material in the disc pelletizer. The machine was put on and the spherical pellets were allowed to form. A scraper was used to wash out the material sticking onto the disc. At the end of the experiments, the pellets were collected and indurated. The green pellets were dried in air for two days to assure the complete evaporation of moisture. Bentonite made pellets were heated up to 300 °C for 1 h and then isothermally indurated at 900 °C for 1 h. Dextrin and molasses made pellets were heated in an air oven at 150 °C for 1 h. At the end of drying/induration, the samples were screened to collect the fraction of less than 5 mm, which is also a measure of the productivity of the pellet.

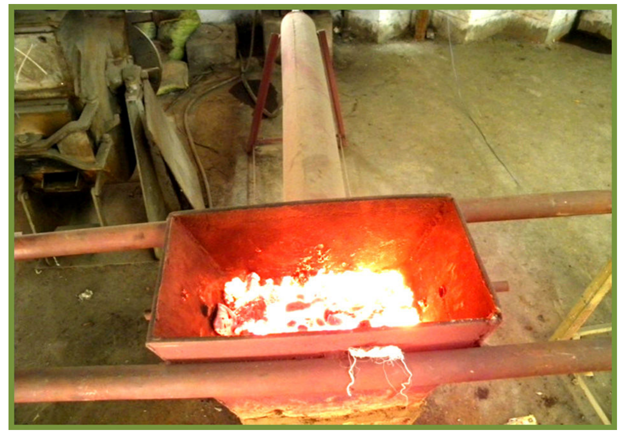

Fig. 3 – Top burning bed of sinter of laboratory grade sintering machine.

These indurated pellets were used in the sintering with iron ore and other ingredients like limestone, coke breeze and dolomite in the laboratory grade sinter machine. A real view of the top burning bed looks as Fig. 3. Productivity is also calculated in case of sintering by taking +10 mm sinter size.

2.3. *Charge calculation for sintering*

Basicity (CaO/SiO_2) is being taken as the basis for charge calculation and was fixed as 1.5, 1.73 and 2.2. The amount of coke breeze and iron ore was fixed to 300 g and 3 kg respectively, whereas the other raw material mixes are calculated for aforesaid basicity of sinter. The sinters produced in experiments have been graded as $S_1, S_2, S_3, \ldots, S_{15}$ by varying limestone fines, i.e. flux and the amount of waste made pellets which are quoted in Table 6.

2.4. *Productivity of the pelletizing machine*

The productivity of the pelletizing machine was calculated as [12]:

$$\text{Productivity} = \frac{\text{Wt. of the pellets of 5 mm size (g) and above}}{\text{Wt. of the charge fed to the disc (g)}} \times 100 \quad (1)$$

Table 6 – Raw material composition for sintering.

Raw material	Basicity = 1.5					Basicity = 1.73					Basicity = 2.2				
Iron ore fines (kg)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Coke breeze (g)	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
Limestone fines (g)	335	383	400	432	465	400	445	471	490	535	550	660	697	770	843
Dust + sludge pellets (g)	0	300	400	600	800	0	300	400	600	800	0	300	400	600	800
I.D. No.	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}

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2.5. *Productivity of sintering machine*

At the end of sintering experiment, the produced sinter was screened over a sieve of 10 mm to determine the productivity of the machine as [12]

$$\text{Productivity} = LSKH/\text{ton}/\text{m}^2/\text{day} \quad (2)$$

S, amount greater than 10 mm; *H*, height of the charge/time of sintering; *K*, bulk density of the sinter; *L*, machine constant.

2.6. *Testing of sinter*

The sinter strength was observed by the series of tests as: (i) shatter test, (ii) tumbler test, (iii) abrasion test and (iv) cold crushing strength (CCS) test. CCS test was carried out in a universal testing machine to judge the breakability of sinter.

2.7. *Reducibility of sinter*

Reducibility of the produced sinters was analysed in a reduction furnace by carbon mono oxide and nitrogen gas mixture in the proportion of 30:70 at the rate of 1.50 L/min, at temperature 900 °C and reduction time 90 min. The weight loss during the process is the clear indication of the reducibility of sinters and weight loss was calculated as:

$$\%\,\text{weight loss} = \frac{(\text{initial weight} - \text{final weight})}{\text{Initial weight}} \times 100 \quad (3)$$

3. Results and discussion

3.1. *Strength of the pellets*

The physical strength of the pellets is shown in Figs. 4–6, showing the shatter index as the varying binder amounts for different types of pellets. Nearly the pattern of shatter index is same in each type of pellets, but there is a considerable change in the values of shatter index with respect to the type of binders used.

The presence of bentonite binder shows the maximum strength of pellets as the graphs shown above. Apart from the choice of binder, the amount of the binder is also important, otherwise, it will adversely affect the further processing as well as the economy of the process. Use of four weight percent of the binders shows an optimum value in each case, otherwise, it will be harmful as said above. Bentonite binder shows the best result among the other binders because it has more of inorganic components which provided the bond of greater strength, whereas in the case of the organic cold setting binders have more of organic components and bond formation between organic and inorganic materials cannot be made easily. Therefore, it could clearly analyse that the four weight % bentonite binder provides the maximum strength in comparison to others binder.

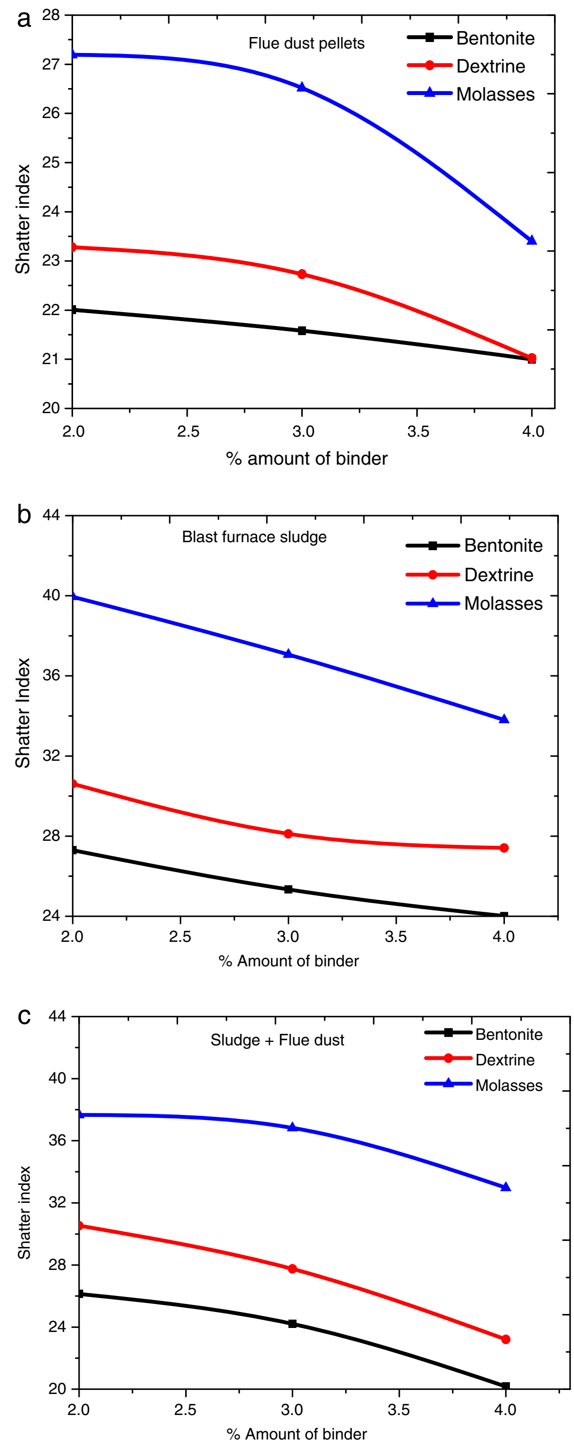

Fig. 4 – Effect of binder amount on pellets strength: (a) flue dust pellets, (b) blast furnace sludge pellets, (c) sludge and flue dust mixed pellets.

3.2. *Productivity of the pelletizing machine*

Fig. 5 illustrates the effect on the amounts of binders on the productivity of the pelletizing machine, it can be seen that the bentonite binder showed the maximum productivity in comparisons to the other same amount of binders.

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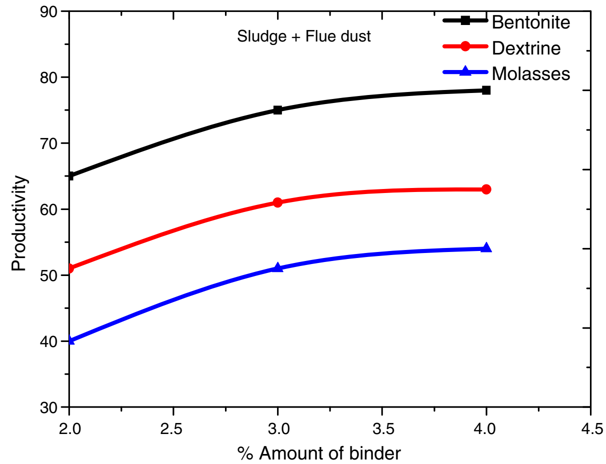

Fig. 5 – Effect of binders on productivity of machine.

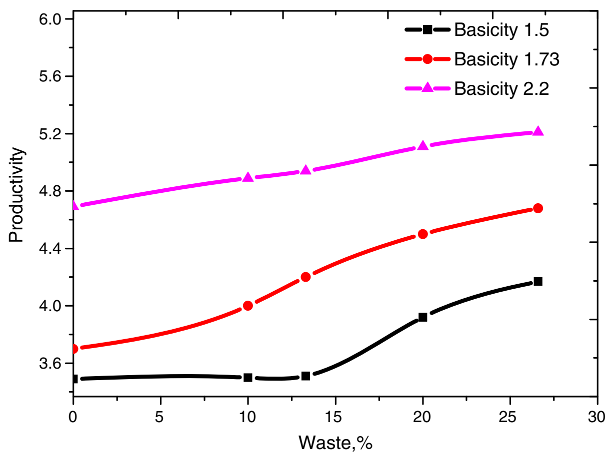

Fig. 6 – Effect of waste made pellets on productivity of sintering machine.

The optimum result was found in the case of 4 wt.% bentonite binder which imparts the maximum productivity (greater than 75) of the pelletizing machine in case of mixed pellets.

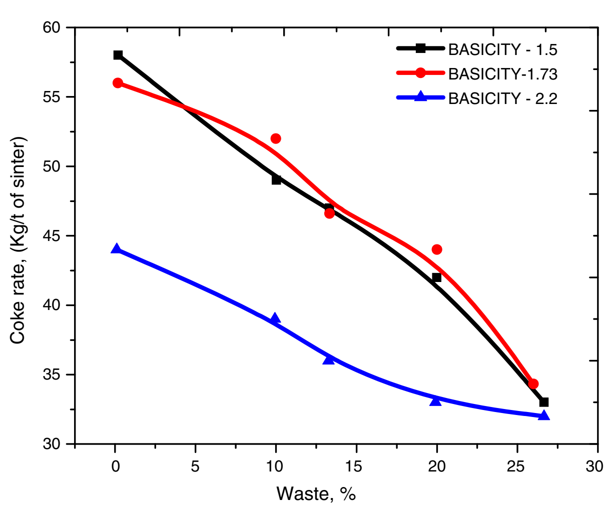

Fig. 7 – Waste addition effect on coke rate.

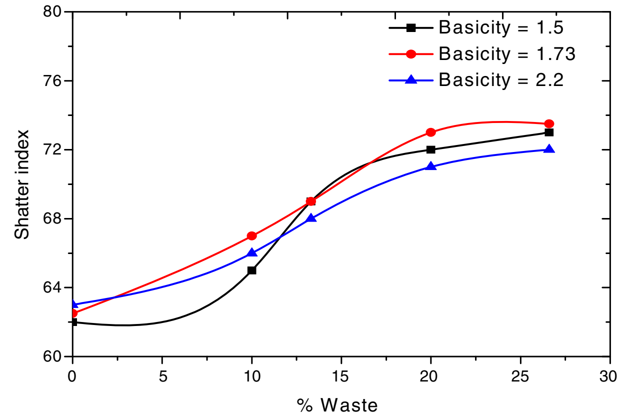

Fig. 8 – Effect of waste on Shatter index.

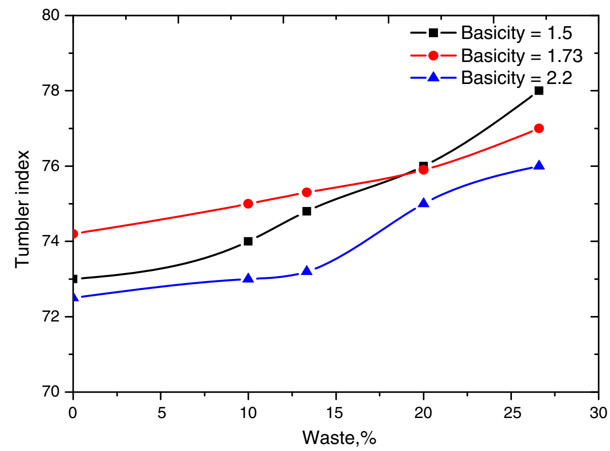

Fig. 9 – Effect of waste on Tumbler index.

3.3. *Influence of waste on productivity of the laboratory grade sintering machine*

Fig. 6 illustrates the waste addition behaviour on the productivity of the sinter machine. The productivity increases with waste addition up to 27–29% as well as with basicity. The maximum productivity was found 4.9 ton/m^2/day at basicity 2.2,

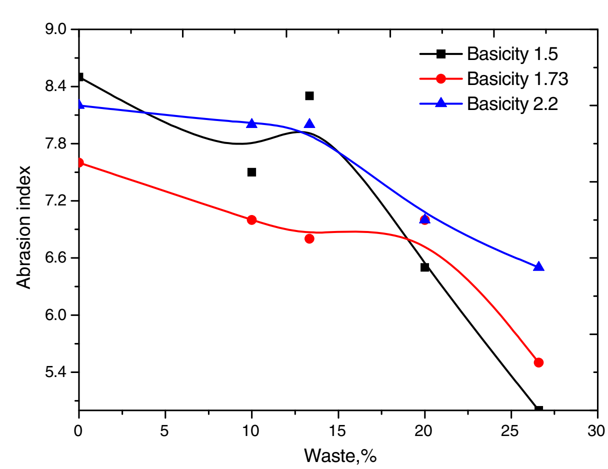

Fig. 10 – Effect of waste on abrasion index.

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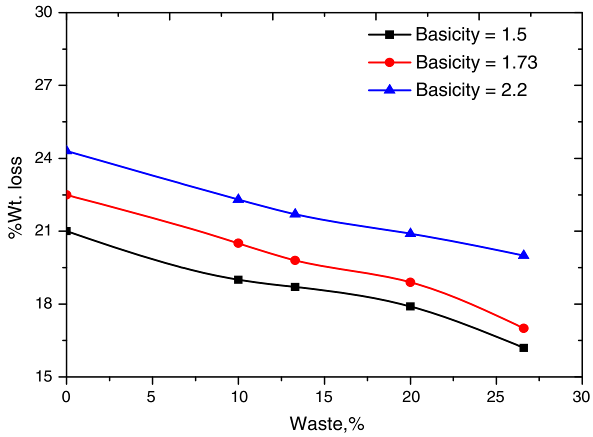

Fig. 11 – Effect of waste on reducibility of sinter.

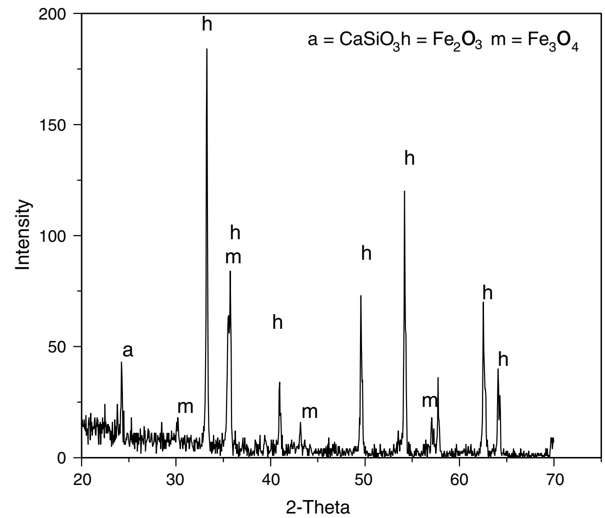

Fig. 13 – X-ray diffraction of iron ore sinter using blast furnace flue dust and sludge pellets.

whereas the productivity value reduced to 4.2 and 3.9 ton/hm^2 for the basicity of 1.73 and 1.5, respectively. A slight increment in productivity by basicity was due to waste pellets addition which provides the better permeability of the bed. At the same time, the presence of fixed carbon in micro pellets meets the heat requirement for all the endothermic reaction with externally added coke.

3.4. *Effect of pellets addition on coke rate*

Fig. 7 shows the effect of waste addition on coke rate, i.e. consumption of coke (kg) per ton of sinter. It is seen that coke rate decreases with an increase in waste addition. The waste contains fixed carbon in flue dust and sludge based pellets, which reduce the coke consumption during actual sintering. Whereas, the basicity of the sinter was varied in between 1.5 and 2.2 and maintained by lime addition.

Fig. 12 – Characterization of the pellets and the sintered product.

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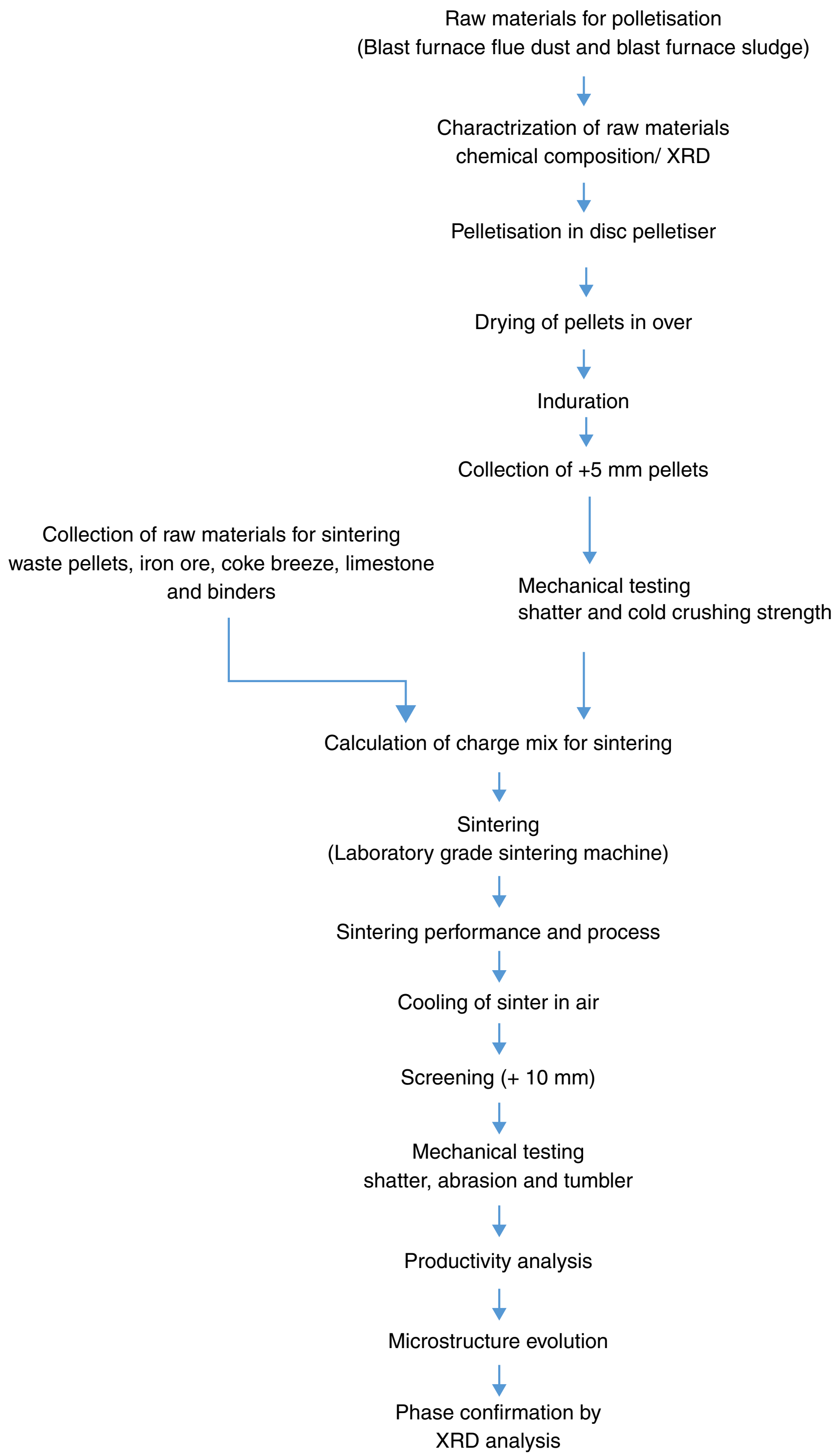

Fig. 14 – Flow sheet of recycling of blast furnace sludge and flue dust.

3.5. *Effect of percent waste on sintering strength*

Sinter strength results are shown in Figs. 8–10, which illustrate the shatter index, tumbler index and abrasion index values of the sinter respectively, as the waste made pellets percentage is increasing at the same time basicity also plays an important role, the strength is good in case of the intermediate value of the basicity, i.e. 1.73. At higher and lower basicity values the product becomes fragile in nature, whereas for intermediate one, it is optimized. The presence of fluxes as constituents (refer Tables 1 and 2) in waste material is responsible for increment in the strength.

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3.6. Reducibility behaviour of produced sinter on addition waste

Fig. 11 elaborates the effect of waste on the reducibility of sinters. It can be clearly analysed from the figure that more waste addition is degrading the reducibility or in other words, it just decreases the weight loss during the reduction process. This may be due to the fact that the magnetite (Fe_3O_4) phase, which is less reducible than hematite (Fe_2O_3), increases in the sinter mix with the increment in the waste. The sinter having the higher basicity will show the higher losses in weight, although the scenario of weight loss with percentage waste addition is same for every basicity values.

3.7. Characterization of the pellets and the sintered product

As seen from Fig. 12(a)–(c), photographs of pellets, hot sinter and cold sinter respectively. Whereas, Fig. 12(d) shows the microstructure of the sinter at 200 μm magnification. It can be clearly analysed that sinter consists of re-oxidized hematite (Fe_3O_4) and few magnetite (Fe_2O_3) phases with slag phase having calcium silicate ($CaSiO_3$) and calcium ferrite ($CaFe_2O_3$) which was also confirmed by the X-ray analysis as shown in Fig. 13.

4. Conclusions

The studies concluded that the agglomeration properties of the flue dust and sludge fines are more appropriate in combined form in comparison to individual of flue dust and sludge. The pellets having good strength were found in the case of mixed pellets (50% of each, flue dust and sludge) by using bentonite binder with very high productivity value as 75 of disc pelletizer. The most suitable pellets (5–8 mm) of wastes (blast furnace flue dust and sludge) are obtained with 4% bentonite binder, effectively used as one of the raw materials for sintering, which confirms the recirculation of wastes of plant efficiently utilized without deteriorating the quality of sinter. Use of wastes made pellets decreases the coke rate in sintering operation due to the presence of some fixed carbon in wastes (flue dust 9.60% and in sludge 12.34%). The productivity of the sintering machine is also increased with the increment in waste addition percentage. The maximum productivity is found as 5 ton/m^2/day at basicity 2.2 for nearly 27% waste addition to the charge mix. The strength of the sinter found up to the mark, but the only thing which is compromised is reducibility, although it is more important than the other properties, but at the same time waste was recycled so that it is manageable.

Conflicts of interest

The authors declare no conflicts of interest.

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