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Proposal for Development of a Graphite Plant

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Abstract. The design of a commercial graphite processing plant is described on the basis of results of beneficiation of a graphite deposit originating from the Malakand area of North Western Frontier Province (NWFP) of Pakistan. The test work was carried out on the bench scale followed by trials on the pilot plant to define all process parameters necessary for the production of graphite concentrate. The Malakand ore containing about 10-16% graphitic carbon was upgraded by froth flotation technique. It is important to note that regrinding of the rougher concentrate followed by three cleanings of rougher concentrate and recirculating the cleaner tailings to the rougher flotation circuit ensured a final concentrate grade of 83-85%, @ > 70% recovery. The pilot scale flotation tests were carried out @ 75-100 kg of ore per h and 7.5-10.0 kg graphite concentrate were produced per batch. Based on these tests, a commercial plant to handle 50 tons of ore per day (8 h shift) has been proposed. The proposed plant costing Rs.26.89 million will daily produce about 5 tons of graphite concentrate. Graphite concentrate, produced @ Rs.10.95 per kg on the proposed processing plant, will be considerably cheaper.

Keywords: graphite concentrate, froth flotation, graphite processing plant

Introduction

Graphite is used in various industries depending upon its grade. For example, according to Khan *et al.* (2004) and Kalyoncu (2001), the pencil industry imports graphite with a grade of above 90% graphitic carbon. Graphite is then mixed with bentonite in varying proportions to get pencils of different hardness. In the crucible industry also, high grade graphite is used but here more important factor is the size of the flake. Generally a flake of 60-80 mesh is considered to be good enough to give a good crucible. For the nuclear industry, graphite of ultra pure quality is essential (Bhima and Patnaik, 2004); a product with a grade of 99.99% graphitic carbon is desired with a limit on such elements as boron etc. Foundry industry is also one of the most important consumers of graphite (Anwar *et al.*, 2006; Gordon, 1995).

Graphite deposits have been discovered at several places in Pakistan. Ahmed and Siddiqi (1993) reported that the most extensive deposits of low graphite ore, containing 10-16% graphitic carbon, have been found in the Malakand, Kel Tarli Domel, Tirah, Parachinar and Besham. Hand (1997) says that this grade is sufficient to exploit the ore on commercial scale for producing graphite concentrate. According to Bhatti *et al.* (2006), Pakistan is importing at present, all its requirements based on graphite concentrate of foundry grade.

An indigenous graphite ore (Malakand, North Western Frontier Province) was processed and flotation parameters were optimized in our laboratory at pilot plant scale to produce graphite concentrate containing 80-85% graphite carbon content with more than 70% recovery. This paper presents a proposal for development of a graphite plant at mine site on the basis of results of beneficiation of the said graphite ore.

Mineralogy and X-ray diffraction studies. The characteristics of Malakand ore were defined by petrography, X-ray diffraction, ore microscopy and by observation in stereomicroscope. X-ray diffraction studies were carried out on Diffractometer D-5000 (Siemens, Germany) to identify different types of minerals present in the ore. Malakand graphite ore is fine grained graphite-mica schist. The gangue mostly comprised of clays with hydrated oxides of iron and predominant quantities of silica and mica. Liberation of graphite particles was determined to be 84% particles passing through 73 microns mesh.

Materials and Methods

Sample preparation. Representative samples of Malakand ore were selected for chemical analysis. Table 1 indicates complete chemical analysis of the ore. Flotation feeds were prepared by subjecting the ore samples to primary and secondary crushing. The lumps of ore, $\leq$ 125 mm in size, were crushed in a jaw crusher of 150 mm x 375 mm size then passed through the crushing rolls of 225 mm (dia) x 150 mm (face) in size. The product was then ground wet in a rod mill (178 x 356 mm) at 1:1 solid/liquid ratio for 6 min to have a flotation feed of 84% passing 73 microns.

Flotation test. The flotation tests were carried out in a Denver D-12 flotation machine under different conditions to optimize

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Table 1. Chemical analysis of Malakand ore

Constituents	Percentage
Graphitic carbon	16.94
Amorphous carbon	3.60
SiO_2	50.81
Fe_2O_3	8.77
Al_2O_3	13.07
CaO	3.38
MgO	0.85
Na_2O	0.18
K_2O	0.82
Other losses (calcite, goethite, limonite)	1.57

various variables. The rougher concentrate obtained was subjected to three stages of cleaning. The first cleaning was carried out at a pulp density of 14-16% without addition of any flotation reagents. This cleaner concentrate was recleaned at a pulp density of 9-10% solids followed by further cleaning of recleaned concentrate at a pulp density of 5-6% solids. Once again, no flotation reagents were used.

Pilot scale test result. A batch ball mill was used to prepare feeds for the pilot scale flotation tests. The mill was of 1220 x 1524 mm size and worked at a speed of 30 rpm. Flotation of the ore was undertaken on the basis of one ton per 8 h. Three flotation machines of 0.5 m^3 size were used for roughing operation. Each machine had a capacity of treating 100 kg of ore per test. One ton Malakand ore yielded 100 kg of graphite concentrate per day (8 h shift) with an energy consumption of 48 kW.

Processing plant. Study on the beneficiation of graphite was carried out on 15-16 tons of graphite ore of Malakand. The metallurgical data generated at the laboratory and pilot plant tests provided the basis for the proposed processing plant with a 50 tons per day (8 h shift) ore treatment capacity. The pilot scale tests were undertaken using the available equipment, after making adjustments for matching capacities.

Production economics. Cost of processing of 50 ton of graphite ore to produce 5 ton of graphite concentrate (80-85% graphitic carbon) per day (8 h shift) at mine site may be calculated as follow:

	Rs. (million)
A. Fixed Capital Cost	
1. Equipment cost (Table 5)	10.500
2. Installation and other expenses like piping, spares, freight, custom duty, import license fee, insurance, internal transport etc. @30% of A1	3.150
3. Civil work (Table 6)	6.140
4. Laboratory set up @15% of A1	1.575
5. Furniture, fixture and office equipment @5% of A1	0.525
6. Maintenance workshop equipment	0.110
Total:	**22.000**
B. Direct Production Cost	
1. Manpower (Table 7)	2.820
2. Raw material (Ore @ Rs.200/t+ reagents @Rs.50/t)	3.075
3. Energy and utilities (Table 8)	4.530
4. Packing @Rs.5/bag	0.150
Total:	**10.575**
C. Indirect Production Cost	
1. Depreciation	
-Process equipment @10% of (A.1+A.2)	1.365
-Office equipment, furniture and fixture @ 20% of (A.4 +A.5+A.6)	0.442
-Building @ 5% of A.3	0.307
2. Insurance premium @2% of A	0.440
3. Contingencies @ 15% of A	3.300
Total:	**5.854**
D. Total Production Cost (B + C) @1500t or 1,500,000 kg per annum (or) Production cost Rs.10.95 per kg	**16.429**
E. Sales Revenues Graphite concentrate @Rs.20/kg (x 1500000 kg)	**30.000**
F. Income [(Sales revenues) - (Total production cost + 14% interest on 50% of working capital)] assuming a tax holiday of 5 years [30.00 - (16.429 + 0.34261)]	**13.22839**
G. Working Capital	
1. Raw materials (one month's stock)	0.256250
2. Product inventory (one month's manufacturing cost)	1.319083
3. Available cash (as in G.2)	1.319083
4. Extended credit (one month's sale)	2.000000
Total:	**4.894416**
H. Capital Investment [A + G] = [Fixed capital cost + working capital]	26.894416 ≅ 26.89
I. Pay off period [H/F] = [Capital investment/Income]	2.03 years

Results and Discussion

The grade (graphitic carbon=16.94%) of Malakand ore presented in Table 1, seems to be sufficient to exploit the ore on commercial scale for producing the graphite concentrate despite presence of other impurities (Bhima and Patnaik, 2004; Hand, 1997). The X-ray analysis (Table 2) confirms the presence of crystalline graphite, amorphous carbon and signifi-

Table 2. X-Ray diffraction analysis of ore

2θ	d	I/I_o
18.143	4.8865	6.55
21.188	4.1907	5.09
24.298	3.6609	2.39
26.905	3.3118	100.00
36.361	2.4693	2.09
36.870	2.4363	3.52
40.608	2.2203	1.51
42.773	2.1128	1.84
45.802	1.9799	6.66
50.451	1.8078	2.86
54.984	1.6690	3.58
60.251	1.5351	1.98

Table 3. Metallurgical balance for graphite flotation

Product	Wt (%)	Grade (%)	Recovery (%)
III Cleaner concentrate	14.80	84.0	74.09
III Cleaner tailings	4.40	14.18	3.72
(II Cleaner concentrate)	(19.20)	(68.00)	(77.81)
II Cleaner tailings	7.76	15.57	7.2
(I Cleaner concentrate)	(26.96)	(52.91)	(85.01)
I Cleaner tailings	23.04	7.97	10.94
(Rougher concentrate)	(50.00)	(32.20)	(95.95)
Rougher tailings	50.00	1.35	4.02
Calculated head sample	100.00	16.78	100.00

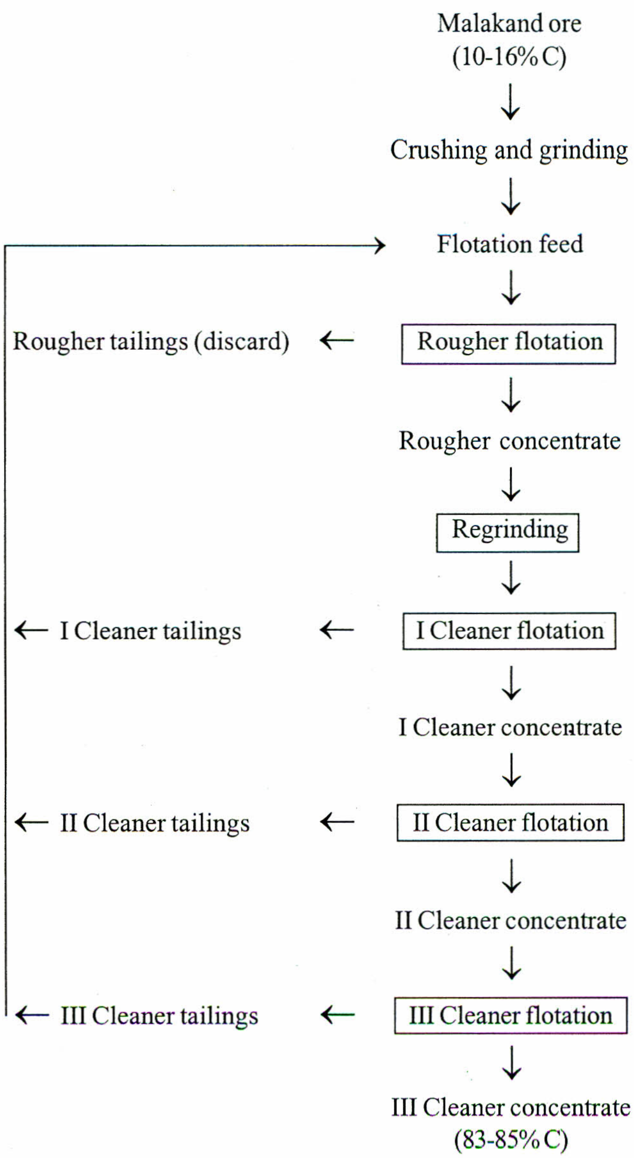

Fig.1. Beneficiation of graphite : Flowsheet.

cant amount of quartz as orthoclase. Weak mica and goethite/hematite and calcite are indicated in the diffraction results of the sample. It is also clear from X-ray analysis that the Malakand ore contains crystalline graphite, so flotation can be considered proper route for its beneficiation (Kalyoncu, 2001). The X-ray diffraction results were verified by JCP.CAT programme provided with the X-ray diffractometer D-5000 (Siemens, Germany). This programme contains D/I values of about 60,000 standards for material evaluation (Mannan *et al.*, 2006). The description of metallurgical balance, presented in Table 3, indicates that Malakand ore can be upgraded to 32.2% at rougher flotation stage @95.95% recovery. This recovery has been obtained, as per other details mentioned in Table 4, at a feed size of 84.81% passing through 73 microns mesh. It is important to note (Fig. 1) that regrinding of the rougher concentrate followed by three cleanings of rougher concentrate and recirculating the cleaner tailings to the rougher flotation circuit ensured the final grade and recovery. The better result at 33% solids (Table 4) is due to fine grain nature of Malakand ore since for flaky ores low pulp densities are recommended (Hand, 1997; Hussain *et al.*, 1967). Alkaline bath flotation also gave better result (Liu and Yuyan, 2003). It may be pointed out that froth flotation is adopted as an easy method for beneficiation of graphite due to its natural hydrophobic behaviour (Ahmed and Siddiqi, 1993). Despite the natural floatability, flotation selectivity is improved by addition of a small amount of kerosene oil and pine oil (Crossley and Peter, 1999). Separation of gangue from ore mineral requires effective treatment. Sodium silicate fulfills the purpose as it efficiently depresses the quartz and silicates (Bhatti *et al.*, 2006).

Based on R&D work on Malakand ore, the proposal for development of a graphite plant has been made. The cost of the equipment for processing 50 tons of ore per day, Rs.10.5 million, has been estimated (Table 5) after consulting different companies (Kurimoto, 2004; Nelson, 2004; Savona, 2004). The cost of civil work (Rs.6.14 million) presented in Table 6, has been calculated @ Rs.0.00614 million per square meter after investigating current civil construction rates. The manpower (nine skilled and twenty one unskilled persons) as per details given in Table 7, required to run such a plant would be hired @ Rs.2.82 million per annum. The salaries proposed in Table 7 have been made slightly attractive for both skilled and unskilled persons. Expenditure on energy and utilities (Rs.4.53 million per annum) given in Table 8 has been calculated at commercial rates. The proposed plant at mine site costing Rs.26.89 million has the capacity to treat 50 tons ore per day to produce 5 t/d graphite concentrate of 80-85% grade at the production cost of Rs.10.95/kg. In the local market the graphite concentrate is available @ Rs.24/kg. If the price of the concentrate, produced on the proposed plant (Rs.10.95/kg) is compared to the market price of concentrate mentioned above, the use of concentrate (containing more than 80% graphitic carbon) as raw material for production of graphite of higher grade as well as of value added products seems feasible.

Table 4. Optimum parameters of graphite flotation

Parameter	Optimum value
Feed size	84.81 % passing 73 μm
Pulp pH	7.5
Pulp density	33% solids
Collector (Kerosene oil)	2.2 kg/ton
Depressant (Sodium Silicate)	0.14 kg/ton
Frother (Pine oil)	0.02 kg/ton
Conditioning time	3 min
Flotation time	11min
Impeller speed	1200 rpm

Table 5. Equipment cost for proposed plant

Item	Cost Rs. (million)
Apron feeder 0.6 m x 5m	0.30
Jaw crusher 0.3 x 0.6 m	0.50
Cone crusher 15 ton/h capacity	1.40
Vibrating screen 5665mm x2360mm	0.10
Bins 3.2m x 4m	0.50
Belt conveyors 0.5m x 9m	0.15
Vibrating feeder 300mm x 120mm	0.60
Ball mill 1.2 m x1.8 m with Classifier/Cyclone	2.20
Flotation cells 0.3 m^3, 22 No.	1.35
Regrinding mill 0.6m x 0.9m	1.00
Thickener 5.8m x 3.9m	0.20
Filter (drum), filtration area 3.8 m^2	1.00
Dryer x 2 (Tray) 8m^3	0.90
Pipes, pumps, spares etc.	0.30
	Total: **Rs.10.50** million

Table 6. Civil work for proposed plant

Shed #	Civil work	Space m^2	Cost Rs.(million)/m^2
1.	Crushing & Grinding Section	300	1.842
2.	Flotation Section	150	0.921
3.	Thickening & Filtration Sections	100	0.614
4.	Drying Section	60	0.3684
5.	Storage, Weighing & Packing Sections	320	1.9648
6.	Laboratory & Office	70	0.4298
			Total: **Rs.6.14** million/1000 m^2

Table 7. Manpower required for proposed plant

Skilled person	Salary Rs.(million)/ month	Unskilled person	Salary Rs.(million)/ month
Plant Manager	0.040	Accountant	0.006
Mill Superintendent	0.025	Typist	0.005
Mechanical Engineer	0.020	Store Keeper	0.005
Electrical Engineer	0.020	Watch Man x 2	0.007
Chemist/Chemical Engineer	0.015	Operator (Shed 1) x 4	0.014
Foreman Workshop	0.012	Operator (Shed 2) x 6	0.021
Incharge Laboratory	0.010	Operator (Shed 3) x 2	0.007
Laboratory Technician	0.008	Operator (Shed 4) x 2	0.007
Laboratory Assistant	0.006	Attendant x 2	0.007
			Total: **Rs.0.235** million/month or Rs.2.82 million/annum

Table 8. Cost of energy and utilities for proposed plant

Item	Unit operation	Consumption /month	Rate	Cost Rs.(million)/ annum
Electricity	Processing (50t/d Ore)	1200 kWh	Rs. 5.0/ kWh	3.60
Water	Processing (50t/d Ore)	20000 gallon	Rs.0.015/gallon	0.18
Gas	Drying (5t/d Concentrate)	75.7576 hm^3	Rs.165/hm^3	0.75
				Total: **Rs.4.53** million/annum

Conclusion

The research and developmental work established that the Malakand ore could be beneficiated to the desired grade assaying more than 80% graphitic carbon content at a recovery rate of 70-75%. This concentrate was found to be quite suitable for the production of graphite-based products. Thus, a graphite processing plant with the ore treatment capacity of 50 t/d (8 h shift) has been proposed. The graphite concentrate produced on this plant costs Rs.10.95/kg. The production of graphite concentrate is quite feasible as no indigenous raw material is readily available in Pakistan for the production of graphite based products. Moreover, the processing cost of graphite ore is much economical as compared to imported graphite concentrate (Anwar *et al.,* 2006).

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