BENEFICIATION OF WEST AFRICAN IRON ORES: PRODUCT CLASSIFICATION BASED ON CHEMICAL DATABASE AND PROCESS TEST WORK

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ABSTRACT

ArcelorMittal Liberian deposits are situated in the North of Nimba region, in the North East of Liberia. Only one deposit is nowadays exploited to produce a DSO product (Direct Shipping Ore). The exploitation of other deposits in the area is yet to be defined, but it is expected in a near future. The Liberian iron ore is amenable to produce several types of final products, such as DSO, sinter feed and fine concentrate. In order to evaluate the resources of a deposit, proportion and quality of each material, geometallurgical approaches should be used to help optimizing the mine planning. Estimation of final product is performed on representative samples by applying beneficiation tests at laboratory scale. The main objective is to perform a simplify laboratory technique in order to simulate their behavior when submitted to a beneficiation plant. Samples are then classified along their response to beneficiation testing; this is the process classification. Concerning the untested drill cores and deposits, another classification was created based on samples' chemical quality and geological situation within the deposit. The aim was first to establish a classification of final products that could be directly applied without any metallurgical testing, and secondly, to warrant and to validate this new classification using the process classification as a reference. After several improvements and adjustments, the chemical classification proved to be accurate about 85% in comparison with the process classification. It allows specifying the final product (on quality and quantity) without any further metallurgical tests and hence, to reduce the samples that have to be tested or to target these tests.

KEYWORDS: West Africa; iron ores; geometallurgy; beneficiation; chemical quality.

RESUMO

Os depósitos da ArcelorMittal Libéria estão localizados no norte da região de Nimba, no nordeste da Libéria. Atualmente, somente um depósito é explorado produzindo DSO (minério pronto para ser comercializado). A exploração dos outros depósitos nesta área ainda está sendo definida, mas é esperada para começar em um futuro próximo. O minério da Libéria é receptivo para a produção de vários tipos de produtos finais, como por exemplo, o DSO, o sinterfeed ou o concentrado fino. Objetivando avaliar os recursos de um depósito, a proporção e a qualidade de cada produto, abordagens geo-metalúrgicas devem ser usadas para ajudar na otimização do plano de lavra. A estimativa de produtos finais é realizada em amostras representativas aplicando-se testes de beneficiamento em escala de laboratório. O principal objetivo do trabalho é realizar um plano simples de trabalho em laboratório para simular o comportamento de amostras quando estas são submetidas ao processo de beneficiamento na usina. As amostras são em seguida classificadas de acordo com a sua resposta ao processo de beneficiamento, isto sendo chamado neste trabalho como classificação de processo. Com relação aos testemunhos de sondagem e as amostras dos depósitos não testadas, outra classificação foi criada baseando-se na qualidade química e na situação geológica das amostras. O objetivo era primeiramente estabelecer uma classificação para os produtos finais, que poderia ser diretamente aplicada sem a execução de testes metalúrgicos, e em segundo plano, garantir e validar esta nova classificação usando a classificação de processo como referência. Após diversas melhorias e ajustes, a classificação química provou ser precisa em 85% em comparação com a classificação de processo. Isto permitiu especificar o produto final (em qualidade e quantidade) sem a elaboração de testes metalúrgicos, reduzindo assim o número de amostras que devem ser testadas.

PALAVRAS-CHAVE: África Ocidental; minérios de ferro; geometalurgia; beneficiamento; qualidade química.

1. INTRODUCTION

ArcelorMittal Liberian deposits all belong to the Nimba mountain range, in the North East of Liberia. All deposits have the same geological setting: first itabirites, a metamorphosed Banded Iron Formation (B.I.F.) constituting the deposit's basement topped by a weathering profile composed, from the bottom to the surface, of a transitional zone and finally a laterite horizon, also called canga. Deposits are mainly composed of three iron oxides: magnetite, hematite and goethite, completed by quartz as the main gangue mineral. Proportions of these mineral phases are varying from the bottom to the top of the deposit, and also from a deposit to the other.

ArcelorMittal actually possesses 3 concessions in the Nimba region (deposits 1, 2 and 3).

In 2013, a processing test campaign named S.P.A.T. (Standard Process Amenability Test), focused on the transition ore of deposits 1 and 2, have been performed in order to identify the several qualities of final product that could be obtained. Because of the very large amount of samples, it has been wanted to know the final products of non-tested samples. It was hence necessary to find a way to identify and to quantify the quality of final products for each zone and without any testing. Therefore, a new geometallurgical model was settled, based on head samples chemical database, that would directly classify samples without any further metallurgical tests (LUND, C. *et al*., 2013, DAVID, D., 2007).

2. MATERIALS AND METHODS

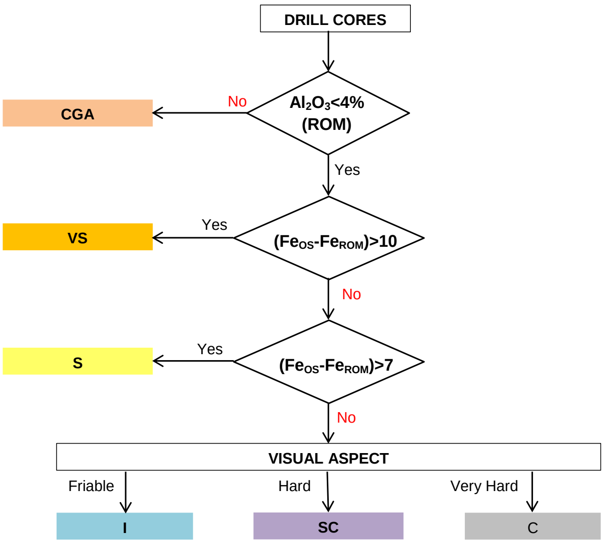
2.1. First criteria and S.P.A.T. classification

A first bench of criteria are applied by the mine geologists directly after sampling:

Table 1. First classification criteria.

Iron grade	Zone	Final product
>58%Fe	DSO	
58%>Fe>50%	Oxide	Sinter Feed (65%Fe)
50%>Fe>42%	Transition Ore	Concentrate (65%Fe)
Fe<42%	Basement	Pellet feed(65%Fe)
Fe<35%	Waste	

The S.P.A.T. (Standard Process Amenability Test) designates a full campaign of processing tests on drill cores. The main objective is to apply a simplified laboratory technique to individual samples in order to simulate their behaviour when submitted to a flowsheet to achieve a defined tonnage of final product. About 200 drill cores samples from the transition ore zone of both deposits 1 and 2 were received and classified along their behaviour in a beneficiation process or their global visual aspect, this is the process classification (Fig. 1).



CGA	Canga
VS	Very Soft (very responsive to process)
S	Soft (responsive to process)
I	Intermediate (no responsive to process)
SC	Semi compact
C	Compact

Fe_{ROM}	Iron content of the Run Of Mine
Fe_{OS}	Iron content of the Oversize

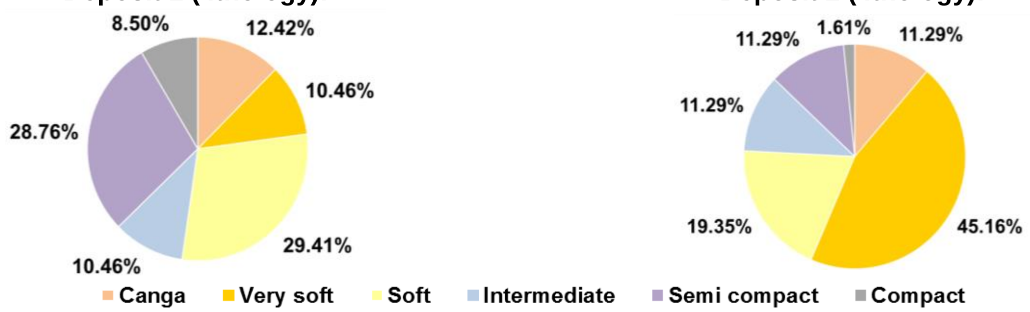
Figure 1. Process classification flowchart.

Along the processing results (Fig. 2), it is confirmed that the very soft and soft classified samples are giving a sinter feed type of final product, the intermediate class would give a fine concentrate and the semi compact and compact ones, a pellet feed. It has been noticed that some of the intermediate samples are rich enough to be concentrated as sinter feed. However in the process classification, they will be all considered as giving a fine concentrate product.

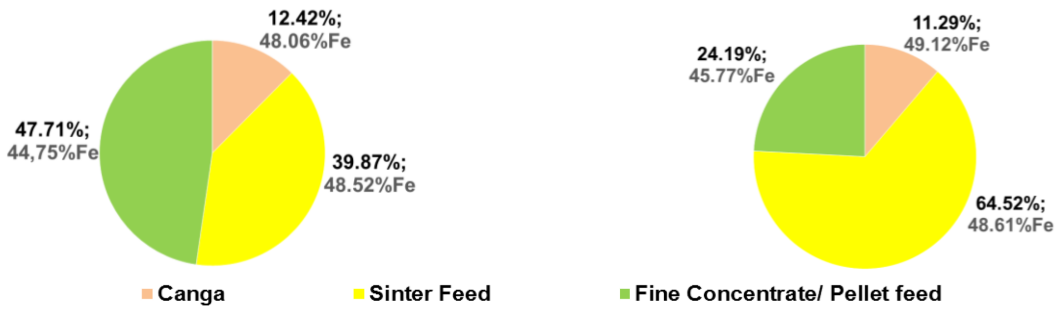
Deposit 1	Canga	Very soft	Soft	Intermediate	Semi compact	Compact
%	12.42%	10.46%	29.41%	10.46%	28.76%	8.50%
Avg%Fe	48.06	50.38	47.86	45.56	44.77	43.66
Avg%SiO_2	15.37	25.08	28.59	30.98	32.62	35.72
Avg%Al_2O_3	8.13	0.73	0.82	0.88	0.78	0.31

Deposit 2	Canga	Very soft	Soft	Intermediate	Semi compact	Compact
%	11.29%	45.16%	19.35%	11.29%	11.29%	1.61%
Avg%Fe	49.18	48.88	47.98	46.68	44.95	45.20
Avg%SiO_2	18.02	26.88	27.48	29.34	33.56	34.20
Avg%Al_2O_3	5.00	0.85	0.86	0.84	0.48	0.23

Deposit 1 (lithology): **Deposit 2 (lithology):**



Deposit 1 (final products): **Deposit 2 (final products):**



***Avg**: Average*

Figure 2. Process classification results.

2.2. Creation of chemical classification

It was created using the processing tests results of deposits 1 and 2, with the aim of estimating the final product that could be obtained without any test and therefore, to target the sampling for processing. A new criterion, based on samples' chemistry was settled down.

Based on a typical oxidation profile of an iron deposit (Fig. 3), the iron and silica grades are varying along the depth of the deposit. Several horizons are defined along the weathering degree. In surface, the weathering waters easily penetrate into the ground. The silicates are dissolved and hence the iron is concentrated. As the depth increases, the weathering waters less penetrate into the ground. The silica grade increases and counter-balances the iron grade. Furthermore, the iron gets oxidized and/or hydrated by these fluids changing the iron oxide's nature. As the depth decreases, the magnetite will be more and more oxidized into hematite and then the hematite will be hydrated into goethite. Taking into consideration these geological mechanisms, the new chemical criterion, called Δ, is representing the difference between iron and the silica grades of the head sample. That way it will estimate the depth of the sample, based on its degree of weathering.

$$\Delta = \%Fe - \%SiO_2 \quad (1)$$

Each deposit has its own particularities such as general iron and silica grades. That is why thresholds for Δ were fixed in comparison with the process classification results.

Finally, the following geometallurgical model was settled for the chemical classification (Fig. 4). It is also taking into account the first criteria applied by the geologists. In this classification, the difference between very soft and soft samples as well as between semi compact and compact is not distinguished since they are giving the same final product. It is important to keep in mind that the Intermediate – C (for which the final product is not known yet) does not correspond to the intermediate from the S.P.A.T.

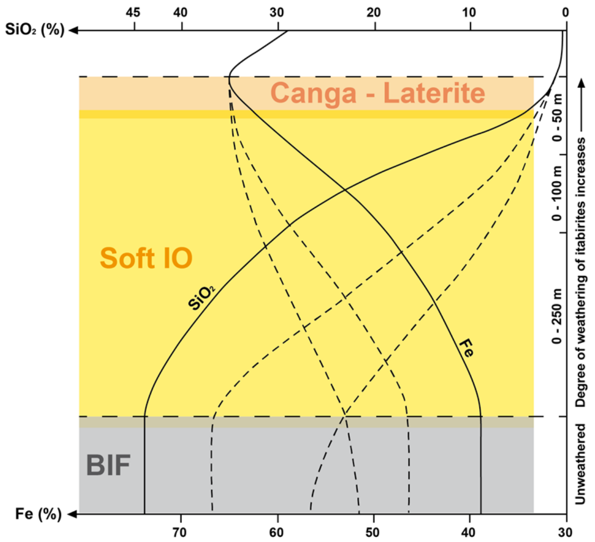


Figure 3. Typical weathering profile.

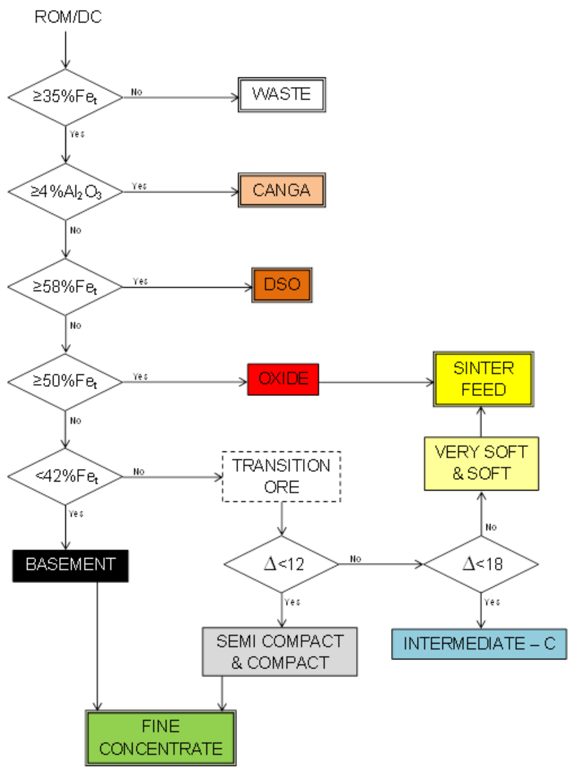


Figure 4. Chemical classification template.

The accuracy of the chemical classification was assayed comparing the process classification and the assessment of the chemical classification on the S.P.A.T. results and using the following formula per lithology:

$$\text{Error}=\frac{\text{Nb. wrong classified samples by the chemical classification}}{\text{Nb. samples in the Process Classification}} \quad (2)$$

A global error of 15% was then calculated taking into account the error on each lithology weighted with the number of samples per lithology for both deposits 1 and 2.

2.3. Assessment on the full databases

The chemical classification was then applied on the full available databases from each Liberian deposit (1 to 3) and a 4th one of the area belonging to another mining company.

As demonstrated before, in order to determine the final product based on drill core's chemical analysis, it is mandatory to know the following measurements: %Fe; %SiO_2; %Al_2O_3. Samples that didn't present these values were removed from the assessed databases (Table 2).

Table 2. Number of sample assessed on full databases.

Deposit	Total samples	Assessed samples	%
1	9932	7007	70.5%
2	7070	4195	59.3%
3	4572	2423	53.0%
4	17266	16302	94.4%

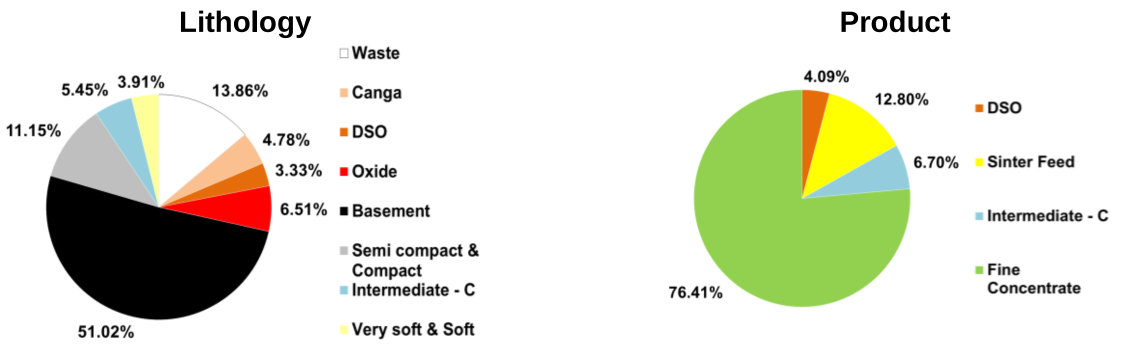
3. RESULTS AND DISCUSSION

3.1. Deposits assessments

3.1.1. Deposit 1 assessment

In term of lithology, it is clear that the basement class is the dominant one, representing 50% of the assessed samples. The transitional zone represents about 20% of the samples with mainly semi compact & compact ones. The intermediate-C represents only 5.5% of the fingerprint (Fig. 5).

Deposit 1	Waste	Canga	DSO	Oxide	Basement	Semi compact & Compact	Intermediate - C	Very soft & Soft
%(No./FDB)	13.86	4.78	3.33	6.51	51.02	11.15	5.45	3.91
Avg %Fe	22.38	49.57	61.95	53.35	39.17	43.65	46.40	48.27
Avg $\%SiO_2$	50.46	13.74	7.01	19.78	40.70	36.65	31.54	26.25
Avg $\%Al_2O_3$	8.57	8.23	1.59	1.28	0.47	0.45	0.74	1.05



***No**: number; **FDB**: Full Database; **Avg**: Average*

Figure 5. Chemical classification assessment on deposit 1's full database.

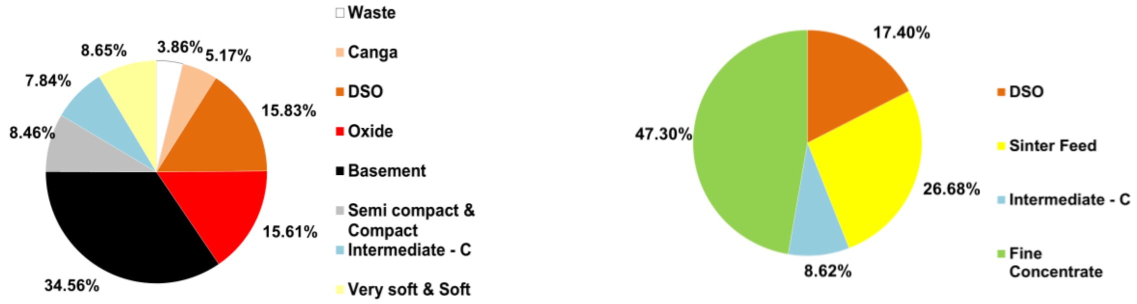
Looking at the products graph, there is a majority of fine concentrate, since it is grouping basement and semi compact & compact classes, which are the most represented. The sinter feed, representing the oxide and the very soft & soft classes, accounts about 13% of the products and the intermediate-C around 6%.

3.1.2. Deposit 2 assessment

The basement is the major class, representing on third of the lithology graph, followed by the DSO and the oxide classes (both around 16%, Fig. 6). Transition ore zone accounts 25% of the total fingerprint, with an equitable distribution between semi compact & compact, intermediate-C and very soft & soft classes (8% each).
In term of products, the fine concentrate represents almost the half of the graph (48%), followed by the sinter feed (27%) and DSO (17%).

Deposit 2	Waste	Canga	DSO	Oxide	Basement	Semi compact & Compact	Intermediate - C	Very soft & Soft
%(No./FDB)	3.86	5.17	15.83	15.61	34.56	8.46	7.84	8.65
Avg %Fe	26.72	53.94	62.64	53.87	38.93	43.43	46.02	48.42
Avg $\%SiO_2$	45.22	7.99	5.13	18.32	40.25	34.94	31.10	26.46
Avg $\%Al_2O_3$	7.75	7.08	1.57	1.33	0.48	0.48	0.66	1.12

Lithology **Product**



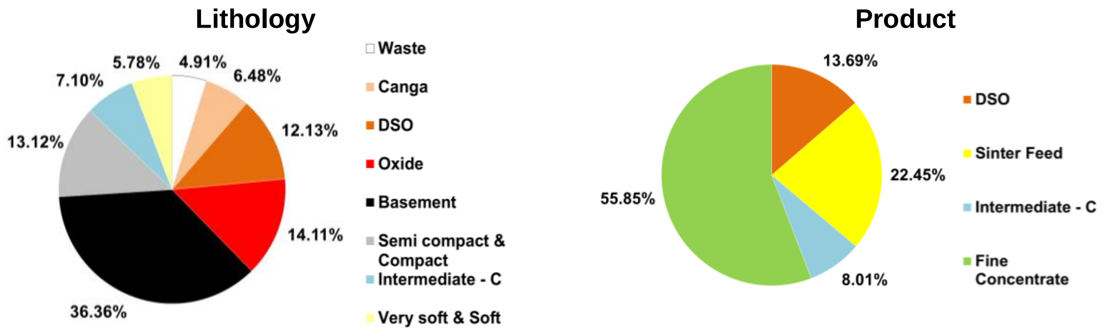
No: *number;* ***FDB***: *Full Database;* ***Avg***: *Average*

Figure. 6. Chemical classification assessment on deposit 2's full database.

3.1.3. Deposit 3 assessment

The chemical classification was then applied on the deposit 3 database (Fig. 7).

Deposit 3	Waste	Canga	DSO	Oxide	Basement	Semi compact & Compact	Intermediate - C	Very soft & Soft
%(No./FDB)	4.91	6.48	12.13	14.11	36.36	13.12	7.10	5.78
Avg %Fe	24.31	51.68	62.21	53.92	39.32	43.41	45.81	48.28
Avg $\%SiO_2$	47.64	10.48	6.14	18.77	39.88	35.43	31.14	26.25
Avg $\%Al_2O_3$	8.50	7.26	1.78	1.31	0.53	0.48	0.84	1.31



No: *number;* ***FDB***: *Full Database;* ***Avg***: *Average*

Figure 7. Chemical classification assessment on deposit 3's full database.

The basement represents one third of the lithology graph, followed by the oxide, the semi compact & compact and then the DSO.

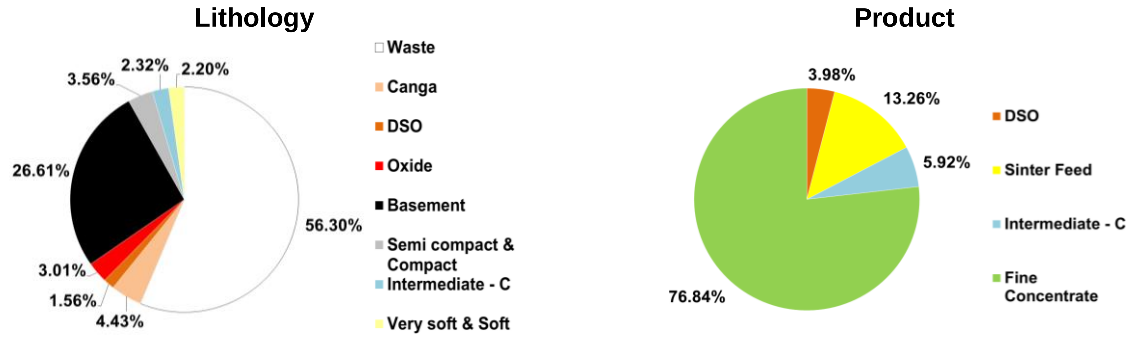
Concerning the products, more than half of the graph is represented by the fine concentrate. Sinter feed represents 22% of the fingerprint, followed by the DSO (14%) and finally the intermediate-C that only accounts 8%.

3.1.4. Deposit 4 assessment

This deposit is situated in a different iron ore range, relatively close to Deposits 1, 2 and 3. Most of the samples are classed as waste, accounting 56% of the graph (Fig; 8). The second most represented class is the basement (27%), followed by the canga, the oxide and then the semi compact & compact classes (4%). The transition zone accounts 8% of the total fingerprint.

For the products, it is quite obvious to find 77% of fine concentrate product. The sinter feed accounts 13% of the fingerprint, followed by the intermediate-C (6%) and then the DSO (4%).

Deposit 4	Waste	Canga	DSO	Oxide	Basement	Semi compact & Compact	Intermediate - C	Very soft & Soft
%(No./FDB)	56.30	4.43	1.56	3.01	26.61	3.56	2.32	2.20
Avg %Fe	11.74	47.00	62.68	53.40	38.17	43.60	45.78	48.00
Avg %SiO_2	59.76	16.38	5.20	18.58	41.06	35.69	31.09	25.19
Avg %Al_2O_3	13.09	7.28	1.63	1.46	0.45	0.47	0.86	1.57



***No**: number; **FDB**: Full Database; **Avg**: Average*

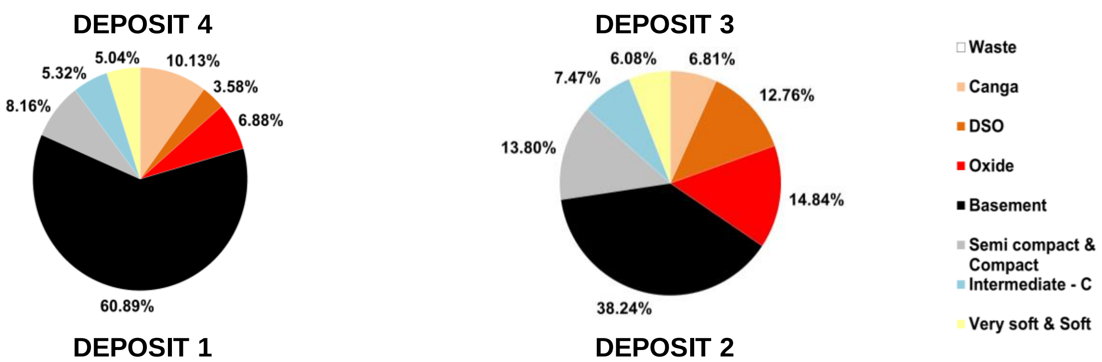
Figure 8. Chemical classification assessment on deposit 4's full database.

3.2. Deposits comparison

The four deposits were then compared in term of lithology and without taking in consideration the waste (Fig. 9).

It seems that the deposit 4 is very close from the deposit 1 and the deposit 3 from the deposit 2. Indeed the deposits 1 and 4 both account 60% of basement with a small proportion of DSO and oxide (around 10% cumulated). In both deposits, the Transition ore is dominated by the semi compact & compact class. Therefore, the deposits 1 and 4 will tend to produce a large amount of fine concentrate and few sinter feed and DSO.

Concerning the deposits 2 and 3, the basement class is limited to one third of the fingerprint (30 to 40%) to the benefit of DSO and oxide classes (another third cumulated). The transition ore zone is accounting 25 to 30% of the graph. Thus, the deposits 2 and 3 will produce a quite large amount of fine concentrate but also significant amount of DSO and sinter feed products.



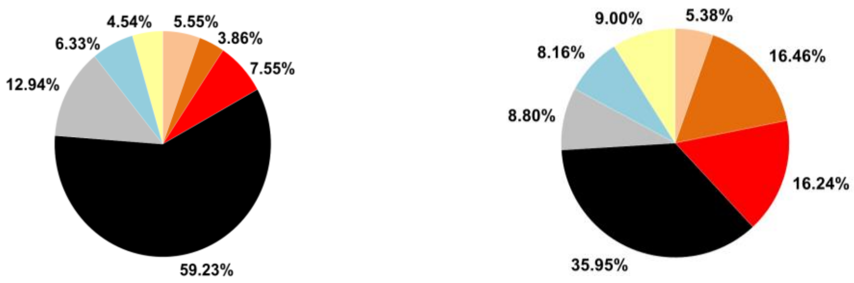


Figure 9. Lithology comparison of the four deposits.

4. RESULTS AND DISCUSSION

Through this geometallurgical approach, it has been seen that the Liberian deposits could be classified into several products only along a chemical criteria. This new chemical classification proved to be 85% accurate in comparison with the process one (S.P.A.T.), taken as a reference.

A global model was settled that could be applied on the four different deposits. This chemical classification allows specifying the final product without any further metallurgical tests. It is hence possible to reduce the number of samples that have to be tested in the laboratory and also to target the tests on specific samples or area of the deposit.

An extra criterion is still to be defined in order to separate the intermediate-C class between the semi compact & compact and the very soft & soft classes from the Transition ore zone.

5. AKNOWLEDGEMENT

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