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The Effect of Additives and Reductants on the Strength of Reduced Iron Ore Pellet

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The higher strength of directly reduced iron (DRI) in pellet form is useful in handling, storing and charging from height without breakage. The DRI pellets commonly exhibit 60 kg cold crushing strength. In this work the effect of reduction temperature, sintering time, quantity/quality of additives and manner of reduction by solid reductant has been studied. The reduced pellet strength could be increased by improving metallic bonds by offering higher reduction temperature (max. 1 250°C) and subsequent sintering. The strength was found to increase by adding slag forming constituents *e.g.* bentonite. The strength of reductant mixed reduced pellet was observed to be affected by the nature of reductant. The reductant with low bulk density and lower carbon content provided higher voidage rendering lower strength. The cold crushing strength (CCS) of reduced pellets observed in this study ranged from 5 to 200 kg exhibiting ductile to brittle behaviour during deformation.

KEY WORDS: DRI; strength; ore-carbon pellet; bentonite; water hyacinth char.

1. Introduction

The increased world steel production is being met mainly by oxygen (BOF) and electric furnace (EAF) steel making as shown in **Fig. 1**.[1] Such practice requires enhanced production of DRI in the world which has exceeded 40 million tonnes.[2] The direct reduced iron (DRI) produced by various techniques finds its application mainly as feed material for EAF, however, certain amount of DRI can be used as coolant in LD converter[3,4] and as a metallic feed for blast furnace (BF).[5–8] While using DRI in any of these units certain physical strength is essential for safe handling by mechanical system consisting of bucket elevator, belt conveyor, magnetic cranes, charging chute/hopper and bin. The DRI is expected to sustain impact during handling, abrasion during movement and crushing strength during storage and burden feeding inside the furnace.

Tsujihata *et al.*[7] showed the changes in DRI strength values during reduction (**Fig. 2**) indicating that the oxide pellet lost strength from 200 to 30 kg during reduction and then strengthened upto 50 kg as a result of sintering and fusion. The cold crushing strength between 40–60 kg is common for reduced pellet made in coal/gas based reduction processes. Such strength value may be sufficient for using in EAF but may not be sufficient for use in LD and BF because the charging height in LD is higher than that into EAF. This strength requirement would be further more (~120 kg) if DRI were used in BF as metallised burden.

Meyer[9] has compiled previous studies and it was observed that the strength of the reduced pellet depends upon bonds between metallic and slag phases. These bonds are influenced by the rate of reduction which in turn is affected by the nature of ore and the used reductant. While using

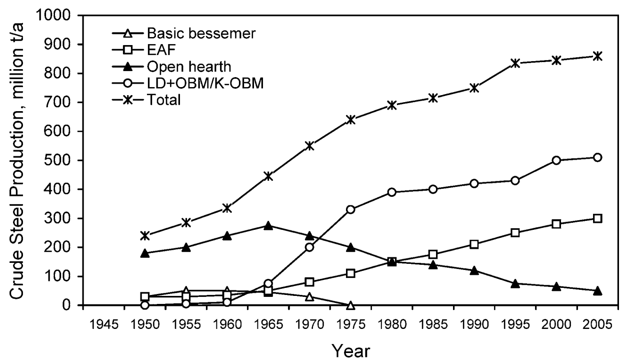


Fig. 1. World crude steel production using various steelmaking technologies.[1]

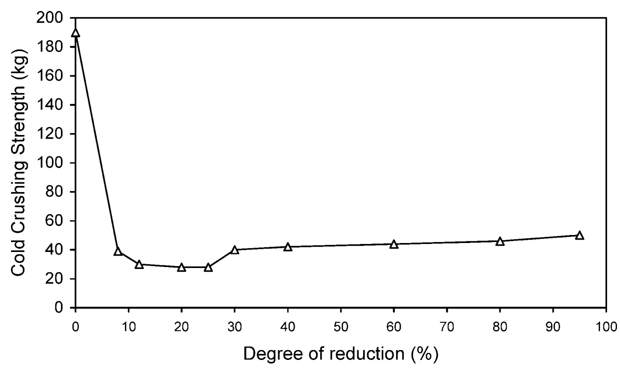


Fig. 2. Changes in pellet strength during reduction of iron ore.[7]

solid reducing agent, as practised in rotary kiln and rotary hearth furnace, the carbon reactivity and ash quality/quantity influence the strength of the reduced pellet. To prepare reduced pellet with sustainable strength it is necessary to know the influence of various parameters on strengthening mechanism, which has been investigated in this study.

2. Experimental

2.1. Raw Material

The iron ore and coke fines were obtained from Bihar state in India and screened to have –210 μm fraction for pelletisation. The composition of iron ore and properties of water hyacinth char (WHC) and coke fines are given in **Tables 1** and **2**, respectively. The bentonite having composition 90 mass% sodium montmorillonite $[(OH)_4Al_4Si_8O_{20}\cdot nH_2O]$ and 10 mass% quartz (SiO_2) with particle size less than 0.25 μm was used in this study.

2.2. Pellet Preparation

Two types of pellets were prepared as given in following sections. The details of each pellet and composition are given in **Table 3**.

Table 1. Chemical composition of iron ore (mass%).

Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO	LOI*	Average particle size (μm)
88.04	2.92	3.62	Trace	Trace	4.27	118

*LOI : Loss on ignition

2.2.1. Type P Pellets: Iron ore Pellets with and without Additive

In this type, the pellets of 15 mm size were hand rolled using 12 mass% moisture and various additives. Some of them contained WHC or coke as a reductant. The pellet without additives served as a reference pellet.

2.2.2. Type S Pellets: Iron Ore Pellets Mixed with Reductant (1 : 3 Molar Ratio)

In this type of pellets, the reductant was mixed in the molar ratio (Fe_2O_3 : C = 1 : 3) to render it as a self reducing pellet during heating. The coke fines and water hyacinth char (WHC) fines were added as a reductant. In the case using water hyacinth char, 66 mass% was required to maintain the given molar ratio due to its very low fixed carbon

Table 2. Properties of coke fines and water hyacinth char (WHC).

	COKE FINES	WATER HYACINTH CHAR (WHC)
VOLATILE MATTER (mass %)	13.62	22.69
MOISTURE (mass %)	1.48	5.59
ASH (mass %)	13.56	42.04
FIXED CARBON (mass %)	70.96	29.68
BULK DENSITY (kg/m^3)	745	233
TRUE SPECIFIC GRAVITY (kg/m^3)	1611	1078
AVERAGE PARTICLE SIZE (μm)	83	64

Table 3. Details of various unreduced pellets used in this study.

Code	Additive materials	Additive		Composition of unreduced pellet mass %				
		Reductant mass %	Bentonite mass %	Iron	Oxygen	Gangue	Carbon	LOI
PELLETS REDUCED IN COKE FINES BED (Type P)								
$P_{1\sim12}$	Without additive	–	–	64.4	27.6	6.54	–	1.46
PB1	Bentonite	–	1	63.76	27.3	7.46	–	1.44
PB2	Bentonite	–	2	63.13	27.05	8.37	–	1.43
PB3	Bentonite	–	3	62.52	26.79	9.27	–	1.41
PB4	Bentonite	–	4	61.92	26.53	10.13	–	1.40
PW5B1	Water hyacinth char and bentonite	5	1	60.75	26.03	9.09	1.39	2.70
PW5B4	Water hyacinth char and bentonite	5	4	59.08	25.32	11.50	1.35	2.63
PW5	Water hyacinth char	5	–	61.3	26.28	8.22	1.40	2.73
PC5	Coke fines	5	–	61.3	26.28	6.86	3.39	2.10
SELF REDUCED PELLETS (Type S)								
SC	Coke fines	30	–	49.90	21.38	8.13	16.03	5.86
SW	Water hyacinth char	66	–	38.62	16.55	20.74	11.81	12.18

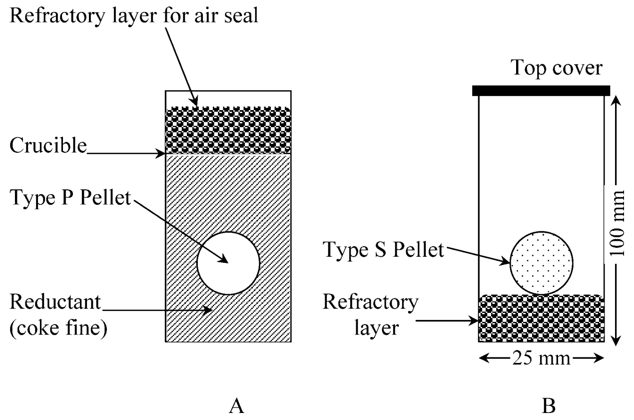


Fig. 3. Arrangement of setting pellets for reduction.

content (30 mass%). Whereas adding 30 mass% was required in the case using coke fines whose carbon content (70 mass%) was higher. Such pellets were hand rolled using 15 mass% moisture without adding any binding agent.

The green pellets of both type P & S (size 15 mm) thus made were dried in air before keeping in drying oven (110°C) for 5 h to remove all the free moisture. The pellets were weighed and their dimensions were recorded to be stored separately in glass bottles with distinct identification codes.

2.3. Pellet Reduction

2.3.1. Type P Pellets

The arrangement of setting pellets in the crucibles is shown in **Fig. 3**(A). The pellets type P were embedded in a bed of coke fines as a reductant held in iron crucibles having 25 mm dia. and 100 mm height. The crucible top was packed with a layer of refractory powder to act as air seal. The numbered crucibles holding pellets of type P were kept in a silicon carbide furnace (length 450, height 350, width 360 mm) and heated gradually to 1 250°C with a heating rate of 0.075 K/s (4.5°C/min) causing reduction. The crucibles were withdrawn at given reduction temperature with given sintering time and kept in air to be cooled. The reduced pellets were taken out from crucible when they were cool enough to avoid oxidation and weighed.

2.3.2. Type S Pellets

The types S pellets had carbon acting as a reductant in-situ . They were kept in iron crucibles over a layer of refractory particles to avoid pellet contacting with iron crucible. The crucibles were closed with loose lid to avoid infiltration of air into crucibles. This arrangement is shown in **Fig. 3**(B). These crucibles were set in a muffle furnace and heated at the rate of 4.5°C/min until 1 250°C. The crucibles were taken out from the furnace after heating at desired temperature and sintering time to be cooled in air. The reduced and cooled pellets were weighed.

The P-type pellet reduced in the bed of coke fines can demonstrate the condition of rotary kiln DRI units using pellets as feed. The S-type carbon mixed self reducing pellets, can simulate the condition in rotary hearth furnace (RHF) to make DRI. The observations made in this study could be useful in developing high strength reduced pellets exploiting rotary kilns or RHF units.

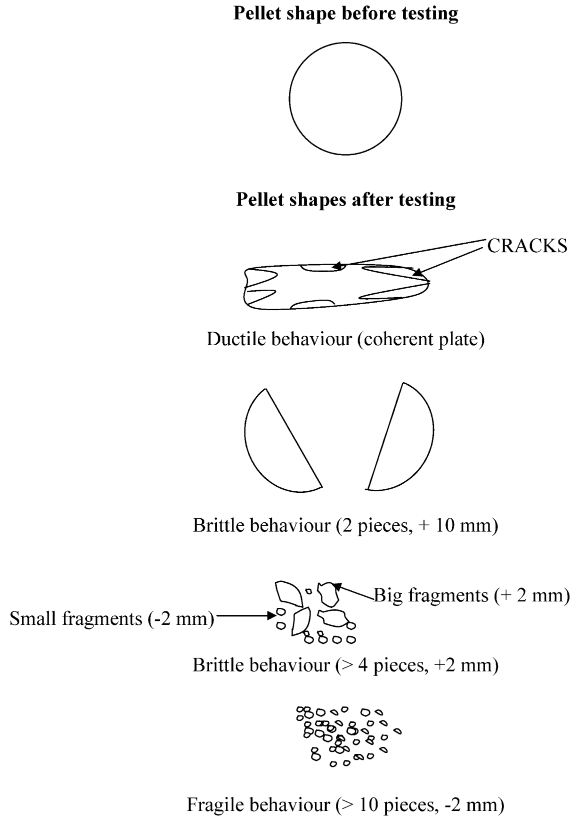


Fig. 4. Schematic shapes of reduced pellet before and after CCS test.

2.4. Cold Crushing Strength (CCS) of Reduced Pellet

The cold crushing strength (CCS) of the reduced pellets were tested at room temperature using a universal testing machine with 3 ton capacity with graduations having 1 kg least count. The pellet was loaded slowly till it yielded. The minimum load required for breakage/deformation of the pellet was recorded as cold crushing strength (CCS) in kg. During CCS test the pellet exhibited two types of breaking behaviour. In some cases the pellets did not disintegrate into pieces but remained coherent as a plate with many cracks on the edges. This behaviour was described as "ductile" behaviour in this work. In other cases the pellet disintigrated into number of big (>2 mm) and small (<2 mm) fragments. This breaking behaviour has been termed as "brittle". The number of bigger (>2 mm size) fragments after crushing test was counted. In weak and "fragile" pellets the fragments obtained after testing were small in size (<2 mm) and difficult to count. These are schematically shown in **Fig. 4**.

3. Results and Discussion

In this study an effort was made to understand strengthening mechanism of reduced pellets affected by various parameters such as reduction temperature, soaking time, additives, nature of carbon and method of providing reductant. The results of this study are summarised in **Table 4**.

The reduction mechanism of iron ore by carbon has been studied by many workers.[10–15] It has been established that in solid reductant based processes using coal, coke, graphite, woodchar *etc.* the gasification of solid carbon is

Table 4. Strength values of various pellets tested after reduction.

Code	Unreduced pellet constituents, mass %				Reduction temperature °C	Sintering time, min	CCS kg	Fracture behaviour	
	O	C	WHC	B				Nature	No. of pieces
P_1	100	-	-	-	900	0	0	Fragile	> 10
P_2	100	-	-	-	950	0	2	Brittle	> 8
P_3	100	-	-	-	1000	0	3	Brittle	> 6
P_4	100	-	-	-	1050	0	4	Brittle	> 6
P_5	100	-	-	-	1100	0	4	Brittle	> 6
P_6	100	-	-	-	1150	0	6	Ductile	> 1
P_7	100	-	-	-	1200	0	20	Ductile	01
P_8	100	-	-	-	1200	5	23	Ductile	01
P_9	100	-	-	-	1200	10	35	Ductile	01
P_{10}	100	-	-	-	1200	15	39	Ductile	> 2
P_{11}	100	-	-	-	1200	20	55	Brittle	> 2
P_{12}	100	-	-	-	1250	0	30	Ductile	01
PB_1	99	-	-	1	1250	0	55	Brittle	> 5
PB_2	98	-	-	2	1250	0	110	Brittle	> 3
PB_3	97	-	-	3	1250	0	180	Brittle	> 3
PB_4	96	-	-	4	1250	0	200	Brittle	> 2
PC_5	95	5	-	-	1250	0	70	Brittle	> 3
PW_5	95	-	5	-	1250	0	5	Fragile	> 10
PW_5B_1	94	-	5	1	1250	0	60	Ductile	1
PW_5B_4	91	-	5	4	1250	0	85	Ductile	2
SW_1	34	-	66	-	1250	0	6	Ductile	1
SW_2	34	-	66	-	1250	10	10	Ductile	1
SW_3	34	-	66	-	1250	20	25	Ductile	1
SC_1	70	30	-	-	1250	0	15	Brittle	> 2
SC_2	70	30	-	-	1250	10	25	Brittle	> 2
SC_3	70	30	-	-	1250	20	30	Brittle	> 2

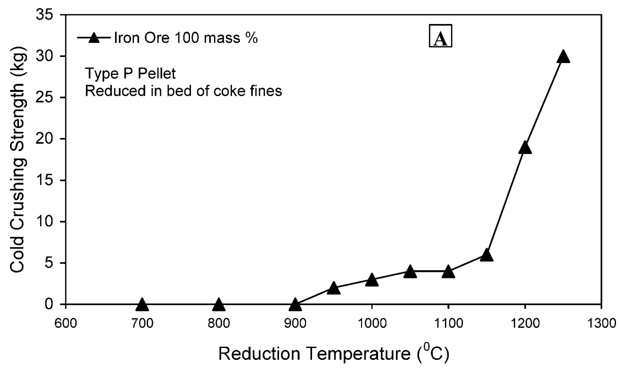
O – Iron Ore, C – Coke Fines, WHC – Water Hyacinth Char, B - Bentonite

the rate controlling parameter for reduction of iron oxide present in pellet or lump form. The higher temperature below fusion, larger reaction sites by increasing porosity/surface area, lower impurities by keeping lower gangue content *etc.* are known to be favourable factors for reduction process.

In the unreduced ore pellet the strengthening during heating is due to bonding of hematite crystals as a result of mutual diffusion or slag bonding. Such bonds get broken during reduction process and replaced by metallic bonds. The change in mechanical strength[7] during reduction process was previously shown in Fig. 2 where 50 kg strength could be noted for reduced pellet in a typical case. The DRI strength could be increased by enhanced metallic bonding or slag bonding. The higher temperature and sintering time would increase the bond strength due to enhanced fusion zone whereas higher metallic iron and gangue constituents would promote more strength due to increased bond contact area. These features have been observed in this study.

3.1. Effect of Reduction Temperature and Time on DRI Strength

The iron ore pellet without additive (Pellet type P) was reduced in the bed of coke fines at different temperatures (700–1 250°C). **Figure 5**(A) shows the result of CCS test, representing strengthening of reduced pellets due to fusion starting at 950°C and rapid increase of strength above 1 150°C. The iron ore pellet reduced at 1 250°C was found



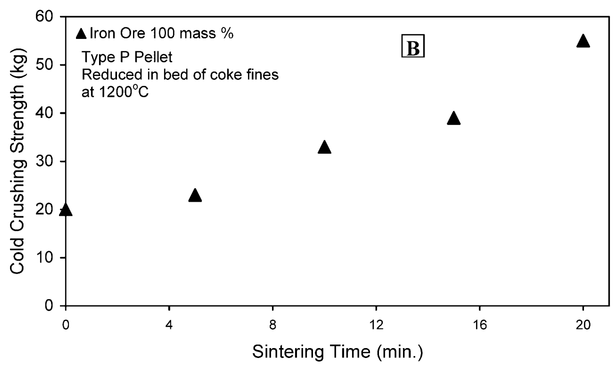


Fig. 5. Effect of reduction temperature (A) and sintering time (B) on the strength of reduced iron ore pellet.

to have 30 kg strength at room temperature. The increased strength was due to metallic bonding as evidenced by ductile behaviour of reduced pellet during crushing strength (see P12 in Table 4).

Figure 5(B) shows the result of CCS test of the pellets reduced by heating up to 1 200°C were subsequently sintered for increased time (5–20 min). The strength of the reduced pellets was increased up to 55 kg by sintering at 1 200°C for 20 min.

All these pellets which had exhibited ductile behaviour without sintering showed increasing brittle tendency (P_7–P_{11}) after sintering. This could be due to fusion of metallic iron and gangue both with increasing sintering time.

3.2. Effect of Additives on DRI Strength

Generally while making oxide pellets, bentonite is added for increasing the strength of green, dry and fired pellet. The addition of carbonaceous materials (*e.g.* coal, coke *etc.*) in oxide pellet is made as well to save heat energy during firing and it has been reported[16,17] to provide increased strength in oxide pellet. In this study the effect of adding bentonite (1–4 mass%) with and without carbonaceous material (5 mass%) on CCS value of reduced iron ore pellet was observed.

3.2.1. Bentonite Addition

The iron ore pellets (P-type) with bentonite (1–4 mass%) was reduced in a bed of coke fines at 1 250°C without subjecting extra sintering time (P_{12}, PB_1–PB_4). The effect of bentonite addition with and without carbonaceous material (WHC) on CCS values is shown in **Fig. 6**. It could be observed that increased addition of bentonite offers more strength to DRI due to increased slag bond. This slag bonding nature is exhibited in fracture (brittle) behaviour during CCS test. The increased slag bond with increased bentonite (1 to 4 mass%) is supported by the fact that number of fragmented pieces after CCS test has been reduced from five pieces to only two pieces. It may be noted that DRI with 200 kg strength could be obtained with addition of 4 mass% bentonite. However, excess addition of bentonite may not be useful in practice due to added gangue content in DRI.

3.2.2. Addition of Carbonaceous Materials

The iron ore pellets with coke fine and water hyacinth char (5 mass%) were reduced in a bed of coke fine at 1 250°C without extra sintering time. The strength of pellet with 5 mass% coke fines exhibited 70 kg strength with brittle type fracture giving more than three pieces (PC_5). The pellet with 5 mass% water hyacinth char (PW_5) gave only 5 kg strength giving many pieces (>10) (Table 4).

The addition of coke fines (5 mass%) provided more strength (PC_5, 70 kg) in comparison to pellet without coke-fine addition (P_{12}, 30 kg). This may be due to added ash of coke fines rendering more slag bond. The addition of water hyacinth char (5 mass%) gave very low strength (PW_5, 5 kg) which may be due to large voids due to low bulk density (233 kg/m^3) of the water hyacinth char. The addition of bentonite in pellets with 5 mass% water hyacinth helped in providing more strength (PW_5B_1, 60 kg with 1 mass% and PW_5B_4, 85 kg with 4 mass% bentonite) which is shown in Fig. 6. The lower strength values of pellets having water hyacinth char could be due to more voidage in reduced pellet. This higher voidage could also be due to longer fibers formed by rapid reduction caused by faster conversion of CO_2 (reaction product) to CO by the presence of very active carbon (water hyacinth char) *in situ*.

3.2.3. Effect of Total Gangue Content on DRI Strength

As we have mentioned earlier that the total gangue quantity and its quality affects the slag bond and DRI strength. The various mineral constituents in iron ore, ash in carbonaceous materials and bentonite added while pellet making constitute total gangue. When CCS values were plotted against total gangue content (**Fig. 7**) it was found that strength values were increased with total gangue content due to increased slag bonds. However, pellets having WHC had lower strength due to high voidage created by WHC, a material with lower bulk density.

3.3. Effect of Reduction Method on DRI Strength

The iron ore could be reduced by keeping its pellet in a bed of reductant (coke fines) as practiced in P-type pellets. Alternately the iron oxide gets reduced to iron (S-type pellets) by carbon available *in situ* when iron ore mixed with carbonaceous material in molar ratio (Fe_2O_3 : C = 1 : 3) was heated in absence of air.

It was noted that 30 kg strength was obtained in iron ore pellet (P_{12}) reduced at 1 250°C in a bed of coke fines (Fig. 5(A)). In contrast, S type pellets containing coke fines (SC_1) and WHC (SW_1) resulted in only 15 kg and 6 kg strength, respectively at the identical reduction temperature. The lower strength values in S-type pellets could be attributed to large voidage provided by the use of carbonaceous

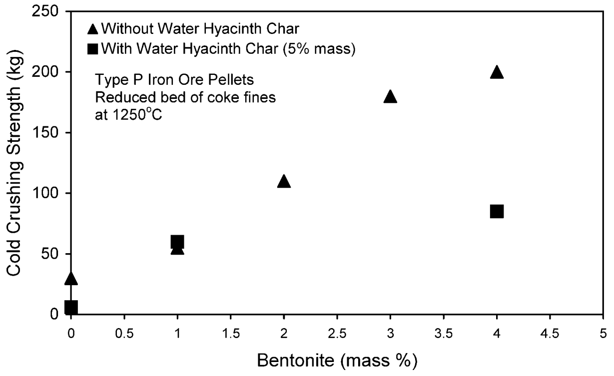


Fig. 6. Effect of bentonite addition with 5 mass% and without Water Hyacinth Char on the strength of reduced iron ore pellet.

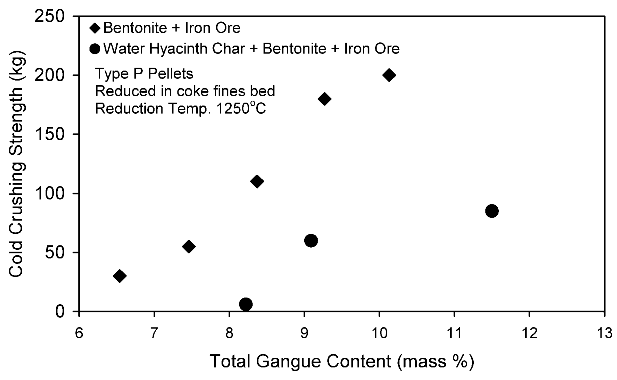


Fig. 7. Effect of total gangue content on the strength of reduced iron ore pellets.

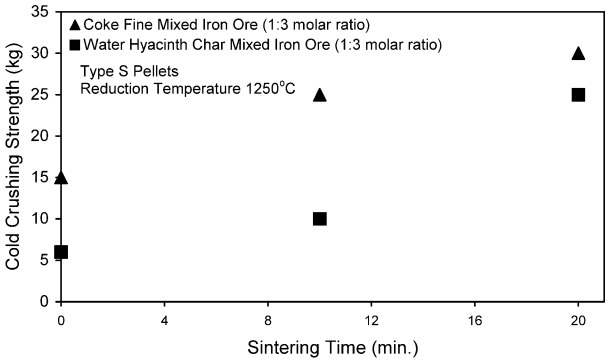


Fig. 8. Effect of sintering time on the strength of reduced iron ore pellet mixed with reductant in molar ratio and reduced at 1 250°C.

material in larger mass proportions (30 mass% coke fines and 66 mass% WHC). Those proportions were necessary to provide sufficient carbon to cause reduction. On the other hand the ash incorporated with coke fines and WHC is expected to provide strength along with fusion of metallic iron. **Figure 8** shows that the increased sintering time helped in gaining strength, and strength reached 30 kg and 25 kg in the case using coke fine and WHC respectively after sintering for 20 min.

4. Conclusions

(1) The strength of the reduced iron ore pellet could be controlled by reduction temperature, sintering time, additive quality/quantity and manner of reduction.

(2) The reduced pellet with strength upto 200 kg was possible with 4 mass% addition of bentonite.

(3) The strength of the reduced pellet could be improved by increasing metallic bonds due to higher reduction temperature and subsequent sintering, and slag bonds due to increased slag forming additives.

(4) The strength of the reductant mixed reduced pellet was also affected by the nature of reductant. The reductant with low bulk density and lower carbon content provided higher voidage rendering lower strength.

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