SINERGI Vol. 27, No. 2, June 2023: 271-280
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2023.2.015

Induced roll magnetic separator applied for high grade ilmenite separation from mining tailing

Wiwik Dahani[1,3], Rita Sundari[2], Subandrio[1], Irfan Marwanza[1], Andriyani[1], Djoko Hartanto[3*], Khuzaimah Arifin[4], Ratna Ediati[3]
[1]Department of Mining Engineering, Faculty of Earth Technology and Energy, Universitas Trisakti, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Mercu Buana, Indonesia
[3]Department of Chemistry, Faculty of Science and Data Analytical, Institute Technology Sepuluh November, Indonesia
[4]Fuel Cell Institute, Universiti Kebangsaan Malaysia, Malaysia

Abstract
This article aimed to separate ilmenite ($FeTiO_3$) mineral from tin tailing applying a single splitter IRMS (Induced Roll Magnetic Separator). Ilmenite mineral is the substantial main source for TiO_2. This work used air table middling for feeding. The mineral components of middling feeding from air table using grain counting analysis were found as follows: cassiterite (48.61%), ilmenite (21.36%), monazite (18.56%), pyrite (4.60%), zircon (5.85%), quartz (0.71%), anatase (0.27%), and tourmaline (0.02%), It was found that electrical current and opening of single splitter affected the degree of separation addressing to ilmenite recovery and ilmenite grade. The finding showed that current of 15 Ampere and single splitter with opening 4.25 cm yielded ilmenite recovery more than 74%. The high grade ilmenite (90.46 %) and recovery of 29.38% was obtained using 5 Ampere with single splitter opening of 1.0 cm. Up to date, the study on ilmenite separation from tailing only focused on the effect of current, however, the effect of single splitter magnetic separator to enhance ilmenite recovery from other paramagnetic minerals such as monazite, siderite, xenotime and tourmaline has not yet been reported.

Keywords:
Ilmenite Grade;
Ilmenite Recovery;
Ilmenite;
IRMS;
Single Splitter;

Article History:
Received: July 18, 2022
Revised: November 19, 2022
Accepted: December 22, 2022
Published: June 2, 2023

Corresponding Author:
Djoko Hartanto,
Department of Chemistry, Faculty of Science and Data Analytical, Institute Technology Sepuluh November, Surabaya, Indonesia
Email: djokohar@its.ac.id

INTRODUCTION

Ilmenite is a paramagnetic mineral found together with monazite in mining tin tailing. Ilmenite is the important source for titanium [1], which is broadly used for automotive bearing due to its strong corrosion resistance and mechanical strength. Usually, ilmenite has been recovered from other minerals through several processes related to gravity, flotation technique, and electromagnetic separation applied in many mining industries. The general process to obtain ilmenite from mining tailing has involved with ilmenite separation from minerals such as titanaugite, cassiterite, monazite, pyrite, forsterite, zircon, and others related to flotation using complex organic compounds, electrical and magnetically properties [1, 2, 3, 4, 5]. The studies of ilmenite separation from titanaugite using BHA complex as selective depressant were reported [2, 5]. Tian et al. [3] applied carboxylated starch in separation of imenite from forsterite using flotation technique. At the same time, Meng et al. [4] studied the separation performance of ilmenite with low grade titanium oxide.

With regard to ilmenite recovery, several investigations used modified flotation technique to enhance the result [6, 7, 8, 9]. Hu [6] applied sodium chlorite to oxidize Fe(II) ion to Fe(III) ion in sodium oleate system in order to improve ilmenite floatability, while Xiao [7] applied Al(III) ion in benzohydroxamide acid (BHA) to form Al-BHA complex yielding stronger effect on ilmenite floatability. As similar method to Hu [6], Miao [8] applied Fenton to oxidize Fe(II) ion to Fe(III) ion in sodium oleate to enhance ilmenite floatability. Instead of Al(III) ion and benzohydroxamide acid used to improve ilmenite floatability [7], Yu [9] used Pb (II) ion and octyl hydroxamide acid (OHA) to increase ilmenite floatability. Instead of flotation technique to improve ilmenite recovery, Yuan [10] used magnetic separation method based on interaction between ilmenite and magnetite yielding stronger magnetic properties of ilmenite from titanaugite. Generally, the previous investigations [6, 7, 8, 9, 10] used expensive chemicals to enhance ilmenite recovery. However, our present study does not need any chemical to obtain ilmenite from cassiterite. This is the benefit of our study.

Since ilmenite has its magnetically properties, a modified magnetic separator was often used in mining industry to separate minerals [11, 12, 13, 14]. However, Khalek [15] used an enhanced gravity separator for mineral beneficiation based on particle size and density. Usually, minerals separation applied combine techniques of gravity and electromagnetic separation. Moreover, Khalek [15] conducted titanium recovery from industrial waste using gravity technique, on the other hand, while Wahyuningsih [16] applied leaching acid (HCl) to extract TiO_2 from ilmenite Furthermore, Singh [13] used dry induced roll magnetic separator for particle flow modeling, while Sitepu [14] studied the current effect on ilmenite recovery from tin tailing applied induced roll magnetic separator. In fact, until today only a few publications emphasizing on ilmenite studies has been reported. So far, mining publications have focused on tin cassiterite recovery applying variable jigs, sieve shaker, and high tension magnetic separator [17, 18, 19].

This study has attempted to isolate high grade ilmenite from air table middling obtain from tin mining in Bangka Belitung Province, Indonesia, applying induced roll magnetic separator (IRMS). Furthermore, this study has investigated the effect of electrical current and opening single splitter on ilmenite product in terms of high grade and low grade. Up to date, only a few reports on ilmenite separation was based on the effect of electrical current of the magnetic separator [14]. The effect of short term adjustment or single splitter opening IRMS has not ever been reported yet. Therefore, this study can be viewed as a new finding with respect to high grade ilmenite concentration.

MATERIAL AND METHODS

Material

The tin mining tailing from Bangka Tin Plant located in Bangka Islands, South Sumatera, Indonesia was used as the raw material, which is rich in cassiterite.

Methods

An air table middling obtained from mining tailing in Bangka Belitung Province, Indonesia, was used as a sample. A round screen was used to sieve sample with particle size of – 20 mesh.

Main equipment used in this study including air table, round screen, and induced roll magnetic separator with single splitter. A grain counting analysis microscope was applied for analysis of mineral dressing from air table middling.

Varied air tables or jigs are commonly used for technical mineral separation in many intermediate minerals processing [18] [20, 21, 22, 23]. Whitworth et al. [21] and Khouia et al. [23] studied various minerals processing (size screening, gravity route, electric and magnetic separation, desulfurization) from mining waste to obtain mineral and metal recovery. Shaking table separation is based on differential mineral density. While Pengsaart et al. [22] reviewed gravity separation route for coal processing.

A combination technique of air table, round screen, and modified magnetic separator is used to enhance mineral recovery in many mineral processing [24, 25, 26].

The partial flowchart as the focus of this study is shown in Figure 1. Moreover, Figure 1 presents the main outline of ilmenite recovery from Bangka tin mining tailing that involved combined technique of gravity, screening, and electromagnetic separation applying single splitter IRMS. This study applied air table middling for feeding with given particle size (– 20 mesh) obtained from a round screen (as seen in Figure 1). Back [24] used air table and magnetic separation for municipal solid waste incineration related to clean city maintenance, while Duarte [25] applied magnetics separation to discard iron ore tailings in cement material.

Firstly, the mining tailing of cassiterite was dried using a rotary dryer and then separated on the basis of difference in gravity applying an air table yielding a concentrate mainly consisted of cassiterite containing tin major element, a middling containing ilmenite, monazite, cassiterite, and zircon, and a tailing containing dust, minor elements and impurities. Gravity separation is commonly used in mineral recovery as Li [26] applied low temperature super gravity to separate boron from boron-bearing iron concentrate, while Lan [27] used gravity separation to enrich cerium from rare-earth concentrates, and Zhang [28] enriched Nb and Ti from carbonatite ore used gravity separation in combining with calcining-slaking route.

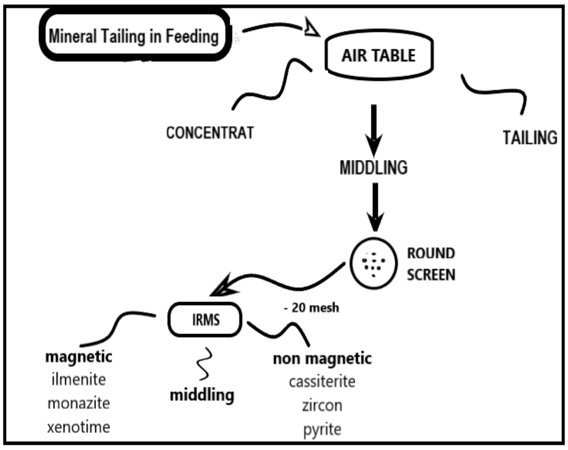

Figure 1. Flow chart diagram of this study. Ilmenite separation using single splitter IRMS.

Figure 2. Air table for mineral dressing in Bangka Tin plant.

Figure 3. Round Screen for sieving air table middling to obtain – 20 mesh.

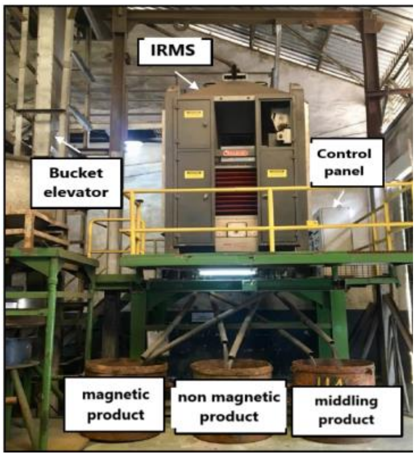

Figure 4. Induced Roll Magnetic Separator (IRMS) for ilmenite recovery.

Gravity route in combination with magnetic separation has many used for metal recovery from minerals due to simplicity and rapidity.

As mentioned above, air table separation is based on gravity properties and magnetic separation based on selective magnetic minerals. In addition, screening or sieving route is also applied in mineral processing in order to enrich metal interest on the basis of particle size related to gravity properties [29].

Secondly, a round screen was used to sieve mineral dressing with particle size of – 20 mesh, the particle size + 20 mesh (larger than 20 mesh) discarded into tailing disposal.

Thirdly, a short-term adjustment single splitter IRMS was applied to separate mineral dressing containing major minerals (monazite, ilmenite, cassiterite, and zircon). The effects of electrical current and opening distance of single splitter of IRMS affect the recovery of high and medium grade ilmenite. The electric current varied from 5 Ampere to 15 Ampere. This study used two opening distance of single splitter IRMS, i.e., 1.0 cm and 4.25 cm adjustment.

The picture of air table, round screen, and IRMS are shown in Figure 2, Figure 3, and Figure 4. The figures illustrate component parts in Amang Bangka Tin plant. The single splitter with short term or opening adjustment (1.0 cm and 4.25 cm) IRMS in Bangka Tin plant is shown in Figure 5. The determination of mineral weight (%) based on fractions is described as follows: e.g.

$$\text{mineral weight (20\#)} = \frac{\text{sample weight (g)}}{\text{total sample weight (g)}} \text{ x } 100\% \qquad (1)$$

Equation (1) is used to determine mineral weight for 20 mesh. The same procedure is also used for mineral weight of other fractions.

Sample weight classified on the basis of particle size of mineral (20 mesh, 50 mesh, 70 mesh, 100 mesh, and – 100 mesh) namely as fractions. Total sample weight is described as mineral weight of all fractions.

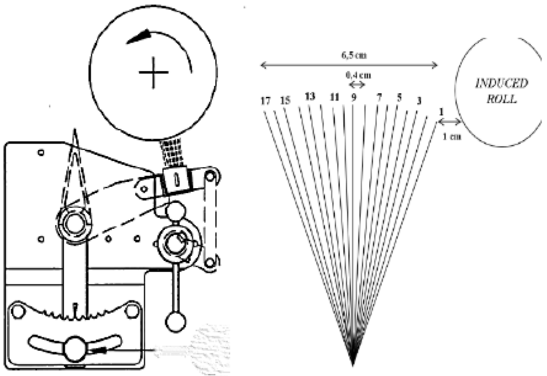

Figure 5. Short term adjustment of Single Splitter integrated to IRMS

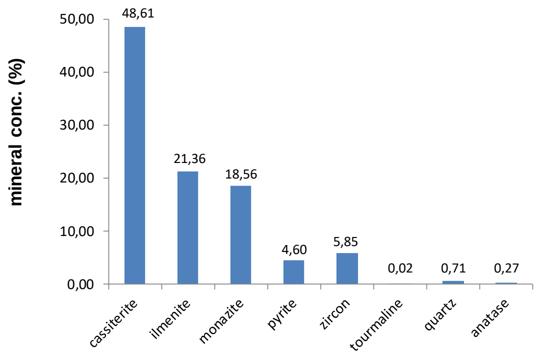

Figure 6. Mineral dressing in feeding using grain counting analysis.

The determination of ilmenite concentration is as follows:

$$\text{concentration of ilmenite (\%)} = \frac{\text{weight of ilmenite IRMS (g)}}{\text{total weight of mineral IRMS (g)}}\ x\ 100 \qquad (2)$$

Weight of ilmenite IRMS (g) =
number of ilmenite particles x density of ilmenite (g/particle) based on approach method.
For determination of ilmenite concentration, particle size was given at – 20 mesh. Number of particles was determined using grain counting analysis method applying microscope.

The determination of ilmenite recovery is as follows:

$$\text{ilmenite recovery (\%)} = \frac{\text{ilmenite IRMS rate x ilmenite conc. IRMS}}{\text{mineral feed rate x ilmenite conc. feed}}\ x100 \qquad (3)$$

Ilmenite IRMS rate = rate of ilmenite in IRMS.
mineral feed rate = rate of mineral in feeding.
Ilmenite conc.IRMS = concentration of ilmenite output from IRMS.
Ilmenite conc.feed = concentration of ilmenite in feeding. For determination of ilmenite recovery, particle size was given at – 20 mesh.

RESULTS AND DISCUSSION

Grain Counting Analysis

The mineral dressing of tailing in feeding was determined by grain counting analysis using a microscope. The results of this study were as follows: cassiterite (48.61%), ilmenite (21.36%), monazite (18.56%), pyrite (4.60%), zircon (5.85%), quartz (0.71%), anatase (0.27%), and tourmaline (0.02%), Ilmenite, monazite, and tourmaline are paramagnetic minerals.

Figure 6 shows the graph of related mineral dressing applying grain counting analysis (- 20 mesh) of mining tailing in Bangka Belitung Province.

Hassan [1] reported ore dressing in Eastern part of Egypt as follows: TiO_2 (26.20%), Fe_2O_3 (50.09%), and SiO_2 (14.35%). The composition and type of ore dressing is varied affected by its genesis history and environmental condition. In relation to monazite, Sarker et al. [30] reported ≈ 9% REE (Rare Earth Elements) in mining tailing of monazite and goethite using XRD (X-ray diffraction) analysis since REE is very important source for renewable energy.

As mentioned above, ilmenite has benefit properties related to strong corrosion resistance and high mechanical strength due to its potential source for titanium, therefore, ilmenite separation from minerals is very substantial. Recently, flotation technique has commonly used for ilmenite recovery due to high ilmenite recovery achievement [6, 7, 8, 9]. As already mentioned in the Introduction section, Hu [6] used sodium chlorite for ilmenite activation achieved ilmenite recovery of about 83%. while Xiao [7] used Al (III) in BHA system to activate ilmenite and obtained recovery of 86%, then Miao [8] used Fenton oxidant to convert Fe(II) to Fe (III), and Yu [9] applied lead ions to form Pb-OHA complex to increase ilmenite adsorption. This study obtained 29.38% ilmenite recovery at pretreatment process using cassiterite tailing and without any chemical agent for isolation treatment. Since ilmenite is often found together with cassiterite, a gravitation technique obtained high cassiterite recovery (≈ 90%) using cinnamohydroxamic acid in cassiterite separation from calcite in Yunnan Province [31]. On other occasion, separation of ilmenite from other mineral may cause air pollution. Toubri et al. [32] reported SO_2 toxic emission generated from ilmenite hematite deposit roasting in Quebec mining, Canada.

However, the ilmenite recovery has increased until 74.83% after using magnetic separator (IRMS). This matter will be elucidated in Table 1 and Table 2 with regard to effects of electric current and single splitter opening adjustment on ilmenite recovery.

Round Screen for Mineral Fractions

The round screen was used for fractional sieving of mineral particles classified as its size namely as mineral fractions. Figure 7 shows the ilmenite concentration (%) on the basis of fractions (particle size) after fractional sieving by round screen. Moreover, Figure 7 presents the ilmenite content (%) based on (%) based on particle sizes (20#, 50#, 70#, 100#, and – 100#) applying fractional sieving in Bangka Tin plant.

The ilmenite concentration in each fraction can be determined applying (4) that can be described as follows:

$$\text{conc. ilmenite of each fraction } (\%) = \frac{\text{weight ilmenite each fraction}}{\text{total weight ilmenite all fractions}} \times 100 \qquad (4)$$

Single Splitter IRMS with 1.0 cm opening adjustment

Table 1 shows the list of electrical current (Ampere), ilmenite IRMS rate (kg/h), ilmenite concentration (%), and ilmenite recovery (%) at constant ilmenite concentration in feeding (21.36%). The short-term single splitter was adjusted as 1.0 cm from Induced Roll Magnetic Separator. Theoretically, the stronger electrical current may yield stronger magnetic power causing lower degree of separation of ilmenite because of attracting other paramagnetic minerals such as monazite (Ce,La,Y,Th)PO_4 and siderite ($FeCO_3$) together with ilmenite ($FeTiO_3$). In relation to magnetic properties, ilmenite separation from titanaugite can be improved by using selective magnetite coating [33].

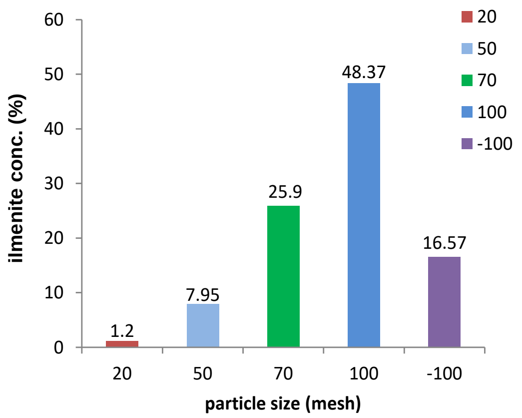

Figure 7, Ilmenite concentration (%) using fractional sieving.

Table 1. Tailing data. Single splitter IRMS opening 1.0 cm. Ilmenite concentration in feeding 21.36%

Amp	Mineral feed rate kg/h	Ilmenite IRMS rate kg/h	Ilmenite conc. (%)	Ilmenite recovery (%)
(1)	(2)	(3)	(4)	(5)
5	464.83	32.26	90.46	29.38
6	456.95	34.38	88.83	31.28
7	493.34	41.58	86.55	34.14
8	514.01	48.53	85.84	37.93
9	534.67	54.65	84.10	40.23
10	550.12	60.77	82.06	42.43
11	595.08	73.69	80.25	46.52
12	778.03	106.27	78.62	50.26
13	876.02	128.02	77.61	53.08
14	916.88	142.49	76.41	55.58
15	961.88	158.00	74.88	57.57

Table 2. Tailing data. Single splitter IRMS opening 4.25 cm. Ilmenite concentration in feeding 21.36%.

Amp	Mineral feed rate kg/h	Ilmenite IRMS rate kg/h	Ilmenite conc. (%)	Ilmenite recovery (%)
(1)	(2)	(3)	(4)	(5)
5	400.36	47.81	79.67	44.53
6	424.19	57.42	78.70	49.86
7	479.70	71.42	75.59	52.68
8	537.41	86.29	73.61	55.32
9	424.33	75.92	70.64	59.16
10	572.11	117.94	65.47	63.17
11	657.94	146.05	62.04	64.46
12	697.46	166.82	60.94	68.22
13	758.45	197.14	59.30	72.15
14	1087.38	292.50	58.15	73.22
15	1205.35	337.28	57.13	74.83

Previous works reported that magnetic properties of ilmenite can be advantaged as oxygen carrier in fluidized bed biomass combustion to increase its mechanical strength [34][35].

On the other hand, if the current is getting weaken, the magnetic power becomes weaker, then it may withdraw lesser ilmenite, thus, the ilmenite concentration getting lower. Therefore, an optimization of electrical current should be adjusted in order to achieve optimum result of ilmenite. Usually, current range of 5 – 15 Ampere are used to find the possibility of ilmenite from medium to high grade [9].

Table 1 shows the data of ilmenite concentration and ilmenite recovery at varied electrical current (5 – 15 Ampere) after passing single splitter IRMS with opening adjustment 1.0 cm. The ilmenite concentration in feeding was setting to be kept constant, i.e., 21.36%.

The data of mineral feed rate and ilmenite IRMS rate were obtained from the equipment. In general, the ilmenite IRMS rate were proportionally increased to mineral feed rate as shown by Table 1. Furthermore, Table 1 shows that ilmenite concentrations are inversely proportional to ilmenite recovery, on the other hand, the values of ilmenite recovery are getting increased as the values of ilmenite concentration are decreased due to increased electric current.

Equation (3) shows as the ilmenite concentration increased due to increased ilmenite IRMS rate in the numerator related to increased mineral feed rate in the denominator (Table 1 column 2, 3, and 4), however, the increment of factors in the denominator is much larger than that in the numerator, thus, the result related to ilmenite recovery (Table 1 column 5) getting decreased, or in the other words, the ilmenite recovery and ilmenite concentration is inversely proportional. The data results of ilmenite concentration and ilmenite recovery as shown by Table 1 applied (3).

Single Splitter IRMS with 4.25 cm opening adjustment

The data of Table 1 is represented in Figure 8. Figure 8 shows the effect of electric current on ilmenite concentration and ilmenite recovery applying single splitter IRMS with opening adjustment of 1.0 cm. With regard to high grade ilmenite, the current of 5A yielding ilmenite conc. of 90.46%, but the ilmenite recovery is too low, i.e 29.38%. The 8A current yielded ilmenite conc. of 85.84% with better ilmenite recovery of 37.93%. The lower limit of high grade ilmenite is in the range of 85% - 90%.

Table 2 shows the same trend as shown by Table 1 in terms of mineral feed rate, ilmenite IRMS rate, as well as, ilmenite concentration and ilmenite recovery due to the effect of electrical current varied from 5 A to 15 A. As the data of ilmenite recovery shown in Table 1, the recovery data in Table 2 obtained by applying (3) and also inversely proportional with ilmenite concentration.

The significant difference between data of Table 1 and data of Table 2 is they used different opening or short term adjustment single splitter IRMS, that the data of Table 1 was based on 1.0 cm opening adjustment, while the data of Table 2 based on 4.25 cm opening.

The short term adjustment single splitter IRMS also affected on both ilmenite concentration and ilmenite recovery. Sitepu [9] only studied the effect of electrical current on ilmenite concentration and recovery, while this study has investigated the effects of both current and opening adjustment single splitter IRMS.

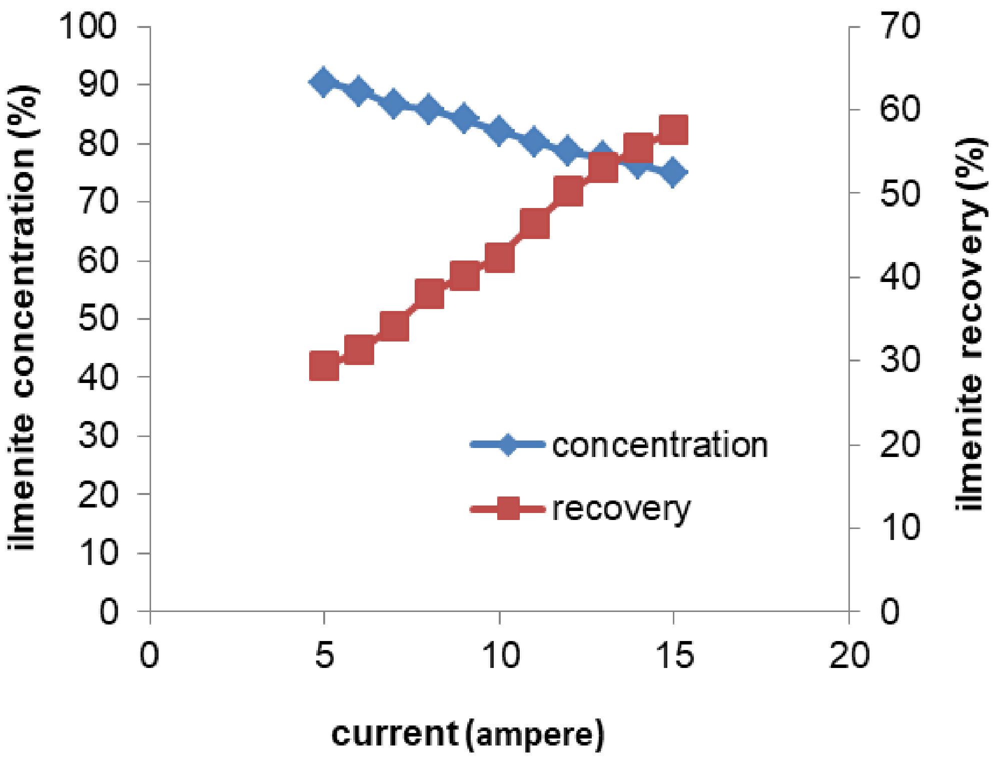

Figure 8. Effect of current on ilmenite concentration and ilmenite recovery.

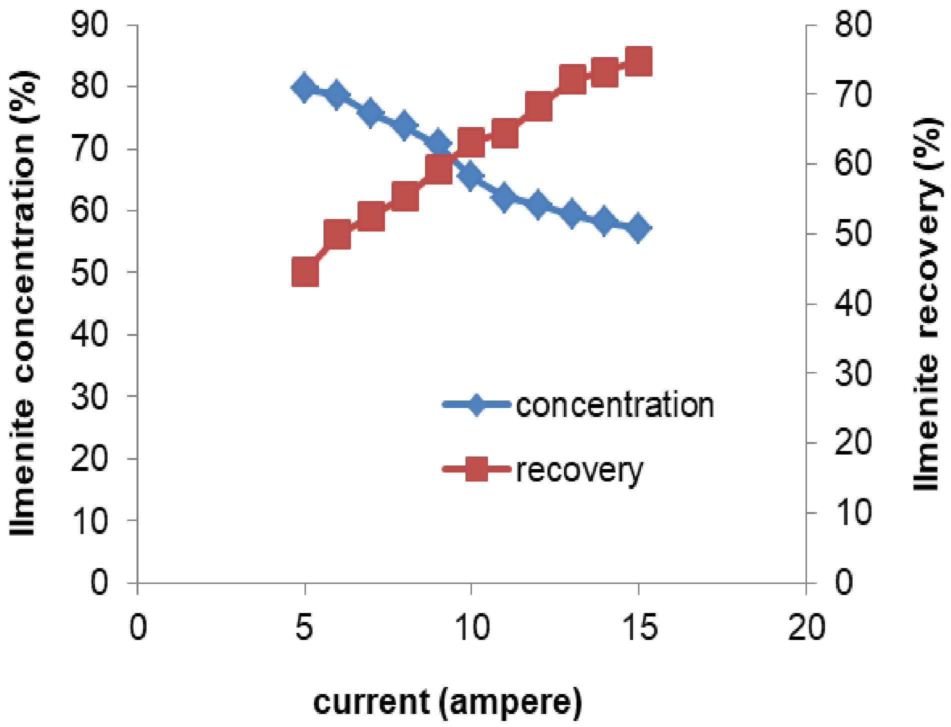

Figure 9. Effect of current on ilmenite concentration and ilmenite recovery.

The data of Table 2 is represented in Figure 9. Figure 9 shows the effect of electric current on ilmenite concentration and ilmenite recovery applying single splitter IRMS with opening adjustment of 4.25 cm. All the varied currents (5A – 15A) yielded medium grade ilmenite. The upper limit of medium grade is lower than 85%. With regard to the production of high grade ilmente, the single splitter IRMS with opening 4.25 cm is not the choice as compared to the more favorable single splitter IRMS with opening 1.0 cm shown by this study. An overview on Figure 9, the 10A current showed the balance result between ilmenite conc. (65.47%) and ilmenite recovery (63.17%). Nevertheless, production of the high grade ilmenite is the first priority in the field of mineral separation. By considering the ilmenite recovery that is not too low, the 8A in Table 1 with single splitter IRMS with opening 1.0 cm can be assumed as the optimum condition for ilmenite separation in this study. The 14A using single splitter IRMS with opening 1.0 cm (Figure 1) shows the cross section between ilmenite concentration (76.41%) and ilmenite recovery (55.58%), however, this condition is not the choice with regard to medium grade ilmenite and higher current energy.

However, Sitepu [9] selected the 14A with yielding > 90% ilmenite concentration as the optimum condition of ilmenite separation without reported the short term adjustment single splitter.

Table 3 shows the effect of opening adjustment or short term adjustment (1.0 cm and 4.25 cm) single splitter IRMS on ilmenite concentration and ilmenite recovery. Having applied the varied current from 5A to 15A, Table 3 shows that all ilmenite concentrations (opening adjustment 1.0 cm) referred to column (2) Table 3 are higher than all ilmenite concentrations (opening adjustment 4.25 cm) referred to column (3) Table 3.

This finding is reasonable since a distance of 1.0 cm is closer to IRMS rather than that of longer distance of 4.25 cm. The closer distance to IRMS meaning closer to the magnetic effect of IRMS leading to higher magnetic effect on ilmenite separation yielding higher ilmenite concentrations (column 2 Table 3) compared to that of ilmenite concentrations of longer distance adjustment (column 3 Table 3). It is not surprising, the expected results show that the ilmenite recovery of 1,0 cm opening (column 4) is lower than that of ilmenite recovery of 4.25 cm opening (column 5).

As seen in Table 3, this study has achieved the highest ilmenite recovery for 74.83% using a magnetic separator (IRMS) with single splitter distance of 4.25 cm and electric current of 15 Ampere.

Table 3. Tailing data. Single splitter IRMS opening 1.0 cm and 4.25 cm. Ilmenite concentration in feeding 21.36%

Amp	Ilmenite conc. (%) 1.0 cm	Ilmenite conc. (%) 4.25 cm	Ilmenite recover (%) 1.0 cm	Ilmenite recover (%) 4.25 cm
(1)	(2)	(3)	(4)	(5)
5	90.46	79.67	29.38	44.53
6	88.83	78.70	31.28	49.86
7	86.55	75.59	34.14	52.68
8	85.84	73.61	37.93	55.32
9	84.10	70.64	40.23	59.16
10	82.06	65.47	42.43	63.17
11	80.25	62.04	46.52	64.46
12	78.62	60.94	50.26	68.22
13	77.61	59.30	53.08	72.15
14	76.41	58.15	55.58	73.22
15	74.88	57.13	57.57	74.83

The application of magnetic separator in ilmenite recovery management may substantially increase ilmenite separation as already proven by Yuan [10]. In the near future, several options of modeling approach used MATLAB software can be developed for process optimization in relation to ilmenite recovery. As Sofwan [36] applied BAT Algorithm with MATLAB software to reduce the operational cost of a power plant, with regard to this matter the operational cost of IRMS for ilmenite recovery can be decreased by considering some factors (gravitational effects in shaking table, chemicals used in froth flotation, particle size in round screen, and oven drying temperature) in the application of BAT Algorithm. On other occasion, Romahadi [37] used Bayesian Network for process optimization of heat exchanger with MATLAB program, this computational approach can be implemented to optimize the ilmenite separation from cassiterite tailing in the IRMS by controlling some parameters (feeding input, opening adjustment, single or double splitter) in a mathematical modeling.

CONCLUSION

This study showed the effect of electrical current and opening adjustment single splitter IRMS on ilmenite separation from mining tailing that can be assumed as a new finding in ilmenite separation. The optimum condition was selected with regard to high grade ilmenite, electrical current energy, and opening adjustment single splitter IRMS.

ACKNOWLEDGMENT

This investigation was supported by Bangka Tin Plant, South Sumatera, Indonesia, who provided facilitations for this research study. We also thank our colleagues from the Department of Mining, Universitas Trisakti, Jakarta, who gave valuable contributions that greatly assisted the research with several insight and expertise.

REFERENCES

[1] S. Hassan, M. A. Youssef, M.A. Khalek et al., "A study on the beneficiation of low grade ilmenite ore for industrial applications," *Australian Journal of Basic and Applied Sciences*, vol. 14, no.9, pp. 12-21, 2020, doi: 10.22587/ajbas.2020.14.9.2.

[2] W. Xiao, Y. Shao, J. Yu, H. He, B. Zhang, Y. Zhang and H. Shu, ''Adsorption differences and mechanism of Pb-BHA and Al-BHA in the flotation separation of ilmenite and titanaugite," *Minerals Engineering,* vol. 197, 108072, June 2023, doi: 10.1016/j.mineng.2023.108072.

[3] F. Tian, P. Li, Y. Cao, H. Hao, W. Peng and G.Fan, "Selective depression of low-molecular-weight carboxylated starch in flotation separation of forsterite and ilmenite," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 648, 129080, September 2022, doi: 10.1016/j.colsurfa. 2022.129080.

[4] Q. Meng, Y. Du, Z. Yuan, Y. Xu, X. Zhao and L. Li, "Study on the mineral characteristics and separation performances of a low-TiO_2 ilmenite, "*Minerals Engineering,* vol. 179, 107458, March 2022, doi: 10.1016/j.mineng.2022.107458.

[5] Q. Meng, Y. Xu, Z. Yuan, X. Zhao and Y. Du, "Separation mechanism of ilmenite from titanaugite with mixed BHA/NaOL collector," *Minerals Engineering,* vol. 176, 107363, January 2022, doi: 10.1016/ j.mineng. 2021.107363.

[6] Y. Hu, G. Ye, Q. Zuo and W. Xiao, "Activation of ilmenite flotation by sodium chlorite in the sodium oleate system," *Separation and Purification Technology*, vol. 305, 122506, 2022, doi: 10.1016/j.seppur. 2022.122506.

[7] W. Xiao, Y. Shao, J. Yu and B. Zhang, "Activation of ilmenite flotation by Al^{3+} in the benzohydroxamic acid (BHA) system." *Separation and Purification Technology*, vol. 299, 121770, 2022, doi: 10.1016/j.seppur. 2022.121770.

[8] Y. Miao, S. Wen, Q. Feng and R. Liao, "Surface modification of ilmenite and flotation improvement using Fenton as an oxidant." *Applied Surface Science*, vol. 555, 149749, 2021, doi: 10.1016/ j.apsusc.2021.149749.

[9] L. Yu, X. Xu, Z. Yuan and Y. Xu, "Effect of lead ions on the selective flotation of ilmenite against titanaugite using octyl hydroxamic acid as collector," *Applied Surface Science*,

vol. 603, 154458, 2022, doi: 10.1016/ j.apsusc.2022.154458.
[10] Z, Yuan, X. Zhao, Q.Meng, Y. Xu and L. Li, "Effect of selective coating of magnetite on improving magnetic separation of ilmenite from titanaugite," *Minerals Engineering*, vol. 149, 106267, 2020, doi: 10.1016/j.mineng. 2020.106267.
[11] I. Ginting, "Experiment of enhancing mangan concentration applying magnetic separator," *Metalurgi*, vol. 26, no.1, pp. 27-34, 2015, doi: 10.14203/metalurgi.v26i1.6.
[12] A. Lusiyana, M. Toifur and F. Rohman, "The examination of magnetic properties of sand beach by determination of relative permeability using Logger Pro," *Jurnal Fisika*, vol. 4, no. 2, pp. 78-91, 2014, doi: 10.15294/jf.v4i2.3830.
[13] V. Singh, S. Nag and S.K. Tripathy, "Particle flow modeling of dry induced roll magnetic separator," *Powder Technology*, vol. 244, p. 85-92, 2013, doi: 10. 1016/j.powtec. 2013.03.053.
[14] S.S. Sitepu, A. T. Arief and H. Iskandar, "The study of electrical current effect on IRMS to enhance ilmenite mineral recovery in Amang Plant, Mineral Processing Division, Metallurgy Unit," *Jurnal Pertambangan*, vol. 1, no. 1, 2016, doi: 10.36706/ jp.v1i1.3819.
[15] M. A. Khalek, "Recover of titanium from industrial waste by enhanced gravity separation," *The Journal of Ore Dressing*, vol. 14, no. 27, pp. 1-5, 2012.
[16] S. Wahyuningsih, H. Hidayatullah and E.Pramono, "Optimizing of TiO_2 separation from Bangka ilmenite by leaching process using HCl," *ALCHEMY Jurnal Penelitian Kimia*, vol. 10, no.1, pp. 54-68, 2016, doi: 10.20961/alchemy.v10i1.16.
[17] C.D. Putra,"The study of soil pump operation effect in mineral suction ship 16 to reduce tin ore lost in Teluk Limau Sea", *Thesis,* Sriwijaya Library, South Sumatera, Indonesia, 2016. [Online]. Available: http:digilib.unsri.ac.id//lib /phpthumb/php.
[18] F.A. Agasi, "The effect of underwater need on pan American jig to enhance tin ore recovery in mineral suction ship 12, Mining Unit Bangka Sea," *Thesis,* Sriwijaya Library, South Sumatera, Indonesia, 2017. [Online]. Available:http:digilib.unsri.ac.id//lib/phpthum b/php.
[19] R. Santosa, "Analysis of low grade tin ore processing based on production, tin concentration and total recovery in Mineral Processing Unit," *Thesis,* Sriwijaya Library, South Sumatera, Indonesia, 2014. [Online]. Available:http:digilib.unsri.ac.id//lib/ phpthumb/ php.
[20] R. Ariputra, "The evaluation of jig variable performance on tin ore recovery in tin suction ship in the region of Bangka Cupat Sea," *M.S. Thesis*, Department of Mining Engineering, Bangka Belitung University, Province of Bangka Belitung, Indonesia, 2015. oai:repository.ubb.ac.id:68.
[21] A.J. Whitworth, E. Forbes, I. Verster et al., "Review on advances in mineral processing technologies suitable for critical metal recovery from mining and processing wastes," *Cleaner Engineering and Technology,* vol. 7, 100451, 2022, doi: 10.1016/j.clet.2022.100451.
[22] T. Phengsaart, M. Ito, N. Hamaya et al., "Improvement of jig efficiency by shape separation, and a novel method to estimate the separation efficiency of metal wires in crushed electronic wastes using bending and "entanglement factors," *Minerals Engineering*, vol.129, pp. 54-62, 2018, doi: 10.1016/j.mineng.2018.09.015.
[23] Y.A. Khouia, B. Mostafa and I. Demers, "Environmental desulfurization of mine wastes using various mineral processing techniques: Recent advances and opportunities," *Minerals Engineering*, vol. 174, 107225, 2021, doi: 10.1016/ j.mineng.2021.107225.
[24] S. Back, K. Ueda and H. Sakanakura, "Determination of metal-abundant high-density particles in municipal solid waste incineration bottom ash by a series of processes: Sieving, magnetic separation, air table sorting, and milling," *Waste Management*, vol. 112, pp. 11–19, 2020, doi: 10.1016/j.wasman.2020.05.002.
[25] M.S. Duarte, B.S. Almada and W.J. Santos, "Influence of mechanical treatment and magnetic separation on the performance of iron ore tailings as supplementary cementitious material," *Journal of Building Engineering*, vol. 59, 105099, 2022, doi: 10.1016/j.jobe.2022.105099.
[26] Y. Li, J. Gao, X. Lan and Z. Guo, "A novel method for efficient recovery of boron from boron-bearing iron concentrate: Mineral phase transformation and low-temperature separation via super-gravity," *Minerals Engineering*, vol. 189, 107899, 2022, doi: 10.1016/j.mineng.2022.107899.
[27] X. Lan, J. Gao, Y. Du and Z. Guo, "Mineral evolution and separation of rare-earth phases from Bayan Obo rare-earth concentrate in a super-gravity field," *Journal of Alloys and*

Compounds, vol. 731, pp. 873–880, 2018, doi: 10.1016/j.jallcom. 2017. 10.100.
[28] S. Zhang, M. Rao and R. Xiao, "Enrichment of Nb and Ti from carbonatite pyrochlore ore via calcining-slaking followed by gravity separation," *International Journal of Mining Science and Technology*, vol. 32, no.3, pp. 615–626, 2022, doi: 10.1016/ j.ijmst. 2022. 02.005.
[29] W, Wang, M. Pan, C. Duan and H. Jiang, "Dry deep screening of spodumene and its mineral processing technology," *Minerals Engineering*, vol. 179, 107445, 2022, doi: 10.1016/j.mineng. 2022.107445.
[30] S. K. Sarker , W. Bruckard, N. Haque , R. Roychand , M. Bhuiyan and B. K. Pramanik, "Characterization of a carbonatite-derived mining tailing for the assessment of rare earth potential," *Process Safety and Environmental Protection*, vol. 173, pp. 154-162, May 2023, doi: 10.1016/j.psep. 2023. 03.030.
[31] S. Nie, Z. Guo, M. Tian and W. Sun, "Selective flotation separation of cassiterite and calcite through using cinnamon - hydroxamic acid as the collector and Pb^{2+} as the activator," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 666, 131262, June 2023, doi: 10.1016/j.colsurfa. 2023.131262.
[32] Y. Toubri, B. Plante, I. Demers and M. Fillion, "Probing cleaner production opportunities of the Lac Tio pyrite-enriched tailings generated to alleviate sulfur dioxide emissions," *Journal of Cleaner Production*, vol. 357, 132027, July 2022, doi: 10.1016/ j.jclepro. 2022.132027.
[33] Z. Yuan, X. Zhao, Q. Meng, Y. Xu and L. Li, "Effect of selective coating of magnetite on improving magnetic separation of ilmenite from titanaugite," *Minerals Engineering,* vol. 149, 106267, April 2020, doi: 10.1016/ j.mineng.2020.106267.
[34] A. Gyllén, P. Knutsson, F. Lind and H. Thunman, "Magnetic separation of ilmenite used as oxygen carrier during combustion of biomass and the effect of ash layer buildup on its activity and mechanical strength," *Fuel*, vol. 269, 117470, June 2020, doi: 10.1016/j.fuel.2020.117470.
[35] R. Faust, I. Lamarca, A. Schaefer and P. Knutsson, "Magnetic properties of ilmenite used for oxygen carrier aided combustion," *Fuel,* vol. 340, 127593, May 2023, doi: 10.1016/j.fuel.2023.127593.
[36] A. Sofwan, M. Febriansyah and S. Sugeng, "Operational cost reduction of gas thermal power plant based on BAT algorithm," *SINERGI*, vol. 25, pp. 185-194, June 2021, doi: 10.22441/sinergi.2021.2.010.
[37] D. Romahadi, F. Anggara, R.P.Youlia, H.L. Habibullah and H. Xiong, "Bayesian network approach on intelligent system design for the diagnosis of heat exchanger," *SINERGI*, vol. 26, pp. 127-136, June 2022, doi: 10.22441/sinergi.2022.2.001.