Physicochem. Probl. Miner. Process., 60(5), 2024, 192832

http://www.journalssystem.com/ppmp

Physicochemical Problems of Mineral Processing

ISSN 1643-1049

Experimental investigation on magnetic-gravity combined beneficiation of low-grade iron ore

Fangping Ye [1], Yaojie Duan [1], Zhiqiang Guo [2]

[1] Key Lab of Modern Manufacture Quality Engineering, Hubei University of Technology, Wuhan 430068, China
[2] SLon Magnetic Separator Co., Ltd., Ganzhou, 341000, China

Corresponding author: m18469157952@163.com (Zhiqiang Guo)

Abstract: Iron ore is an important raw material for manufacturing steel, while the grade of domestic iron ore is relatively low in China, thus it is difficult to concentrate. The low-grade iron ore with a total iron content of only 33.51% is innovatively upgraded by the magnetic-gravity combined beneficiation method. The effects of three key operating parameters of magnetic induction, grinding concentration, and centrifuge speed on magnetic-gravity combined beneficiation are investigated. These results show that the magnetic-gravity combined beneficiation method significantly improves the iron grade of the concentrates at high recovery. The feasibility is further confirmed through continuous expansion semi-industrial tests with the optimized parameters. The grade of the iron ore concentrate is increased from 33.51% to 63.58% with an iron recovery of 71.01% and a productivity of 37.43%. It is thus concluded that the magnetic-gravity combined beneficiation method has provided a technical reference for the recovery of iron resources from low-grade ores.

Keywords: low-grade iron ore, magnetic-gravity combined beneficiation method, continuous expansion semi-industrial tests

1. Introduction

Iron is a widely distributed element in the earth's crust, constituting up to 4.75% (Tang, 2021). Steel and ferroalloys are widely used in industries such as mechanical manufacturing, transportation and construction, etc. (Liu et al., 2022; Nunna et al., 2021). Since the beginning of the 21st century, with the rapid development of the steel industry, the supply of iron ore in the international market has been tight (Ma et al., 2018). The consumption pattern of steel showing an increasing trend these days is a matter of concern as the high-grade iron ores are getting depleted very fast (Subhnit et al., 2020). With high-quality iron ores having been almost exhausted, processing methods for low-grade iron ores should be developed and utilized (Xu et al., 2023; Song et al., 2019). China is the world's largest consumer of iron ore. According to the 2023 China Mineral Resources Report, China's apparent iron ore consumption (domestic production and net imports) is 1.42 billion tons. Among them, the amount of imported iron ore is 1.124 billion tons, accounting for 80% of the total. China is rich in iron ore, but the ore grade is very poor. To meet its iron ore needs, a large portion of iron ore needs to be imported from other countries, such as Brazil, Australia, and India (Liu et al., 2021). Therefore, in the face of such a negative situation, the significance of comprehensive separation and utilization technology for low-grade ore is quite necessary (Yue et al., 2021; Lima et al., 2020). Iron ore beneficiation and metallurgy produce large quantities of iron tailings, which are hazardous wastes. More than 10 billion tons of iron tailings are deposited in iron tailings dams globally every year. At present, the cumulative amount of iron tailings has reached 6 billion tons in China (Deng et al., 2023). The comprehensive utilization of iron tailings has attracted global attention. Various recovery technologies including gravity separation (LIU et al., 2019), flotation (Tiu et al., 2022), magnetic separation (Guiral-vega et al., 2022), bioleaching (Han et al., 2023), etc., are developed for the development of abundant iron resources in iron tailings based on the unique characteristics of iron oxide and gangue minerals. However, the comprehensive utilization rate of iron tailings is still about 20%, which is still far from

DOI: 10.37190/ppmp/192832

the average level of the comprehensive utilization rate of tailings in China. In addition, there are still problems such as low added value of products in the resource utilization of iron tailings in China (Du et al., 2024). Actually, many experts and scholars have been innovating their technology to improve the efficiency of mining and refining low-grade ore. The commonly used low-grade iron ore refining methods mainly include flotation, gravity separation, and magnetic separation in the mineral process (Dudchenko et al., 2024; Baawuah et al., 2020; Das and Rath, 2020).

In the past few decades, flotation has been fully researched, and it has been widely used in iron ore upgrading. Iron ore flotation generally adopts two technical routes: iron oxide direct flotation and reverse flotation of gangue minerals inhibited by iron oxides. Nowadays, reverse flotation is the most commonly used route in iron ore flotation. Cationic reverse flotation and anionic reverse flotation are applied in the iron ore dressing industry. Anionic collectors such as fatty acids are adsorbed on the mineral surface through chemical adsorption. Cationic collectors such as amines are adsorbed on the mineral surface using electrostatic interaction. However, these methods have their limitations; for example, in the reverse flotation process of iron ore, non-target minerals are often collected, which reduces the selectivity (De Matos et al., 2022; Fan et al., 2020; Rath and Sahoo, 2022; Dehghani et al., 2022). Magnetic separation is a method often employed in the iron ore beneficiation process (Wan et al., 2022). The magnetic separator for iron ore beneficiation is simple in operation and high in separation efficiency as the magnetic separation technology throws out unqualified tailings in advance, reduces the amount of grinding, and improves the economic benefits of iron ore plants. But, for low-grade iron ore using a single magnetic separation, the grade of iron ore increases by a small margin (Kukkala et al., 2024; Xie et al., 2022; Sivrikaya and Arol, 2012). Hematite, limonite, and siderite are typically purified by gravity separation according to different mineral properties. Gravity separation is also usually used to treat coarse-grained disseminated ores (Terzi et al., 2021). Gravity separation has a significant effect on improving the grade of lean iron ore. Compared with reverse flotation, gravity separation is relatively simple and does not pollute the environment, and its separation principle was introduced in detail by Rodrigues et al. (Rodrigues et al., 2023). However, only using a single gravity separation method leads to a relatively high tailings grade and a low iron recovery rate, which is not conducive to the comprehensive recovery and utilization of minerals (Mitchell et al., 2023; Nayak et al., 2021).

According to previous studies, low-grade iron minerals are difficult to refine using single magnetic separation. A single gravity separation method produce high-grade ore. Nevertheless, it is difficult to guarantee the recovery rate. Thus, a magnetic-gravity combined beneficiation method is innovatively proposed. It is conceivable that the low-grade iron ore is subjected to magnetic separation, with guaranteed recovery, and then gravity separation is used to increase the grade of the iron ore to obtain a satisfactory concentration (Chang et al., 2020). In this investigation, the magnetic-gravity combined beneficiation method is used to improve the grade of lean iron ore, and the effects of main operating parameters on the separation performance are introduced in detail. In addition, its feasibility is further confirmed by the continuous expansion semi-industrial tests.

2. Materials and methods

2.1. Chemical multi-element analysis and occurrence state analysis of raw ore

The materials used in this survey are from Hubei Province, China. The low-grade iron ore test sample is analyzed by chemical composition multi-element analysis and mineral composition using an X-fluorescence spectrometer (ZSXPrimuslll+) manufactured by Rigaku (Gu et al., 2024). The results of the analysis are presented in Tables 1 and 2.

From Table 1, the TFe content in the crude iron ore is 33.51%, so the crude iron ore is a low-grade ore. The main impurities contained in crude iron ore are SiO_2 and Al_2O_3, with the contents of 37.61% and 4.28%, respectively. The content of other impurities is relatively small. From Table 2, the main metallic minerals in this crude iron ore are hematite and magnetite, with content of 21.61% and 9.3%, respectively. There is also a small amount of limonite at 1.59%. The composition of other metallic minerals is negligible.

2.2. Experimental investigation

Chemical phase analysis results of the sample ore indicate that the ore iron is mainly distributed in

Table 1. The chemical composition of crude iron ore (wt.%)

Element	TFe	SiO_2	Al_2O_3	CaO	MnO	TiO_2
Grade	33.51	37.61	4.28	0.11	0.19	0.48
Element	K_2O	MgO	P	Na_2O	S	Li_2O
Grade	0.16	0.81	0.044	0.057	0.075	0.26

Table 2. Metallic mineral composition of crude iron ore (wt.%)

Mineral	Hematite	Magnetite	Limonite	Silicate iron ore	Others	Sum
Content	21.61	9.83	1.59	0.37	0.11	33.51
Distribution rate	64.49	29.33	4.75	1.10	0.33	100.00

hematite and magnetite. Other iron minerals are too low in content to be valuable for development. Magnetite is a strongly magnetic mineral, while hematite is a weakly magnetic mineral. As a result, weak and strong magnetic separations are used to recover them respectively. Since the original ore is low-grade ore, it is difficult to obtain high-grade ore only using magnetic separation. In the process, gravity separation is added to improve the ore grade effectively.

The experimental ore sample in this research is low-grade iron ore, with the TFe content of 33.51%. Firstly, coarse-grained magnetic separation and tailing treatment are carried out on the raw ore. This method greatly reduces the cost of beneficiation due to the low-grade of the ore. After that, the obtained coarse concentrate is ball milled (Wan et al., 2022), and then the coarse concentrate after grinding treatment is selected using magnetic-gravity combined beneficiation method. In the process of magnetic separation, the strong magnetic minerals are separated employing the SCT-44 permanent magnetic separator, and the weak magnetic minerals are separated utilizing the SLon-100 periodic pulsating high gradient magnetic separator. Finally, a SL-400 centrifugal separator is used to purify the coarse concentrate after strong magnetic separation. Each experimental product is filtered, dried, weighed, sampled, and analyzed separately, and the final product indicators are calculated. The specific experiment process is shown in Fig. 1. The above equipments are manufactured by SLon Magnetic Separator Co., Ltd., Ganzhou.

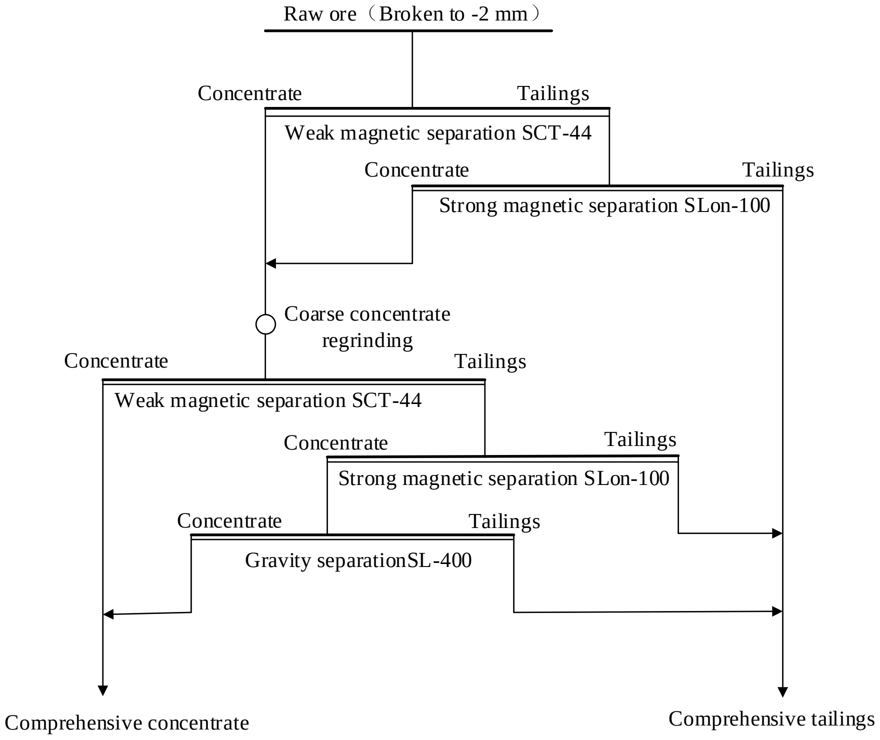

Fig. 1. Experiment flow chart

2.3. Industrial tests

After the parameters are obtained through experiments, to ensure the effectiveness of the beneficiation method and various parameters in industrial applications, continuous expansion semi-industrial tests are carried out to further verify them. SCT-44 permanent magnet separator is used for the magnetic separation of strong magnetic minerals, and the SLon-500 periodic pulsating high gradient magnetic separator is used for the separation of weak magnetic minerals. In order to effectively improve the grade of iron ore, the SL-400 centrifugal separator is used for selection. Finally, the physical composition of the concentrate is analyzed by an X-ray powder diffractometer (D8 Advance) produced by Bruker AXS GmbH in Germany.

3. Results and discussion

3.1. Conditional experiments

3.1.1. The effect of magnetic induction intensity on coarse-grained tail throwing

The TFe content of the raw ore is only 33.51%, and the coarse-grained tail-throwing method is used. This method increases the grade while reducing the milling treatment capacity, and also improves the economic efficiency of the beneficiation plant and reduces the cost. Some minerals in the ore exhibit strong magnetic properties, necessitating a preliminary weak magnetic separation process. The SCT-44 Permanent Magnetic Separator is used to separate strong magnetic minerals from low-grade ores with weak magnetic induction intensity. The magnetic induction intensity of weak magnetic separation is determined through conditional experiments.

As illustrated in Fig. 2, the iron recovery rate exhibits a notable increase with elevated magnetic induction intensity, although the grade of the recovered iron ore declines. Once the magnetic induction intensity reaches 0.1 T, the recovery of iron ore essentially ceases to increase, while the grade of iron ore declines significantly. This is because a small amount of impurity particles are entrained by metallic iron particles. Thus, with increasing magnetic induction intensity, the small impurity particles, entrained by the iron particles, are then dressed into the magnetic product. This may explain why the grade of iron ore decreases as the intensity of the magnetic induction increases. So the magnetic induction intensity is not too high or too low, just 0.1 T is appropriate (Liu et al., 2017).

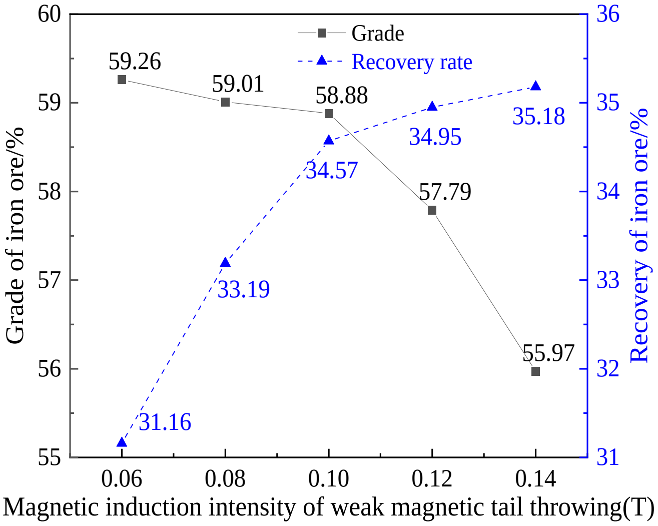

Fig. 2. Coarse grain tail throws weak magnetic induction intensity experimental results

As the weak magnetic separation tailings also contain some valuable weak magnetic minerals, the weak magnetic separation tailings are subjected to further strong magnetic separation experiments. Weak magnetic minerals are separated using the SLon-100 periodic pulsating high gradient magnetic separator. The intensity of the strong magnetic induction is determined through conditional experiments.

As illustrated in Fig. 3, the recovery of iron ore exhibits a continuous increase with an augmenting magnetic induction intensity, while the grade undergoes a gradual and slow decline. When magnetic induction intensity exceeds 1.3 T, iron ore recovery remains largely unchanged, while iron ore grade declines rapidly. Accordingly, the results obtained from the experimental investigation demonstrate that a magnetic induction intensity of 1.3 T is optimal. The combination of a concentrate derived from weak magnetic separation and a concentrate derived from strong magnetic separation is considered a coarse concentrate.

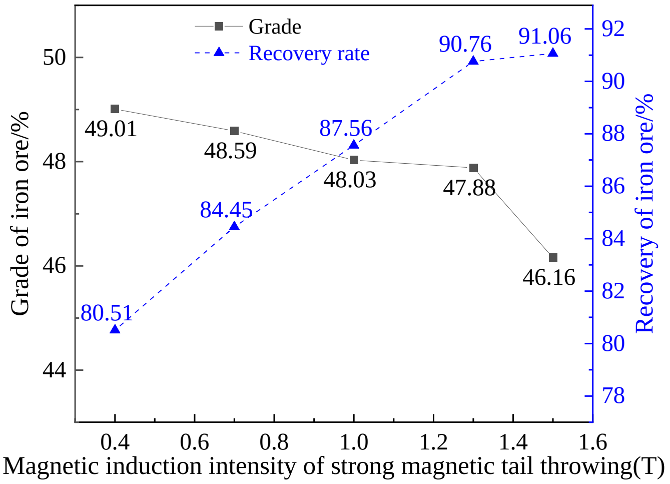

Fig. 3. Coarse grain tail throw strong magnetic induction intensity experimental results

3.1.2. The effect of grinding particle size

The treatment of coarse tailings has been demonstrated to significantly enhance the iron ore grade. In order to achieve a higher grade, it is necessary to subject the coarse concentrate to further grinding and re-screening. The grinding particle size is determined by conditional experiments. The grinding particle size is variable, with a weak magnetic induction intensity of 0.1 T.

From Fig. 4, it is clear that the quality of the concentrate obtained by weak magnetic separation increases as the grinding particle size gets finer, while the recovery rate goes in the opposite direction. If the 0.074 mm grinding size accounts for more than 85%, the iron ore grade does not improve and the recovery rate is obviously reduced. This observation is interpreted by the fact that at finer particle sizes, the liberation of magnetite is higher, resulting in better-quality iron concentrate. The reason for the decline in recovery that it is more difficult to capture fine magnetite by magnetic separation compared to coarse magnetite. Since the magnetic force is proportional to the cubic of the particle diameter, the magnetic force decreases dramatically as the particle diameter decreases. Few ultrafine particles are captured in the attraction zone when the magnetic force is inadequate to drive fine particles, whereas the majority of ultrafine particles flow into the tailings due to drag and gravity forces (Dai et al., 2023; Liu et al., 2022; Yu et al., 2017). To balance the grade and recovery of the concentrate, and taking into account the cost of grinding, a grind size of -0.074 mm for 85% is appropriate.

3.1.3. The effect of magnetic induction intensity on weak magnetic separation of coarse concentrate

After grinding, the coarse concentrate is again selected by weak magnetic separation. In order to determine the magnetic induction intensity of weak magnetic separation with the condition of grinding particle size of-0.074 mm accounting for 85%, it is necessary to use SCT-44 permanent magnet magnetic separator to test the magnetic induction intensity of weak magnetic separation.

As shown in Fig. 5, as the magnetic induction intensity is increased, the recovery of the concentrate rises continuously, but the grade progressively declines. At magnetic induction intensity in excess of 0.1 T, there is almost no change in the recovery of iron ore, while the grade is significantly reduced. Therefore, it is more appropriate to select the magnetic induction intensity of the pre-selected concentrate as 0.1 T in weak magnetic separation.

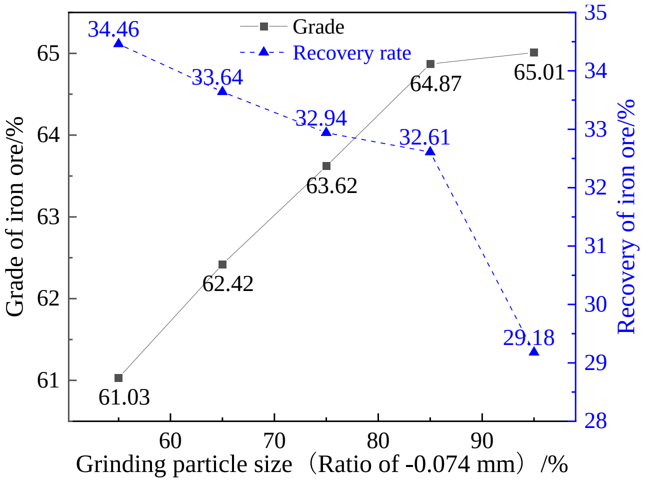

Fig. 4. Experimental results of grinding fineness

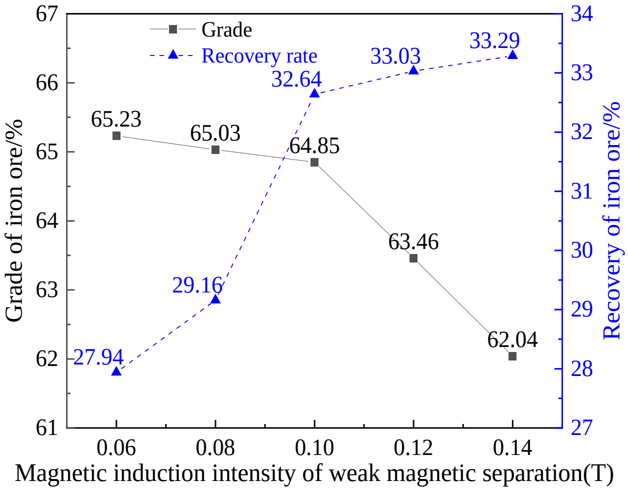

Fig. 5. Weak magnetic separation magnetic induction intensity experimental results

3.1.4. The effect of magnetic induction intensity on strong magnetic separation of coarse concentrate

Although the pre-selected concentrate grade following weak magnetic separation is relatively high, the recovery of iron ore remains low. Consequently, it is imperative to implement robust magnetic separation of the coarse concentrate tailings subsequent to the weak magnetic separation, to enhance the recovery of iron ore. In order to determine the magnetic induction intensity of strong magnetic separation, the magnetic induction intensity condition experiments of strong magnetic separation are carried out by using a Slon-100 vertical ring pulsating high gradient magnetic separator.

As illustrated in Fig. 6, the recovery of the concentrate from strong magnetic separation exhibits a pronounced increase with rising magnetic induction intensity. However, the grade exhibits an inverse relationship. It has been observed that as the magnetic induction intensity exceeds 0.8 T, the recovery of iron ore increases at a slower pace, while the grade decreases at a more rapid rate. Accordingly, a determination of the magnetic induction intensity of 0.8 T in strong magnetic separation is more appropriate.

3.1.5. The effect of centrifuge speed

The experimental results presented above demonstrate that strong magnetic separation results in the production of a relatively low-grade concentrate. In order to further improve the grade of the concentrate obtained through strong magnetic separation, the concentrate is subjected to gravity separation by centrifuge, thereby improving the grade. The pre-selected concentrate resulting from magnetic separation and the concentrate derived from gravity separation are combined into a composite concentrate. The grade of composite concentrate needs to be above 63% to be considered acceptable. To ascertain the centrifugal velocity of the centrifuge, the SL-400 centrifuge is employed to conduct gravity separation condition experiments.

As illustrated in Fig. 7, the recovery of the composite concentrate increases with an increase in centrifuge speed, while the grade tends to decrease. At centrifuge speeds in excess of 450 r/min, the grade of the composite concentrate drops dramatically, while recovery increases minimally. Because of the increased centrifugal force, more gangue minerals are entrained in the concentrate. Therefore, when the centrifugal speed is too high, the grade of iron ore drops sharply (Nirlipta and Bhatu, 2013). Furthermore, it is essential to guarantee that the grade of the composite concentrate exceeds 63%. Therefore, it is established that a centrifuge speed of 450 r/min is more appropriate.

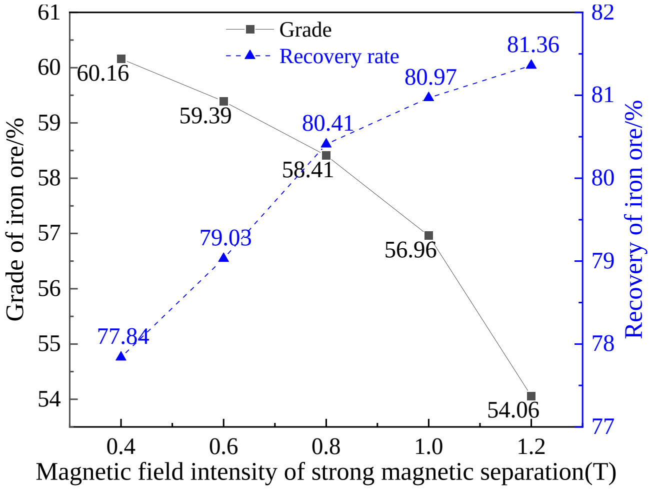

Fig. 6. Strong magnetic separation magnetic induction intensity experimental results

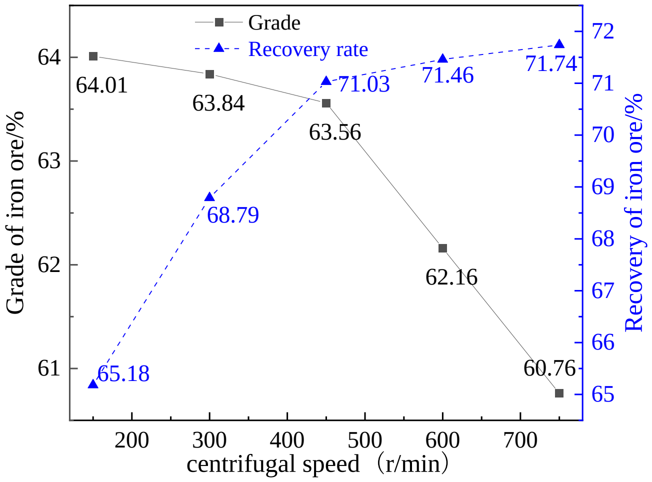

Fig. 7. Centrifugal beneficiation experimental results.

3.2. Continuous expansion semi-industrial tests

Through the previous conditional experiments, it is determined that the magnetic induction intensity of weak magnetic tailings is 0.1 T, the magnetic induction intensity of strong magnetic tailings is 1.3 T, the coarse concentrate grinding particle size of-0.074 mm accounts for 85 %, the magnetic induction intensity of the weak magnetic separation is 0.1 T, the magnetic induction intensity of the strong magnetic separation is 0.8 T, and the centrifuge speed is 450 r/min.

Based on the above data, continuous expansion semi-industrial tests are conducted. The SCT-44 permanent magnet magnetic separator is used as a weak magnetic separator, the SLon-500 vertical ring pulsating high gradient magnetic separator is used as a strong magnetic separator, and the SL-400 centrifugal separator is used for gravity separation, and the test results are shown in Fig. 8.

According to the test results in Fig. 8, the productivity of the composite concentrate is 37.43%, the grade is 63.58%, and the rate of recovery is 71.01%. The experimental indicators are good, providing a reference for the recovery of poor iron ore. Finally, X-ray diffraction analysis is performed on the composite concentrate, and the analysis results are shown in Fig. 9.

From Fig. 9, the predominant forms of iron in the composite concentrate are Fe_2O_3 and Fe_3O_4. It also contains a small number of associated minerals such as Mn, and the gangue mineral is mainly SiO_2. The content of other impurities is minimal, and the mineral composition of the concentrate is relatively straightforward.

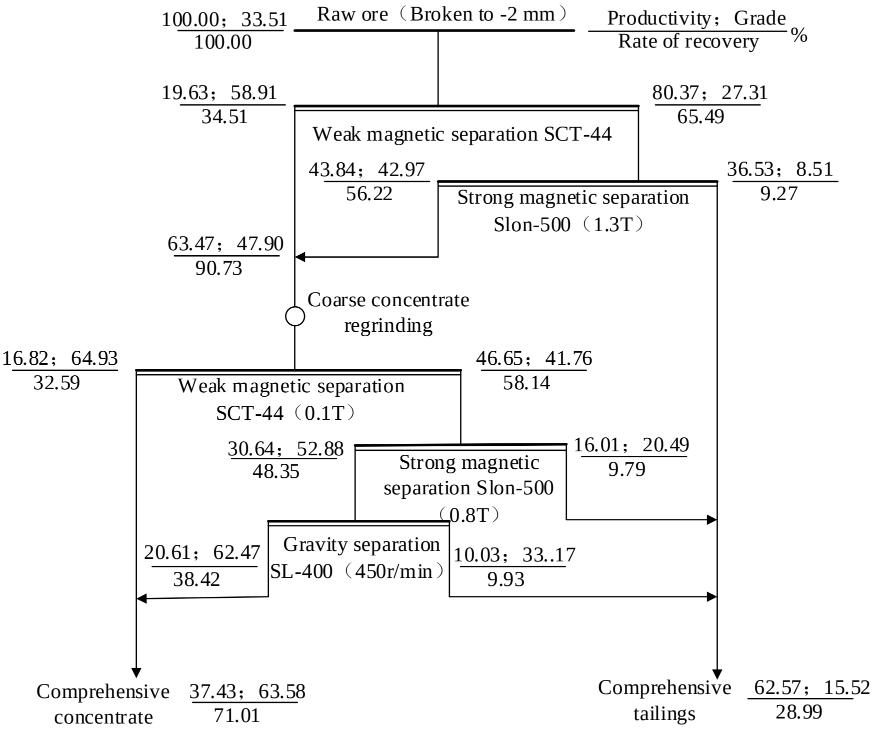

Fig. 8. Continuous expansion semi-industrial test results

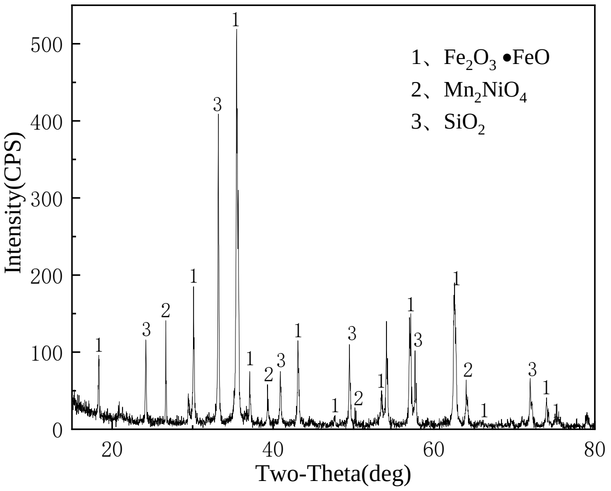

Fig. 9. XRD analysis results of concentrate

4. Conclusions

(1) The low-grade iron ore from China has a TFe content of 33.51% and a relatively simple chemical composition. Following a series of preliminary trials, the magnetic-gravity combined beneficiation method has demonstrated its efficacy in the recovery of iron minerals from low-grade ores. Through conditional experiments, it is determined that the magnetic induction intensity of weak

magnetic tailings is 0.1 T, the magnetic induction intensity of strong magnetic tailings is 1.3 T, the coarse concentrate grinding particle size of-0.074 mm accounts for 85%, the magnetic induction intensity of the weak magnetic separation is 0.1 T, the magnetic induction intensity of the strong magnetic separation is 0.8 T, and the centrifuge speed is 450 r/min.

(2) The results of the continuous expansion semi-industrial tests indicate that the productivity of the composite concentrate is 37.43%, the grade of iron is 63.58%, and the recovery rate of iron is 71.01%. The tests indexes are of an excellent quality. The success of the continuous expansion semi-industrial tests provides a reference and basis for the full industrial test. Continuous expansion semi-industrial tests has proved that the process effectively improves the grade of low-grade iron ore in industrial applications. Compared to other methods such as flotation, the cost is lower and the efficiency is higher. The magnetic-gravity combined beneficiation method does not require the use of large quantities of chemicals and therefore has a lower environmental impact.

(3) The process flow of the method is relatively simple, and it is easy to operate and maintain. However, the scope of application of this method is limited, and the effectiveness of magnetic separation and gravity separation may be reduced for very fine-grained minerals. If the ore contains a variety of minerals with different properties, especially when the physical properties of these minerals are similar, the magnetic-gravity combined beneficiation does not achieve the desired separation effect. Despite the low operating costs, the initial investment costs for magnetic separation and gravity separation equipment are relatively high for large-scale industrial production. For the magnetic-gravity combined beneficiation technology, it is necessary to further study how to optimize the magnetic-gravity combined beneficiation process for complex ores containing multiple minerals.

Acknowledgments

The work is supported by Natural Science Foundation of Hubei Province of China (Grant No. 2023AFB400), and the authors are grateful to the Key Laboratory of Transport Industry of Port Cargo Handling Technology (Wuhan University of Technology), Ministry of Transport, PRC (No. GKZX 2023003) for the support to this investigation work.

References

BAAWUAH, E., KELSEY, C., ADDAI-MENSAH, J., SKINNER, W., 2020. *Assessing the performance of a novel pneumatic magnetic separator for the beneficiation of magnetite ore.* Minerals Engineering. 156.

CHANG, J., LI, H. J., ZHENG, K. D., LIU, C. G., WANG, L. M., LI, B., BU, X. N., SHAO, H. Z., 2020. *Mineralogical characterisation and separation studies on the recovery of Cr2O3 in the high carbon ferrochrome slag.* Physicochemical Problems of Mineral Processing. 56(3), 460-470.

DAI, M. B., ZHOU, Y. C., XIAO, Q. F., LV, J. F., HUANG, L. Y., XIE, X., HU, Y. M., TONG, X., CHUN, T. J., 2023. *Arsenic removal and iron recovery from arsenic-bearing iron ores by calcification-magnetic roasting and magnetic separation process*. Frontier of Environmental Friendly Recycling Technology for Metals. 16(21), 6884.

DAS, B., RATH, S. S., 2020. *Existing and new processes for beneficiation of Indian iron ores.* Transactions of the Indian Institute of Metals. 73(3), 505-514.

DEHGHANI, F., KHOSRAVI, R., PAZOKI, A., KEBE, M., JAHANIAN, R., SIAVOSHI, H., GHOSH, T., 2022. *Application of magnetic separation and reverse anionic flotation to concentrate fine particles of iron ore with high sulfur content.* Physicochemical Problems of Mineral Processing. 58(3).

DE MATOS, V. E., NOGUEIRA, S. D. S., KOWALCZUK, P. B., DA SILVA, G. R., PERES, A. E., 2022. *Differences in etheramines froth properties and the effects on iron ore flotation. Part I: Two-phase systems.* Mineral Processing and Extractive Metallurgy Review. 43(2), 209-216.

DENG, J. H., NING, X. A., QIU, G. Q., ZHANG, D. Y., CHEN, J. Y., LI, J. Y., LIANG, Y. Z., WANG, Y., 2023. *Optimizing iron separation and recycling from iron tailings: A synergistic approach combining reduction roasting and alkaline leaching*. Journal of Environmental Chemical Engineering. 11(3), 110266.

DUDCHENKO, N., PONOMAR, V., OVSIIENKO, V., CHEREVKO, Y., PERELSHTEIN, I., 2024. *Mineral magnetic modification of fine iron ore tailings and their beneficiation in alternating magnetic fields.* Metals. 14(1).

DU, X., FU, G. H., CHU, H. C., YANG, X. F., FU, Y. F., DONG, Z. H., LIU, J. J., MAN, X. F., ZHI, H., 2024. *Characteristics analysis of iron tailings and current status and prospects of its utilization technology*. China Mining Magazing. 33(2), 115-124.

FAN, G. X., WANG, L. G., CAO, Y. J., LI, C., 2020. *Collecting agent-aineral interactions in the reverse flotation of iron ore: A brief review*. Minerals. 10(8).

GUIRAL-VEGA, J. S., PEREZ-BARNUEVO, L., BOUCHARD, J., URE, A., POULIN, E., DU BREUIL, C., 2022. *Particle-based characterization and classification to evaluate the behavior of iron ores in drum-type wet low-intensity magnetic separation*. Minerals Engineering. 186. 107755.

GU, J. T., YUAN, Z. T., DU, Y. S., LU, J. W., YANG, C., LV, H. Y., 2024. *Enhancement of ilmenite magnetic properties by oxidation roasting and magnetic separation*. Physicochemical Problems of Mineral Processing. 60(4), 190706.

HAN, X. Y., WANG, F., ZHAO, Y., MENG, J. P., TIAN, G. Y., WANG, L. J., LIANG, J. S., 2023. *Recycling of iron ore tailings into magnetic nanoparticles and nanoporous materials for the remediation of water, air and soil: a review*. Environmental Chemistry Letters. 21, 1005-1028.

KUKKALA, P. C., KUMAR, S., NIRALA, A., KHAN, M. A., ALKAHTANI, M.Q., ISLAM, S., 2024. *Beneficiation of low-grade hematite iron ore fines by magnetizing roasting and magnetic separation.* Acs Omega. 9(7), 7634-7642.

LIMA, L., ALBERTIN, E., CORREA, E. R., RABELLO, R. B., UEHARA, S., 2020. *Pearlite refining strategies for hypoeutectic gray cast iron.* International Journal of Metalcasting. 14(3), 766-773.

LIU, B. B., ZHANG, Y. B., LU, M. M., SU, Z. J., LI, G. H., JIANG, T., 2019. *Extraction and separation of manganese and iron from ferruginous manganese ores: A review*. Minerals Engineering. 131, 286-303.

LIU, J. J., XIE, S. P., LI, X. D., LU, D. F., WANG, H., YAO, Q., YANG, X. F., FU, Y. F., 2022. *Separating efficiency of ferromagnetic particles and principle of low-intensity dry magnetic separator under different air supply modes:Based on multi-physical modeling*. Powder Technology. 415.

LIU, J. S., XING, Z. X., CHENG, G. J., XUE, X. X., DING, X. Y., 2022. *Study on the grinding kinetics and magnetic separation of low-grade vanadiferous titanomagnetite concentrate*. Metals. 12(4), 575.

LIU, S., ZHANG, B., MIN, H., AN, Y. R., ZHU, Z. X., LI, C., 2021. *X-Ray Fluorescence Spectroscopy Combined With Discriminant Analysis to Identify Imported Iron Ore Origin and Brand : Application Development.* Spectroscopy And Spectral Analysis. 41(1), 285-291.

LIU, Z. G., CHU, M. S., WANG, Z., ZHAO, W., TANG, J., 2017. *Study on metallized reduction and magnetic separation of iron from fine particles of high iron bauxite ore*. High Temperature Materials and Processes. 36, 79-88.

MA, B. D., CHEN, Y. T., ZHANG, S., LI, X. X., 2018. *Remote sensing extraction method of tailings ponds in ultra-low-grade iron mining area based on spectral characteristics and texture entropy*. Entropy-based Data Mining. 20(5), 345.

MA, W., ZHU, X., WANG, M., 2013. *Forecasting iron ore import and consumption of China using grey model optimized by particle swarm optimization algorithm*. Resources Policy. 38, 613-620.

MITCHELL, K., URADE, S., KERSHAW, A., CHU, P. B., JIN, Y. F., 2023. *3D printing of conical centrifuge system for mineral particle separation.* Separation and Purification Technology. 306.

NAYAK, A., JENA, M. S., MANDRE, N. R., 2021. *Application of Enhanced Gravity Separators for Fine Particle Processing: An Overview.* Journal of Sustainable Metallurgy. 7(2), 315-339.

NIRLIPTA, P. N., BHATU, K. P., 2013. *Separation behaviour of iron ore fines in kelsey centrifugal jig*. Journal of Minerals and Materials Characterization and Engineering. 1(3), 85-89.

NUNNA, V., SUTHERS, S. P., POWNCEBY, M. I., SPARROW, G. J., 2021. *Beneficiation strategies for removal of silica and alumina from low-grade hematite-goethite iron ores.* Mineral Processing and Extractive Metallurgy Review. 43(8), 1049-1067.

RATH, S. S., SAHOO, H., 2022. *A review on the application of sarch as depressant in iron ore flotation.* Mineral Processing and Extractive Metallurgy Review. 43(1), 122-135.

RODRIGUES, A. F. D. V., JUNIOR, H. D., RODRIGUES, O. M. S., ZHOU, J. M., GALVIN, K. P., 2023. *Gravity separation of fine itabirite iron ore using the Reflux Classifier-Part I-Investigation of continuous steady state separations across a wide range of parameters.* Minerals Engineering. 201.

SIVRIKAYA, O., AROL, A. I., 2012. *Evaluation of low grade iron ore deposit in erzincan-turkey for iron ore pellet concentrate production.* Physicochemical Problems of Mineral Processing. 48(2), 475-484.

SONG, Y., WANG, N., YU, A., 2019. *Temporal and spatial evolution of global iron ore supply-demand and trade structure.* Resources Policy. 64, 101506.

SUBHNIT, K. R., DEEPAK, N., SWAGAT, S. R., 2020. *A review on the enrichment of iron values of low-grade iron ore resources using reduction roasting-magnetic separation*. Powder Technology. 367, 796-808.

TANG, M., 2021. *Composition of the Earth's Crust.* Encyclopedia of Geology, 2nd ed. 178-186.

TERZI, M., UNVER, I. K., CINAR, M., OZDEMIR, O., 2021. *Digital image processing (DIP) application on the evaluation of iron-rich heavy mineral concentrates produced from river sand using a sequential mineral processing approach.* Physicochemical Problems of Mineral Processing. 57(3), 21-35.

TIU, G., GHORBANI, Y., JANSSON, N., WANHAINEN, C., BOLIN, N. J., 2022. *Ore mineral characteristics as rate-limiting factors in sphalerite flotation: Comparison of the mineral chemistry (iron and manganese content), grain size, and liberation*. Minerals Engineering. 185, 107705.

WAN, H., LU, X. L., LUUKKANEN, S., QU, J. P., ZHANG, C. H., CHEN, Y. X., BU, X. Z., 2022. *Properties of flash roasted products from low-grade refractory iron tailings and improvement method for their magnetic separation index.* Physicochemical Problems of Mineral Processing. 58(6).

XIE, S. P., HU, Z. C., LU, D. F., ZHAO, Y., 2022. *Dry permanent magnetic separator: Present status and future prospects.* Minerals. 12(10).

XU, G., LI, F., JIANG, P. P., ZHANG, S. Q., 2023. *Preparation of red iron by magnetization roasting-hydrothermal method using ultra-low-grade limonite*. Sustainable Metallurgical Processing and Industrial Solid Waste Recycling. 15(6), 4708.

YUE, Q., BU, Q. C., LI, X., ZHAO, F., HE, J. H., LI, Y., 2021. *Value chain and statistical entropy analyses based on iron flows in China during 1990-2015.* Journal of Iron and Steel Research International. 28(8), 938-948.

YU, J. W., HAN, Y. X., LI, Y. J., GAO, P., 2017. *Beneficiation of an iron ore fines by magnetization roasting and magnetic separation*. International Journal of Mineral Processing. 168, 102-108.