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Study of Iron Ore Processing Technology of Tamir Gol Deposit in Mongolia

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Abstract

Iron ore processing for steel production is crucial to the development and economy of Mongolia. Regardless of having abundant natural resources and raw materials, Mongolia almost doesn't produce final products. So far, most mining and mineral beneficiation plants export raw materials only subjected to beneficiation process. Out of more than 200 deposits in Mongolia, 91 deposits had been explored with different methods and stages, and estimated the resource of 33 reserves. Without processing the iron ore, it is impossible to use it for steelmaking due to its high sulfur and phosphorus impurities. Therefore, to study the processing of iron ore deposits in Mongolia, we did a preliminary investigation of iron ore deposits and took samples from the Tamir Gol deposit with high silica and phosphorus content that is difficult to process. Then, conducted mineral analysis and determined the grain structure and beneficiation characteristics of Tamir Gol iron deposit.

Keywords

Resource, Ore Structure, Reserve, Analysis, Composition

1. Introduction

Iron ore is a strategic mineral. It is impossible to imagine machines and technology without iron. In the upcoming years, the consumption of iron ore is increasing not only in our neighboring countries Russia and China, but also in the world. Worldwide, there are 23 iron ore exporting and 33 importing countries.

In recent years, development of metallurgical industry has increased rapidly in Mongolia. Exploration of iron ore deposit is intensified, and the total resource amount increased along with the mining and beneficiation plants. The total amount of 23 iron ore reserves is 1.2 billion tons in Mongolia. Out of 21 companies with iron ore export licenses in Mongolia in 2022, 9 companies did not operate due to the market and other factors and the 12 companies exported iron ore to China. According to the statistics of the Mineral Resource Authority of Mongolia, 4.7 million tons of iron ore is mined and exported in 2022.

Mongolia used to be an iron ore exporter, but now it is aiming to become a producer of final products with added value through processing. In this regard, the government policy aimed at supporting heavy industry has resulted in the development of the metallurgical and manufacturing industry.

Geologists have studied that most of the iron deposits in Mongolia are amenable to traditional processing.

Significant iron ore deposits consist of ferruginous quartzite and magnetite-hematite. Ferruginous quartzite is characterized by the fact that they were formed only during the Archaean-Proterozoic period. 93% of all reserves of iron ore in the world are concentrated in ferruginous quartzite during Archaean-Proterozoic, and only 7% is formed in the Phanerozoic era. The main ore-forming minerals in ferruginous quartzite are magnetite, hematite and quartz, and the average iron content is 30% - 35%.

Deposits with up to 50 million tons of resources are small, 50 - 250 million tons are medium, 250 - 1000 million tons are large, and more than 1 billion tons are considered as huge deposits. The huge deposits mostly include ferruginous quartzite and sedimentary deposits. Bayantsogt and Tumurtei deposits are large deposits. Iron content in iron-rich ores is more than 50% and less than 25% in iron-poor ores which requires beneficiation [1] [2]. The average iron content in the iron ore of Mongolia is more than 50%.

Therefore, we studied iron deposits in Mongolia and took samples from profitable deposits with production possibilities for detailed mineralogical analysis.

2. Main Part

Out of 200 discovered iron ore deposits in Mongolia [3], 42 deposits have been explored [4], and 25 reserves have been identified [5]. In terms of resource, quality, and geographical location, Tamir Gol reserve in Arkhangai province; Tumurtei, Tumurtolgoi, Bayangol, Khust-Uul reserves in Selenge province; Bayanjargal, Ereen, Dartsagt, Bargil-Ovoo reserves in Dornogovi province; Khachim Gol reserve in Khuvsgul province; Tumurtiin-Ovoo, Khar-Undur reserves in Sukhbaatar province are the largest. Among the above deposits, the Tamir Gol deposit is difficult to process due to its high content of silica and phosphorus.

In this study, we aimed to process quartzite-containing minerals to obtain high-quality concentrates. Therefore, we did a detailed study on the Tamir Gol deposit in Arkhangai province.

In 1975-1976, V.I. Shamrayev and V.M. Grinchyenko carried out geological and geophysical research on the scale of 1:25,000 - 1:5000, in 1977-1978 J.

Tsend-Ayush and V.I. Popov did exploration and evaluation, and in 2006-2007 "Beren Group" explored the southern part of the Tamir Gol deposit [3] [6] [7].

Ore bodies of the Tamir Gol deposit are classified into the Group III of the sedimentary-metamorphogenic type based on its geological formation, morphology, microstructure, useful minerals and impurities.

From the mineral analysis, the main mineral is magnetite, and a small amount of hematite up to 1.055%. Iron content in the remaining minerals including quartz, hornblende, feldspar, and biotite is very low, and the amount of ore oxidation is considered low in these minerals [5].

Experiments and analysis were carried out by crushing, grinding, and separation process regarding the poor iron content, small grain size, and the uniformity of minerals.

According to the phase analysis, magnetite content was 44.50%, hematite 10.55%, iron sulfide 0.05%, iron carbide 0.15%, iron silicate 0.30%, and iron 35.55%.

In the previous study, by identifying ore and non-ore minerals, 3 types of ore were distinguished: magnetite, hematite, and magnetite-hematite [5]. Iron ore types are presented in **Table 1**.

Magnetite ore and its mineral types have dark bluish or greenish color. It has strong magnetic properties and contains 0.5 - 2.0 cm thin layers of shale and quartzite. It has a fine layered texture and granoblastic and microgranular structure. In all types of magnetite ores, the main mineral content varies considerably, reaching 20% - 70% magnetite, 10% - 25% dolomite, 10% - 50% chlorite, 5% - 20% biotite, and 5% - 10% muscovite. The total iron content is 46.67% - 49.15%, and contains 2.95% - 3.56% manganese oxide, 0.22% - 0.31% sulfur, 9.10% - 9.94% silicon oxide, 1.94% - 1.95% phosphorus tetroxide, 3.93% - 4.0% aluminum oxide, 3.64% - 3.78% calcium oxide, 2.42% - 4.65% magnesium oxide, and the amount of total alkaline is 0.35% - 0.61%.

Hematite ore and its mineral types are all very fine-grained and vary in color from bright red, brown, and maroon to steel-gray depending on the hematite content. The composition of hematite ore includes 40% - 85% hematite-I, 15% - 25% chlorite, 15% - 25% dolomite, 5% - 50% quartz, 1% - 2% muscovite, 0.3%

Table 1. Iron ore types of the Tamir Gol deposit.

No	Ore Type	Mineral Type
1	Magnetite ore	Dolomite-chlorite-magnetite Dolomite-mica-magnetite Dolomite-mica-magnetite
2	Hematite ore	Chlorite-hematite Dolomite-hematite Quartz-dolomite-hematite
3	Magnetite-hematite ore Hematite-magnetite	Dolomite-chlorite-magnetite-hematite Quartz-mica-hematite-magnetite

chalcopyrite, 0.1% chalcosine, up to 5% hematite-II 5%, and up to 1% of hematite-III. Iron content in hematite ore is 37.07% - 44.73%, and contains 5.36% - 10.12% manganese oxide, 0.06% - 0.13% sulfur, 1.13% - 1.47% phosphorus tetroxide, 10.2% - 13.8% silicon oxide, 4.62% - 7.67% aluminum oxide, 2.80% - 3.92% calcium oxide, 2.1% - 3.03% magnesium oxide, and a very small amount of other metals.

Hematite-magnetite and magnetite-hematite mixed ores and their mineral types are dense, have brownish or reddish brown, micro-grained structure, and weak magnetic properties. It has a fine layered texture, and in most cases, thin magnetite-hematite layers a formed. Composition of this mixed ore type includes 25% - 30% of magnetite, 30% - 50% of hematite, and 1% - 2% of hematite-III. Also, consists of non-ore minerals including 20% - 25% dolomite, 20% - 30% chlorite, 10% quartz, 25% muscovite, and 3% apatite.

Samples of the experimental research are from "Beren Group" concentration plant, located in the southern part of the Tamir River deposit. Sample locations presented in Figure 1.

According to the exploration the probable iron ore reserves are 1805.0 thousand tons, and the possible reserves are 2736.156 thousand tons in the south part of Tamir River iron ore deposit.

The ore body in the southern part mainly consists of hematite, magnetite-hematite ore, magnetite and magnetite sulfide occurs in some parts. It has monolithic and shale textures, and has a layered structure. All ore bodies have milky white post-mineralization quartz veins. The stratified ore bodies consist magnetite, hematite, magnetite-hematite, chlorite-magnetite, and occasionally formed shale, quartzite, and chlorite veins.

The ore has a fine layered texture, and in most cases fine alternating veins of magnetite-hematite are formed. The ore also contains thin layers of chlorite-bearing shale, grey-red non ore-bearing quartzite, red shale, and quartz-biotite shale lenses. Ore consists of non-ore minerals including dolomite 20% - 25%, chlorite 20% - 30%, quartz 10%, muscovite 25% and apatite 3%.

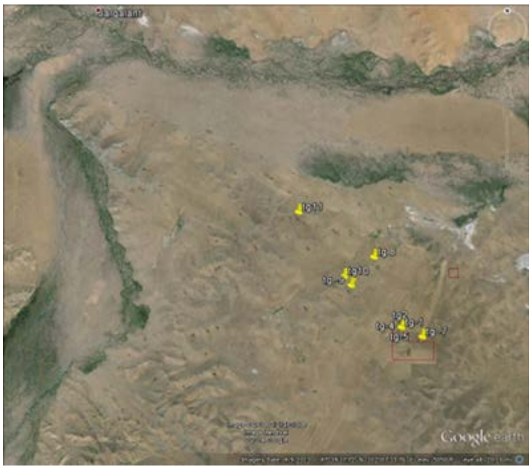

Figure 1. Sample locations.

2.1. Sample Analysis Results of Rock and Ore

In the experimental study, about 400 kg samples were selected from Tamir Gol deposit, which located in Arkhangai province and from the quarry wet and dry wastes of the beneficiation plant. The largest size of used ore particles was 400 mm.

The experiment was carried out at the Laboratory of the Geological Research Center of the School of Geology and Mining of the Mongolian University of Science and Technology. The study was conducted using a Nikon E6000 microscope.

The following samples were used:

11 piece anschliffe

Тг-1-2ш, Тг-3, Тг-4-2ш, Тг-5, Тг-6-2ш, Тг-7, Тг-9, Тг-11,

5 piece schliffe

Тг-3, Тг-8, Тг-10, Тг-12, Тг-13

5 wet and 3 dry wastes

Samples were taken from the following points depending on the magnetic properties of the minerals and vein color, and prepared according to standards (**Table 2**).

Sample 1: Quarry 21st body is shown in **Figure 2** is 10 - 13 m thick and 350 m long. Forming a clear boundary with its host, hematite and hematite-magnetite banded ores alternately contain iron quartzite layers. The chemical composition is Fe 21.62% - 52.94%, S 0.03% - 0.04%, and P 1.29% - 2.63%, and on average, Fe 40.83%, S 0.03%, and P 1.84%.

After selecting petrographic and mineral analysis from the incoming samples, start experiment of ore preparation and enrichment technology (**Figure 3**).

Sample 2: Quarry 22nd object. Hematite ore is dominant, which is compatible with mineralized quartzite. The chemical composition is Fe 34.0% - 43.52%, P 11.32% - 2.3%.

Table 2. Coordinate of samples taken from south part of Tamiriin Gol deposit.

Sample number	Remarks	Longitude	Latitude
ТГ-1	Quarry 21st object	47˚35'38.3"	102˚14'47.6"
ТГ-2		47˚35'39.8"	102˚14'48.1"
ТГ-3			
ТГ-4		47˚35'39.9"	102˚14'47.2"
ТГ-5		47˚35'40.8"	102˚14'46.0"
ТГ-6	Hematite ore /wastes/	47˚35'42.49"	102˚14'3.21"
ТГ-7	Former excavated place	47˚35'17.41"	102˚15'5.41"
ТГ-8	Stone containing central part	47˚38'13.1"	102˚13'18.9"
ТГ-9	First ore object central part	47˚37'11.1"	102˚12'04.4"
ТГ-10	The largest ore object central part	47˚37'31.3"	102˚11'41.7"
ТГ-11		47˚39'52.5"	102˚09'12.9"

Figure 2. Samples were taken from following location in the beneficiation plant.

Figure 3. Strong magnetic sulphide containing magnetite ore.

Sample 3: Quarry 23rd body. Ore contains quartz-biotite-chlorite shale. The ore body contains hematite and hematite-magnetite ores and contains quartzite lenses, banded quartz and chlorite veins. The chemical content of the ore is 28.7% - 43.60% Fe, 0.28% - 10.09% S, and 0.37% - 1.83% S.

Sample 4: Quarry 24th and 25th body. Hematite-magnetite and magnetite ores are formed in the low-relief part of the northwestern part of the region, and are formed by monolithic, banded, small and fine-grained, cut by quartz veins. The length of the ore body is 500 m.

Sample 5: Quarry 25th body occurs in a depth of 39.6 - 71.8 m. A magnetite-type mineralization with nest-like sulfides cut mainly by quartz chlorite veinlets is found. At the end of the ore, chlorite increases and the content reaches 50%. The chemical content is 30.13% - 51.3% Fe, 0.36% - 2.97% S, 2.09% - 2.84% P. On average, Fe 41.93%, S 1.23%, and P 2.33%.

2.2. Petrographic Studies

For petrographic research, 5 samples of ТГ-3, ТГ-8, ТГ-10, ТГ-12, and ТГ-13 were selected and 5 slides were prepared and studied.

Sample ТГ-3 Quartzite

The rock is cut by quartz veins and contains 6% - 8% ore minerals. Sericite and chlorite were found in a small amount (**Figure 4**).

Sample ТГ-12 Shale with quartz chlorite

The ore minerals in the rock contain up to 10% of veins and small grains. It is also cut by quartz capillaries. In the rock, the ore is separated as veins and is cut by quartz capillaries (**Figure 5**).

Sample ТГ-8 Shale with quartz chlorite carbonate

The rock is a mixture of chlorite, epidote, quartz and carbonate rocks. Ore minerals are isotermically distributed in chlorite-epidote rocks. Ore minerals were formed in the areas dominated by colored minerals with chlorite (**Figure 6**).

Sample ТГ-13 Shale with chlorite quartz carbonate

The rock is a mixture of chlorite, epidote, and quartz carbonate. Ore minerals are distributed isometrically in chlorite-epidote rocks (**Figure 7**).

Sample Description

11 samples were prepared for each sample chosen for ore recording. These includes, 2 pieces from ТГ-1, ТГ-4 and ТГ-6 samples, 1 piece from ТГ-3, ТГ-5, ТГ-7, ТГ-9 and ТГ-11 samples were prepared.

ТГ-1 Strong magnetic magnetite ore

85% percent of the rock is magnetite. Due to small amount of oxidation, iron oxides such as hematite and goethite are formed. Magnetite has square isometric shape and uneven distribution (**Figure 8** and **Figure 9**).

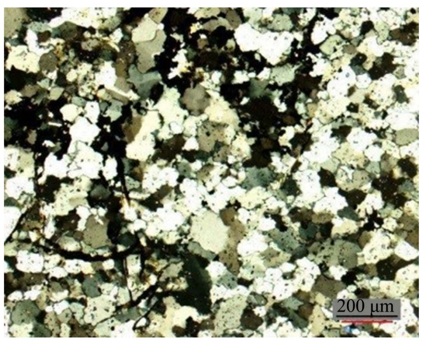

Figure 4. Veined and isometric ore minerals formed between the quartz grains.

Figure 5. Figure Shale with quartz chlorite.

Figure 6. Shale with quartz chlorite carbonate.

Figure 7. Formation of ore minerals in shale with chlorite.

Figure 8. Magnetite.

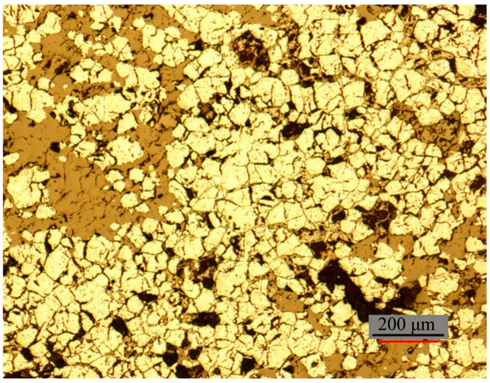

Figure 9. Magnetite granules.

TГ-3 Magnetite hematite ore

The ore is dense, fine-grained and magnetic. It contains 60% - 70% magnetite. The rest is occupied by fine-grained hematite and goethite, and cut by quartz veins (Figure 10).

TГ-4 Hematite ore

The ore has become porous due to weathering and it is non-magnetic. The ore contains 25% - 30% hematite, and a few magnetite grains occur up to 5% (Figure 11).

TГ-5 Magnetite-hematite ore

The ore is magnetic and contains 30% magnetite and 10% hematite. The rest is transformed into goethite (Figure 12).

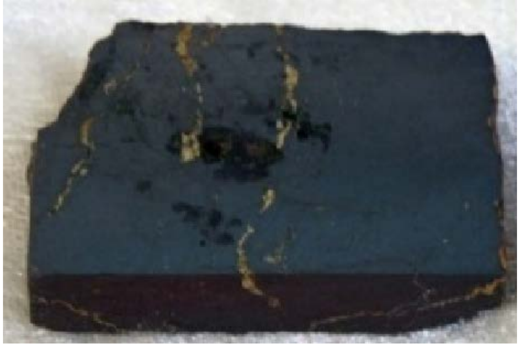

Figure 10. Magnetite hematite ore.

Figure 11. Hematite ore.

Figure 12. TG-5 Magnetite hematite ore.

TT-6 Magnetite-hematite ore

The ore contains 50% - 60% magnetite, and it is isolated as solid and veined forms. It is slightly metamorphosed/transformed into hematite. It has strong magnetism in the magnetite part. The rest of the red-brown host rock is mottled, veined, and mainly ore-bearing.

Magnetite slightly altered to hematite. Flaky hematite's formed around the magnetite, and magnetite became irregularly shaped residual grains (**Figure 13**).

TT-7 Magnetite ore

The ore contains 80% magnetite and 5% hematite, and strongly magnetic and solid dense (**Figure 14**).

TT-9 Hematite ore

The hematite ore has fine capillary veins and is formed in the main part in the form of small platelets. Ore consists of 20% hematite, 50% goethite, and 20% is rock (**Figure 15**).

TT-11 Magnetite ore

The ore contains up to 85% magnetite. It is magnetic and dense solid. Quartz capillaries occurs in a small amount (**Figures 16-18**).

Samples of dry waste and wet waste of the iron ore from the beneficiation were prepared and the ore content was studied. Prepared 5 pieces from dry waste and 3 pieces from wet waste.

When preparing thin section, it is classified into fractions by grain size. All the waste samples were magnetic which indicates high magnetite content (**Figure 19** and **Figure 20**).

Fractions larger than 20 mm are magnetic, and magnetite-hematite content is up to 50%. The fraction of 10 - 15 mm was magnetic, magnetite-hematite content was 50%; the fraction of 5 - 10 mm was magnetic and magnetite-hematite content was 35%; the fraction of 1 - 5 mm was magnetic and the magnetite content was 25%. All particles of wet waste were magnetic, magnetite-hematite content was 30% in fractions above 1 mm, and 25% in fractions of 1 - 0.1 mm and in the fraction less than 0.1 mm, it was up to 25%.

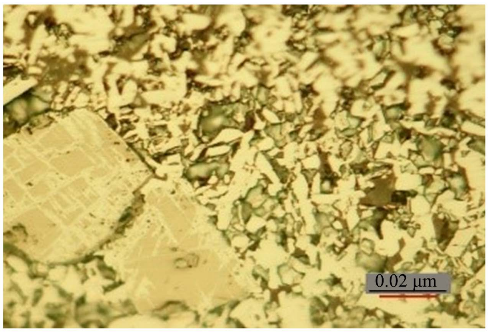

Figure 13. Magnetite, hematite grains.

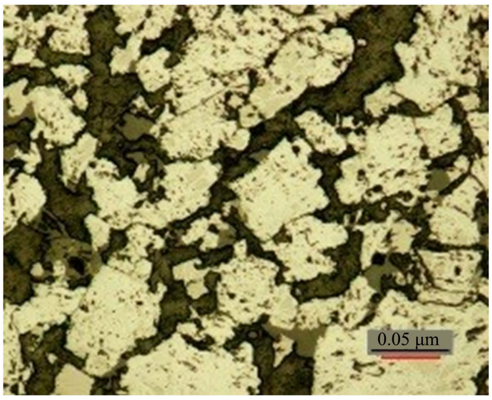

Figure 14. Square crystals of magnetite.

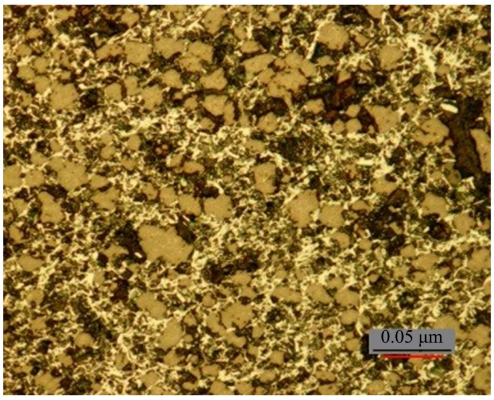

Figure 15. Flaky hematite grains in a goethite-dominated core.

Figure 16. Magnetite.

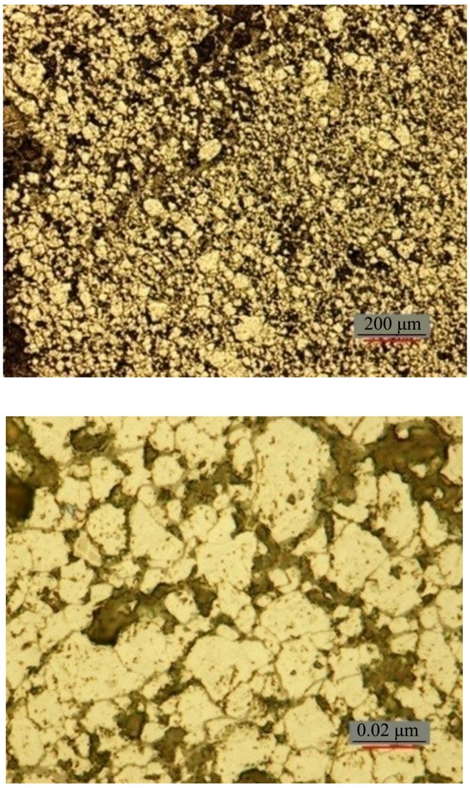

Figure 17. Isometric grains of magnetite.

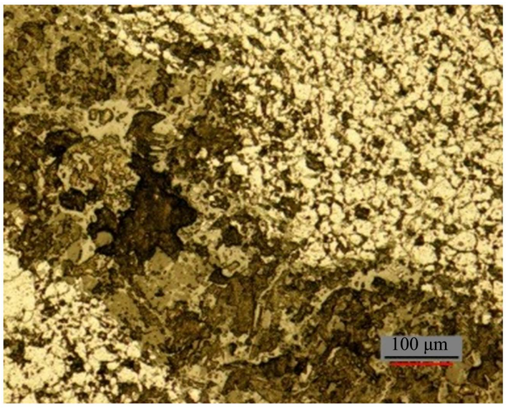

Figure 18. The ore is cut by quartz veins.

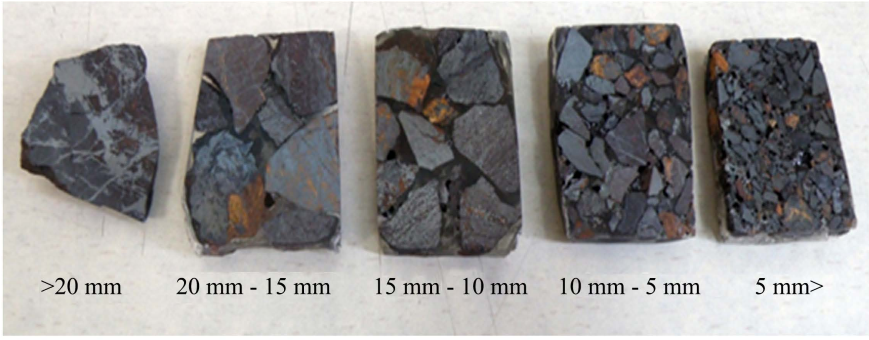

Figure 19. Fraction of dry waste.

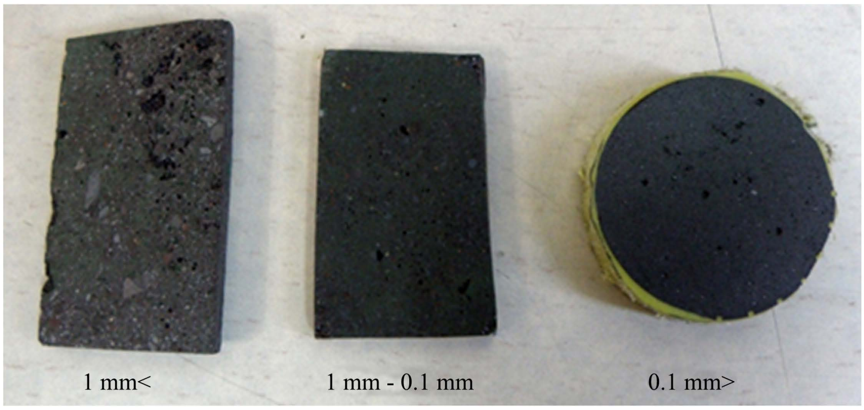

Figure 20. Fraction of wet waste.

2.3. Experimental Research on Beneficiation Technology

Chemical analysis of primary samples of each point, as well as samples of dry and wet wastes of mineral beneficiation were tested at the Central Geological Laboratory to determine the main and added elements, and impurity content. The results are presented in Table 3 and Table 4.

According to the results above, iron contents in the primary samples are different and the silicon oxide (SiO_2) content is relatively high in some samples. The iron content in the iron concentrate of beneficiation plant is 62.59%, impurity and silicon dioxide (SiO_2) content is 4.92%, while the aluminum oxide content is low. The iron content of dry and wet waste is very high and between 42.34% - 42.83% of iron concentrate is wasted. Hence, products with higher iron concentrate than the permissible amount are being wasted because the technology of Tamir Gol iron ore beneficiation plant is not optimal.

The main minerals of the primary ore are magnetite and hematite. It is present in ores in a very much embedded form. Therefore, it is possible to obtain a concentrate meets the requirements of high-quality standards by pulverizing the primary sample, enriching it and completely freeing the useful minerals from the empty rocks. The beneficiation of weak magnetic iron ores with a magnetic separator will be poor, and gravity concentration is more suitable [8] [9].

Based on the mineralogical and substance composition studies, X-ray fluorescence (RFA) and spectral analysis of iron ore samples, the following beneficiation process was developed.

- Preparation of samples for testing
- Chemical analysis of primary samples
- Sieve analysis
- Setting the sample grinding mode
- Magnetic separation (Separation of iron ore according to magnetic and non-magnetic properties)

- Enrichment test by wet magnetic separation method:

Strong magnetic magnetite, weak magnetic hematite, and mixed samples from the quarry are taken for the beneficiation experiment.

Table 3. Sample element analysis result.

No	Sample No	Element, %		
		FeO	Fe_2O_3	Fe
1	1	5.51	52.62	36.83
2	3	3.73	84.39	59.07
3	4	<0.25	26.93	18.85
4	5	4.09	52.83	36.98
5	6	5.33	69.97	48.98
6	7	9.24	70.59	49.41
7	9	3.02	56.29	39.40
8	11	3.87	85.99	60.19
9	Concentrate	9.59	89.41	62.59
10	Wet waste	<0.25	60.49	42.34
11	Dry waste	0.53	61.18	42.83

Table 4. Result of the chemical analysis of samples.

No	Sample No	Element, %								
		SiO_2	TiO_2	Al_2O_3	ΣFe_2O_3	CaO	MgO	Na_2O	K_2O	MnO
1	1	10.43	0.072	2.40	52.62	16.78	0.05	0.02	0.02	1.564
2	3	6.40	0.062	0.71	84.39	4.60	<0.01	0.01	0.01	0.129
3	4	45.29	0.479	7.12	26.93	1.70	0.34	0.66	0.66	7.965
4	5	16.16	0.459	8.53	52.83	5.59	1.65	0.06	0.06	9.317
5	6	15.27	0.238	4.30	69.79	4.37	<0.01	0.02	0.02	0.605
6	7	24.35	0.075	1.77	70.59	1.46	<0.01	0.07	0.07	0.416
7	9	16.08	0.495	8.67	56.29	1.98	1.42	0.01	0.01	12.834
8	11	4.90	0.149	2.89	85.99	1.38	0.12	0.18	0.18	0.998
9	Б1	4.92	0.135	1.56	89.41	0.88	0.05	<0.01	0.11	1.778
10	H1	14.35	0.361	5.75	60.49	2.83	0.58	0.30	0.42	9.678
11	X1	16.24	0.302	5.68	61.18	2.64	0.67	0.26	0.30	7.006

Samples include:

- ТГ-1 Strongly magnetic magnetite ore
- ТГ-4 Non-magnetic hematite ore
- ТГ-5 Magnetite-hematite ore

The particle size of the primary sample was relatively large, and according to the technological scheme, some samples were manually crushed to −80 mm.

Three parts of the primary sample were crushed with −10 mm crusher and thoroughly mixed by the cone-ring method. Then, divided with a Johnson splitter, half of it was prepared for testing and the other half for stock. The samples are also mixed and quantified by the cone-ring method, divided into 2 parts, crushed to −5 mm. Also, samples are reduced several times to meet the requirements. The technological scheme of the sample preparation and the Johnson splitter is shown in Figure 21 and Figure 22.

2.4. Primary Sample Screening Analysis

For sieve analysis, samples prepared up to −5 mm from points 1, 4, and 5 were tested. Primary samples are sieved to −0.2 + 0.1 mm, −0.1 + 0.088 mm, −0.088 mm and determined the distribution of granulation and useful minerals.

According to the results of magnetite ore sieve analysis, grain distribution is not uniform, content of −3 + 1 mm class is high and yield decreased as grain size decreased, and iron content in each grade was evenly distributed. By the metal balance calculation, the average iron content of the primary sample is 52.67%, and the average particle size is 1.19 mm (Figure 23).

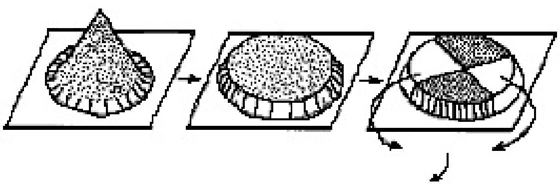

Figure 21. Sample preparation.

Figure 22. Johnson splitter.

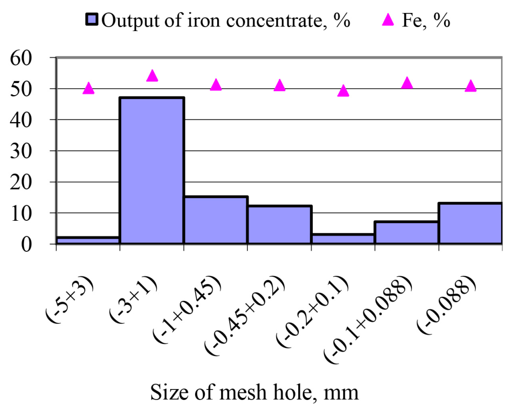

Figure 23. Grain size distribution curve.

From the results of the hematite ore sieve analysis, the proportion of the −5 + 3 mm and −3 + 1 mm grade is high, and as the grain size decreases, the content of the class decreases, and the content of the −0.2 + 0.1 mm class decreases to 1.33%. Also, the distribution was not uniform, and the average grain size was 2.24 mm (**Figure 24**).

From the results of the sieve analysis of magnetite-hematite ore, the average grain size is 1.72 mm, the distribution of grains is not uniform, the grade content decreases as the grain size decreases. The iron content in each grade is evenly distributed, with an average of 36.89% in primary ore based on metal balance calculations (**Figure 25**).

2.5. Determination of Grinding Mode

In the experiment to determine the ore grinding mode, the loss of minerals and the content of the −0.074 mm class were determined by using a ball mill.

In the experiment, 1 kg of each sample crushed to −5 mm and the grinding test was performed using a ball mill and the grinding time was 20, 25, 30, 35, and 40 minutes with 5 minutes increment [10]. Test conditions, ratio of solid, liquid and steel balls (L:W:B) was adjusted to 1 × 1 × 3 in the mill and performed under constant conditions for each sample.

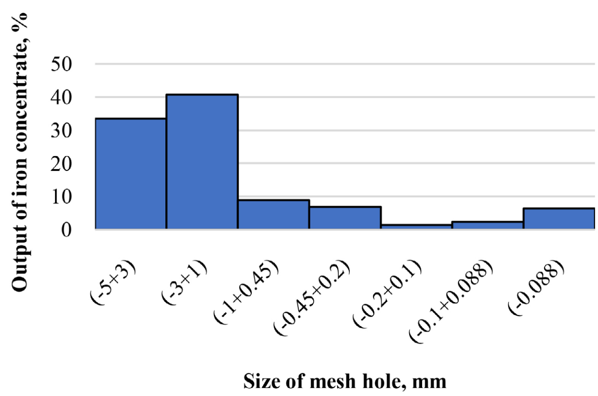

Figure 24. Grain size distribution curve.

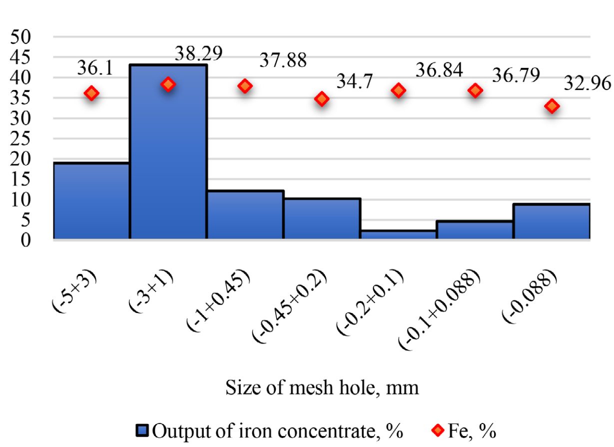

Figure 25. Grain size distribution curve.

Each grinded product was weighed after wet sieving and dried in a wet environment with a mesh of −0.074 mm, and the yield was calculated to determine the content of the −0.074 mm class. The test results are shown in **Figure 26** and **Figure 27**.

Depending on the grinding mode, it is necessary to determine the concentration quality, and each ground product was beneficiated in a wet magnetic separator.

2.6. Beneficiation with Wet Magnetic Separator

In the test, the magnetic field voltage of the wet magnetic separator was adjusted to weak and strong magnetic fields with 2A and 4A accordingly, and each category was beneficiated in a wet environment to obtain 2 products: concentrate and waste, **Figure 28** and **Figure 29**.

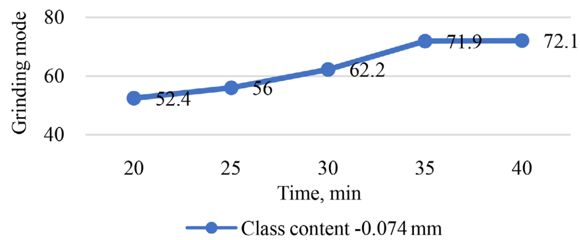

Figure 26. The characteristics of magnetite samples dependent on the grinding time (−0.074 mm class content)

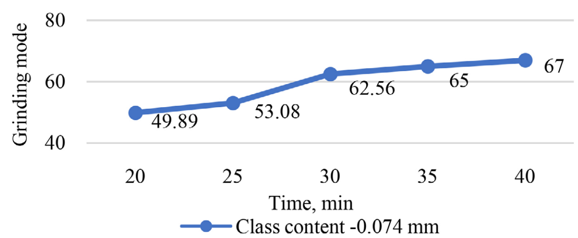

Figure 27. The characteristics of magnetite hematite samples dependent on the grinding time (−0.074 mm class content)

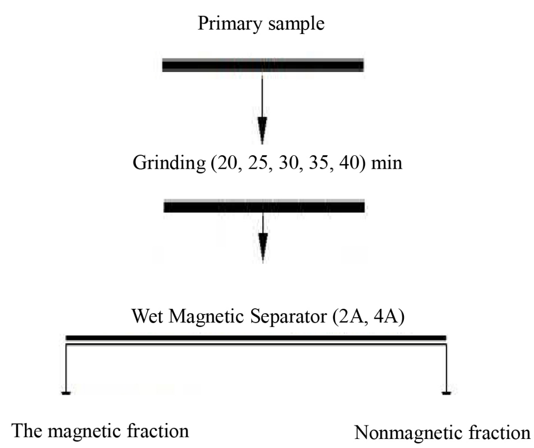

Figure 28. Wet magnetic beneficiation scheme.

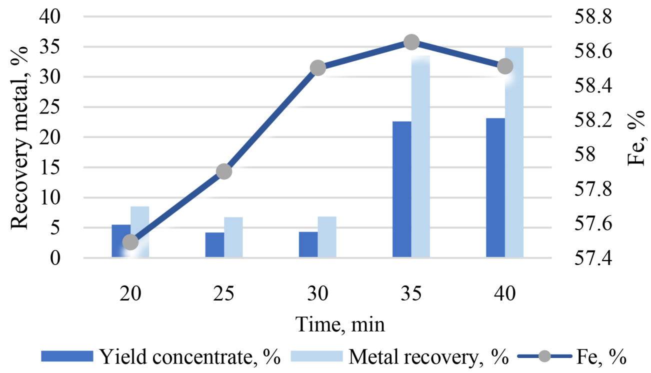

Figure 29. Wet magnetic beneficiation 2A.

Beneficiation of mixed samples of magnetite-hematite in a weak magnetic field was very poor. Grinding time was 20 - 30 minutes and for −0.074 mm class, iron content is up to 62%, average concentrate yield is 4% - 5%, metal recovery is 6% - 8%, and concentrate content is 57.49% - 58.5%, and waste content is 35.81% - 35.97%. When the grinding time was 35 - 40 minutes, the yield and metal recovery increased slightly, the metal recovery of the concentrate was 33.51% - 34.83%, the yield was 22% - 23%, and the content of the concentrate was enriched to 58.65%. When beneficiating the sample in a weak magnetic field, as the beneficial minerals become weaker, the concentrate content and metal recovery increases, but it does not reach a sufficient level, and the waste content decreases to a small extent as the grinding time increases, but it is discarded with high content. Therefore, the beneficiation of magnetite-hematite samples in weak magnetic fields is poor (**Figure 30**).

When the magnetite-hematite sample was concentrated in a strong magnetic field, the metal recovery of the concentrate reached 65.29% and the yield reached 44% at the 30 minutes of grinding time. According to the test results, the content of the concentrate was enriched to 55.74% - 57.99% depending on the grinding mode, and the maximum content of the concentrate was 57.99%, the metal recovery was 54.43%, the yield of the concentrate was 33.76%, and the waste content was 24.74%.

From the test above, the magnetite-hematite sample is dominated by weak magnetic iron oxides and is poorly beneficiated in the strong magnetic fields (**Figure 31**).

According to the results of the analysis, the amount of impurities in the concentrate beneficiated in the weak magnetic field is small. As the grinding time increases, the iron content in the concentrate increases and the impurity content decreases.

Aluminum oxide (Al_2O_3) is low in the concentrate beneficiated with 2A, and with increasing grinding time, Al_2O_3 content decreases to 2.53% - 2.33%, and Al_2O_3 content is 2.89% - 2.47% with 4A. The silicon oxide (SiO_2) content decreased from 5.09% to 4.56% in 2A concentrate and 5.57% to 4.83% in 4A concentrate, and it decreased to a certain extent with increasing grinding time.

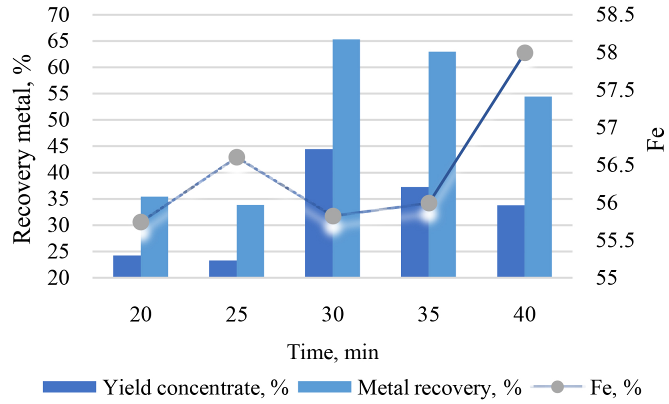

Figure 30. Wet magnetic beneficiation 4A.

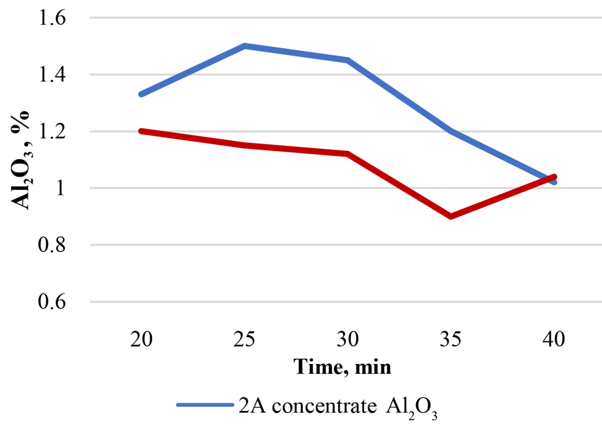

Figure 31. Comparing toxic impurities in concentrates enriched in strong and weak magnetic fields (TG-1).

Phosphorus content decreased uniformly to 0.5% - 0.4% in 4A concentrate and 0.44% - 0.38% in 2A concentrate. According to this, as useful minerals are weakened, the quality of the concentrate is improved by removing toxic impurities.

Beneficiation experiments in weak and strong magnetic fields show that magnetite hematite samples are dominated by weak magnetic iron minerals and are poorly concentrated in magnetic separators (Figure 32).

According to the results of beneficiation test in weak magnetic field, the beneficiation of magnetite sample was poor, the concentrate metal recovery and yield was very low and, iron ore content was high in the tailing. As the test shows, as the content of −0.074 mm grade increases, the content of concentrate and metal recovery increases, when grinding for 40 minutes, the content of −0.074 mm grade is 72%, while the content of concentrate is 62.14%, metal recovery is 29.35%, and the yield of 26% is enriched in the waste. The iron content is high at 52.43%. From the above test, as the content of −0.074 mm class increases, the waste content increases from 49.36 to 52.32%. This suggests that the magnetite sample has lost its magnetism through oxidation, and as the weak magnetic iron oxides are released from the host rock and they are transferred to non-magnetic tailings.

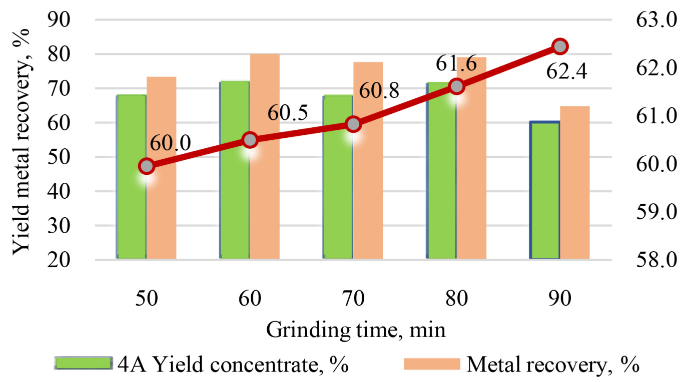

Figure 32. Wet magnetic beneficiation.

According to the beneficiation test in the strong magnetic field, the concentration content of a sample ground for 20 minutes is 61.22%, the metal recovery is 81.4%, the yield is 71.18%, and the iron content in the tailings is 34.56%. Depending on the grinding time, as the content of the −0.074 mm class increased, the useful minerals were released from the empty rock, and the iron content in the concentrate increased. After 30 minutes, the iron content in the concentrate increased from 62.2% of the −0.074 mm class to more than 62%. The quality of the concentrate was high at 40 minutes of grinding time, the concentrate content was 62.31%, the metal recovery was 71.81%, the concentrate yield was 63%, and the iron content in the waste was 41.81%.

Mineral chemical analysis was performed in the internationally recognized SGS laboratory to determine the content of beneficial minerals and toxic impurities in the concentrated test concentrate by changing the magnetic force of the wet magnetic separator depending on the grinding mode. The results of the analysis are shown in the graph below (**Figure 33**).

According to the test results of the analysis, as the grinding time increases, the content of the toxic impurities in the concentrate decreases and the content of beneficial minerals increases. In the total concentrate, the content of sulfur aluminum oxide Al_2O_3 is low, and the content of silicon oxide SiO_2 and P is relatively high.

Aluminum oxide (Al_2O_3) is low in concentrate beneficiated in 4A and decreases to 1.19% - 0.94% and 1.32% - 1% in concentrate 2A as the content of −0.074 mm class increases. The content of silicon oxide SiO_2 is high in the total concentrate, and with increasing grinding time, it decreased to a certain extent and decreased to 6.12% - 5.37% in 4A concentrate and 6.14% - 5.6% in 2A concentrate. Phosphorus content decreased uniformly to 0.49% - 0.4% in 4A concentrate and 0.46% - 0.42% in 2A concentrate depending on the grinding time (**Figure 34**).

According to the above results, as the content of the −0.074 mm grade increases, the beneficial minerals are weakened from the toxic mixture of empty rock, and when the concentrate content is high, the toxic mixture is the lowest when it is ground for 40 minutes.

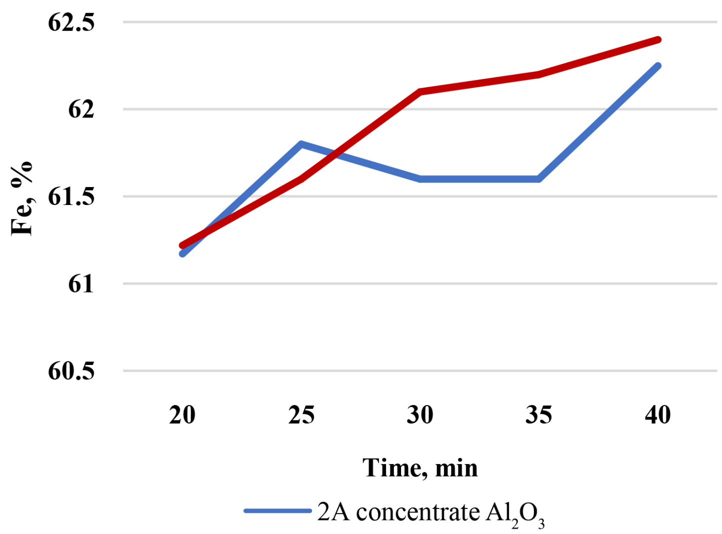

Figure 33. Comparing beneficial minerals in concentrates enriched in strong and weak magnetic fields (TG-1).

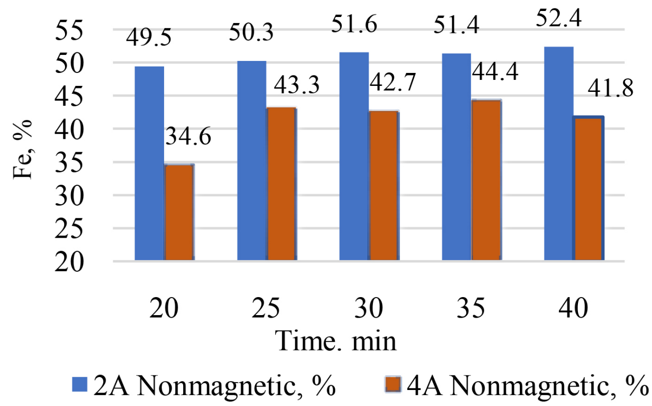

Figure 34. Iron content in the non-magnetic fraction.

The high waste content of wet magnetic concentration is due to the presence of weakly magnetic iron oxides, and the waste content increases with increasing grinding time.

According to the wet beneficiation test results:

TG-1 or magnetite sample was enriched by changing the magnetic strength of wet magnetic separator, and the quality of enrichment in a weak magnetic field is poor, but the concentrate content and metal recovery are high in a strong magnetic field, which shows that the concentration of the sample in a weak magnetic field is less efficient.

As the period of mineral grinding in iron ore increases, the quality of the concentrate increases and the amount of toxic impurities decreases, but the content of silicon oxide and phosphorus is high. According to this, silicon oxide and phosphorus are very embedded, which could not be completely released from useful minerals. Therefore, in order to reduce the amount of toxic impurities, it is necessary to release beneficial minerals to a sufficient level.

3. Conclusions

1) Laboratory experiments were carried out on mixed ore of TG-1 magnetite, TG-4 hematite, and TG-5 magnetite hematite from the currently used quarry of the Tamir main deposit concentrator.

2) According to the results of chemical analysis, the content of iron in the primary ore varies, and the content of silicon oxide (SiO_2), which is a toxic impurity, is relatively high.

3) According to the results of sieving and chemical analysis of primary ore, the content of useful minerals in each category is evenly distributed.

4) The TG-4 hematite sample was not concentrated in the electromagnetic analyzer, and when the mixed sample of TG-1 magnetite and TG-5 magnetite hematite was concentrated, as the particle size decreased, the useful minerals weakened and the iron content in the concentrate increased. Beneficial minerals in the coarse-grained category are not completely released from the void rock, reducing the quality of the concentrate. When TG-1 samples were concentrated in an electromagnetic analyzer, the content of iron concentrate in the −0.1 + 0.088 mm and −0.088 mm categories reached a sufficient level of 61.16% - 65.75%, the yield was 65% - 66%, and the metal recovery was 76.11% - 78.69%. The concentration quality of TG-5 sample in electromagnetic analyzer was poor, as the grain size decreased, beneficial minerals weakened and concentrate content increased, and the concentrate content reached 57.35% in the −0.088 mm class. According to the experiments, it is possible to concentrate the iron ore by grinding and separating the useful minerals from the empty rocks by magnetic method.

5) According to the test to determine the grinding mode, when the grinding time was increased to 20 - 40 minutes, the content of the −0.074 mm class increased steadily, and the optimal mode was 40 minutes. When the grinding time is 40 minutes, the content of the −0.074 mm grade of the TG-5 sample is 67%, and the content of the −0.074 mm grade of the TG-1 sample is 72.1%. In order to improve the quality of the TG-1 magnetite sample concentrate and reduce the amount of toxic compounds, the grinding time was increased to 90 minutes, and the grade of −0.074 mm reached 93.11%, P80% = 58 μm.

6) In the XCRS wet magnetic separator of the laboratory, the mixed samples of TG-1 magnetite and TG-5 magnetite hematite were concentrated by changing the magnetic field strength to 2A and 4A.

7) When TG-5 magnetite hematite mixture samples were concentrated in a strong magnetic field, the concentrate content was enriched to 55.74% - 57.99% depending on the grinding mode. Mixed samples of magnetite hematite are dominated by weakly magnetic iron oxides and are poorly enriched in strong magnetic fields.

8) When TG-1 magnetite samples were concentrated in a weak magnetic field in a wet magnetic separator, depending on the grinding mode, the concentrate content reached 61.15% - 62.14%, but the yield and metal recovery were very

low, and the iron content in the waste was high. Concentration in a strong magnetic field increases concentrate yield and metal recovery, while −0.074 mm grade content is 72%, concentrate content is 62.31%, metal recovery is 71.81%, concentrate yield is 63%, and iron content in waste is 41.81%. In the concentrate, the content of Al_2O_3, which is a toxic mixture, is 1.02%, the content of SiO_2 is 5.37%, the content of P is 0.4%, and the content of S is low.

9) According to the experiment to improve the quality of the concentrate by completely releasing the useful minerals, when the grinding time increased, the yield and metal recovery of the wet magnetic concentration concentrate increased, but the number of toxic impurities did not decrease. The amount of toxic impurities contained in the iron concentrate enriched by a wet magnetic separator has been reduced to a certain extent depending on the grinding, but it has not reached the required level.

10) The high content of wet magnetic beneficiation waste is due to the presence of weakly magnetic iron oxides, and the waste content increases as the beneficial minerals become weaker.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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