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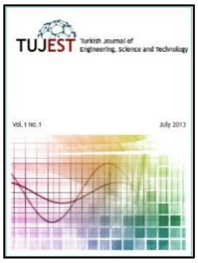

Studies On Optimization Of Rougher Wet High Intensity Magnetic Separator To Recover Ilmenite From Placer Heavy Minerals

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Abstract

This paper details the optimization of rougher Wet High Intensity Magnetic Separator (WHIMS) using response surface methodology. The optimization is in parametric form and takes account of the major operating variables in WHIMS operation such as current in ampere and grid gap in inch. The objective is to recover ilmenite mineral from red sediment deposits of Srikakulam, India by optimizing the rougher WHIMS. We predict mineral recoveries as a function of current and grid gap. Combination of these predictions with assay data provides predictions of mineral grades and recoveries. The optimized response was validated against data derived from laboratory-scale rougher WHIMS test work, comprising (i) mineral grade, (ii) mineral recovery, and (iii) separation efficiency of the process. We observed close match between the experimental and the predicted data over most of the operational range. This paper describes how the optimization was carried out using the response surface methodology along with MATLAB. The response surface was used to closely investigate the separation of ilmenite mineral by varying ampere and grid gap. The results show that under optimum conditions such as 3.5 amp current and 2 inch grid gap the mineral grade could reach as high as 87.9% in the concentrate with 74.3 % recovery and 74.4% yield.

1. Introduction

India, endowed with a coastline of over 6000 km, hosts some of the largest and richest shoreline placer deposits containing heavy minerals such as, ilmenite, garnet, zircon, rutile, sillimanite etc. These heavy minerals and their value added products have been gaining much attention because of rapid growth of population and their standard of leaving, growth of different industries like electric, electronic and ceramic industries etc. In view of this, Government of India is recommending for exploitation of new deposits for placer minerals and its processing technologies for future programme and foreign collaborations for the development of beach sand industry. However, the beach sand industry globally and particularly in India confronts with new challenges for reducing the environmental footprint.

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Hence, in this present study an attempt has been made on red sediment deposits which are new resource exploited for beneficiation and recovery of heavy minerals. The red sediment placer deposit under the sand dunes at Chinna Vastavalasa, Andhra Pradesh, India are potential resources for heavy mineral concentration which contain maximum percentage of ilmenite followed by the other minerals such as sillimanite, garnet, rutile, zircon, monazite etc. [1].

Ilmenite is a mixture of iron and titanium dioxides, is used as a furnace lining in the steel industry and also as a blasting medium. After eliminating the iron particles, ilmenite can be further processed to produce synthetic rutile, which can be further developed to make titanium dioxide. So, ilmenite is considered as a titanium (TiO_2) bearing mineral that, directly or indirectly, supplies in excess of 90% of the feedstock to the large TiO_2 pigment industry as well as to the very significant and growing Titanium sponge/Metal market, plus some smaller industrial applications. The TiO_2 pigment industry is a large world-wide industry with total production valued in excess of US$ 10 Billion per year, making it one of the world's most important inorganic chemical industries. The Titanium sponge/Metal industry is also very significant with total world production having a value of around US$ 2 Billion per year.

In most of mineral separation plants recovery of total heavy minerals is the first step by using spiral concentrators. This preconcentrate is subjected to magnetic separator for recovery of magnetic minerals. Magnetic separation method is based on differences in magnetic intensity.

The ilmenite mineral can be reported by using wet/dry and low or high intensity magnetic separators. This is due to fact that mostly the ilmenites are separated between 0.2 to 0.7T magnetic intensity. However, some highly weathered ilmenites need even 1.0 to 1.4T magnetic intensity. Beach placer ilmenites vary both in magnetic intensity, particle size, surface properties and chemical composition. Hence, single unit operation may not give high grade ilmenite with recovery. Thus, it needs number of stages of cleaning to achieve the high grade ilmenite. Keeping it from the point of view of recovery of high grade ilmenite by magnetic separation, an attempt is essential to recover maximum ilmenite at every stage of cleaning. Hence, it is necessary to optimize the process variables for achieving the goal to recover maximum ilmenite. In view of this, at first instance using software is essential to reduce the number of experiments for optimization of process.

RSM and Box–Behnken design is one of the methods to optimize the process parameters. It has been applied in the grinding experiments of coal samples [2] and modeling of high tension roll separator for separation of titanium bearing minerals from beach sand [3]. Optimization of process parameters for producing graphite concentrate was also done using RSM by Aslan et al [4]. There is no attempt made on optimization of wet high intensity of magnetic separator for recovery of heavy minerals.

In this present study an attempt has been made for recovery of maximum grade ilmenite from the red sediments by using the rougher wet high intensity magnetic separator and the experimental results are analyzed by using software like Design expert 6.0.6 (RSM), ANOVA and MATLAB 8.1. The optimum conditions obtained from experimental design and that from using software are compared in the present investigation.

2. Materials And Methods

2.1. Raw material and preparation

The typical picture of red sediment placer deposit under the sand dunes at Chinna Vastavalasa, Andhra Pradesh is shown in Fig. 1. These red sediments are generally of 6 meters thickness present below the sand dune deposit (With layers of heavy mineral concentration). Red sediment samples were collected in a grid pattern up to the water table level. These red sediment samples were thoroughly mixed and prepared a composite sample. Representative sub samples were prepared from the bulk sample using standard riffler sampler. Initially, the representative sample was deslimed by using hydrocyclone. Sub samples were studied for physical characterization, sink-float studies and mineralogical studies.

Figure 1. Typical red sediment placer deposits under the sand dunes at Chinna Vastavalasa, Andhra Pradesh

2.2. Methods

Mineralogical modal analysis of deslimed sample was carried out using a Lecia petrological optical microscope. Powdered scrubbed deslimed feed was subjected to X-ray diffraction (XRD) using PANalytical (X'pert) powder diffractometer, (scan speed- 1.2°/min from 6° to 40°, by Mo Kα radiation) to identify the mineral phases. Sink float test was carried out for deslimed feed with Bromoform ($CHBr_3$; specific gravity 2.89), as a medium for separation of heavier fractions (total heavy minerals) from the lighter. Methylene iodide (di-ido methane; specific gravity 3.3) heavy medium was used to determine very heavy minerals and light heavy minerals from the total heavy minerals. The deslimed sample was subjected to rougher, cleaner and scavenging spirals for recovery of 99.1% total heavy minerals (THM). The concentrate obtained from spiral was subjected for magnetic separation. The scheme of experiments to recover ilmenite from placer heavy minerals is given in Fig. 2.

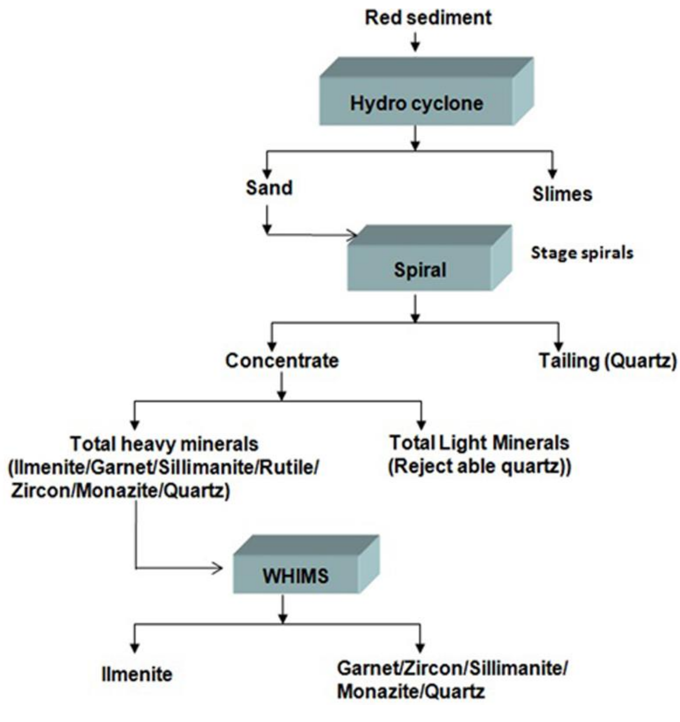

Figure 2. The scheme of experiments to recover ilmenite from placer heavy minerals

In this present investigation magnetic separation studies were carried out by a WHIMS magnetic separator type A1/4523, serial No. J 51930 supplied by Rapid Box-Mag separator, U.K. Magnetic intensity of WHIMS which is varied with current and separating grids. About 100 gm of sample of 20% pulp density was subjected to WHIMS. The magnetic fraction was trapped on the plates where as non-magnetic fraction was collected at the bottom. The magnetic fraction was recovered from the separating grids by washing with water in the absence of the magnetic field. The magnetic and non-magnetic fractions thus collected separately were dried and analyzed to check the purity and the recovery of the products. The variables such as grid gap and current were varied according to experimental design given by Design Expert where as other factors such as pulp density, feed rate and wash water are kept constant. Each factor at three different levels was studied. The variables at different levels are given in Table 1.

Table 1. The level of variables chosen for central composite design

Variables	Symbol	Coded variable level		
		Low	Centre	High
		-1	0	+1
Current, Ampere	x_1	2	4.5	7
Grid gap, inch	x_2	1	1.5	2

In the present study, central composite design was chosen to find out the relation between the response functions (grade, recovery and separation efficiency) and two variables of WHIMS (grid gap and current). The separation efficiency of the process was calculated using the following Equation -1 [5].

$$E = \frac{(R-Y)}{(1-f/ma)} \quad (1)$$

Where, E = Separation efficiency in %

R = Recovery of magnetic minerals in %

Y = Yield of magnetic minerals in %

f = Magnetic minerals, % in the feed

ma = maximum magnetic minerals, % in the yield of magnetic fraction

2.3. Central Composite Design

In statistics, a central composite design is an experimental design, useful in response surface methodology, for building a second order (quadratic) model for the response variable without needing to use a complete three-level factorial experiment. CCD for two factors at three levels with α = 1, equivalent to a 32 factorial design, was chosen as the experimental design. This is an effective second-order experimental design associated with a minimum number of experiments to estimate the influence of individual variables (main effects) and their second-order effects. To investigate the factors systematically, a central composite design was employed. As shown in Equation-2, a statistical model incorporating multi regression analysis was used to evaluate the responses.

$$\mathrm{Y} = \beta0 + \beta1\,\mathrm{X1} + \beta2\,\mathrm{X2} + \beta3\,\mathrm{X12} + \beta4\,\mathrm{X22} + \beta5\,\mathrm{X1}\,\mathrm{X2} \quad (2)$$

3. Results And Discussion

3.1. Physical characterization studies

The studies on physical properties of deslimed red sediment sample of Chinna Vatsavalasa indicate that the bulk density of the sample is 1.61 g/cm3. The d80 passing size of the sample is 345 µm obtained from the size analysis of deslimed feed. The slime content in sediment sample is 21.3% by weight. The deslimed sample contains 31.5% Total Heavy Minerals (THM), out of which 24.5% Very Heavy Minerals (VHM) and 7.0% of Light Heavy Minerals (LHM). It is also observed that the sample contains magnetic heavies of 23.2% and non magnetic heavies of 8.3%.

The mineralogical modal analysis of THM of typical red sediment samples indicate that the sample mainly contains ilmenite (70.3%) followed sillimanite (11.7%), garnet (10.0%), zircon (3.7%), rutile (1.1%) and other heavy minerals (3.1%). The mineralogical data indicate that the specific gravity difference between heavy minerals such as ilmenite, rutile, zircon, sillimanite etc and gangue mineral quartz is very much significant. The XRD pattern of THM of red sediment sample is shown in Fig. 3 which indicates that the sample contains maximum peaks of ilmenite followed by sillimanite, garnet, zircon and rutile.

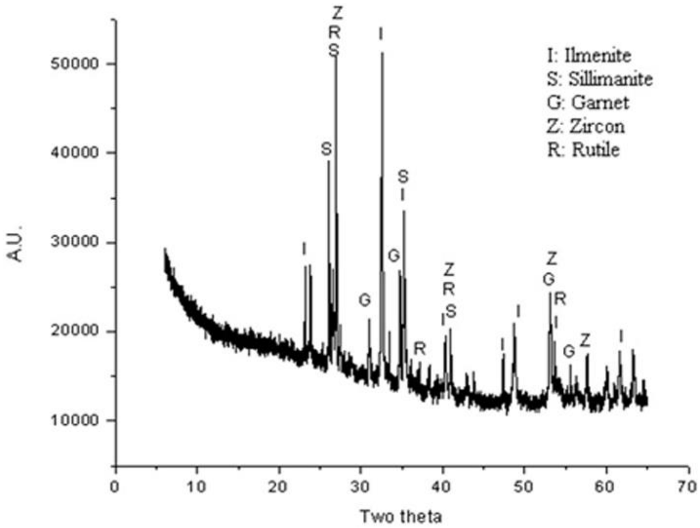

Figure 3. XRD of THM of red sediment sample

3.2. Optimization studies

The performance of magnetic separation units is also based on interaction between magnetic, hydrodynamic, gravitational and their inter particle forces and also developed a mathematical model using a computational fluid dynamics framework to follow the separation behaviour of particles in wet high intensity magnetic separator [6].

A two-factor central composite design was used to determine the response for the grade, recovery and separation efficiency of the ilmenite by optimizing wet high intensity magnetic separator. The current (x1) and grid gap (x2) were two independent variables studied to predict the responses (Y1, Y2 and Y3). Using the relationships in Table 1, the coded levels of the variables for each of the experiments in the design matrix were calculated and experimental results obtained as given in Table 2.

Table 2. Central composite design with actual/coded values and results

Run no	Actual and coded level of variables		Observed results		
	Current , Amp (x_1)	Grid gap, inch (x_2)	Grade, %	Recovery, %	Separation efficiency, %
1	4.5	2.0	82.6	82.7	68.0
2	7.0	1.0	56.4	60.6	12.9
3	4.5	1.0	76.7	82.3	56.4
4	4.5	1.5	79.8	85.7	64.9
5	4.5	1.5	79.8	85.7	64.9
6	4.5	1.5	79.8	85.7	64.9
7	2.0	1.0	82.6	80.6	66.3
8	4.5	1.5	79.8	85.7	64.9
9	2.0	2.0	90.2	52.3	52.3
10	4.5	1.5	79.8	85.7	64.9
11	7.0	1.5	61.3	66.6	21.7
12	7.0	2.0	72.3	77.8	45.0
13	2.0	1.5	88.5	57.3	55.1

From the experimental results listed in Table 2 and Eq. (2), the second-order response functions representing grade and recovery of ilmenite mineral and separation efficiency of process. This could be expressed as functions of current and grid gap of magnetic separator. The model equations for grade, recovery and separation efficiency of ilmenite mineral is given in Eqs. (3), (4) and (5).

Model equation for grade:

$$Y_1 = 79.71 - 11.88x_1 + 4.90x_2 - 4.60{x_1}^2 + 0.15{x_2}^2 + 2.08x_1x_2 \tag{3}$$

Model equation for recovery:

$$Y_2 = 84.95 + 2.47x_1 - 1.78x_2 - 19.37{x_1}^2 + 1.18{x_2}^2 + 11.38x_1x_2 \tag{4}$$

Model equation for separation efficiency:

$$Y_3 = 63.74 - 15.68x_1 + 4.95x_2 - 22.43{x_1}^2 + 1.37{x_2}^2 + 11.53x_1x_2 \tag{5}$$

The responses at any regime in the interval of our experiment design could be calculated from Eq. (3 to 5). Experimental results and predicted values obtained by using Eqs. (3 to 5) are tabulated in Table 3.

Table 3. Actual and predicted values for ilmenite mineral

Expt. No	Grade, %		Recovery, %		Separation efficiency, %	
	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	82.6	84.7	82.7	82.7	68.0	69.1
2	56.4	56.4	60.6	59.7	12.9	11.0
3	76.7	74.9	82.3	86.3	56.4	59.1
4	79.8	79.5	85.7	81.7	64.9	61.1
5	79.8	79.5	85.7	81.7	64.9	61.1
6	79.8	79.5	85.7	81.7	64.9	61.1
7	82.6	84.4	80.6	77.5	66.3	65.5
8	79.8	79.5	85.7	81.7	64.9	61.1
9	90.2	90.0	52.3	51.2	52.3	52.3
10	79.8	79.5	85.7	81.7	64.9	61.1
11	61.3	63.2	66.6	66.4	21.7	24.7
12	72.3	70.4	77.8	78.9	45.3	44.3
13	88.5	86.9	57.3	61.5	55.1	55.9

The actual and predicted values of responses obtained using model equations (Eqs. 3 to 5) are also presented in Fig. 4 (a-c). Predicted values match with the experimental data points, indicating a good fitness (R^2 value of 0.98 for the grade, R^2 value of 0.95 for the recovery and R^2 value of 0.98 for the separation efficiency).

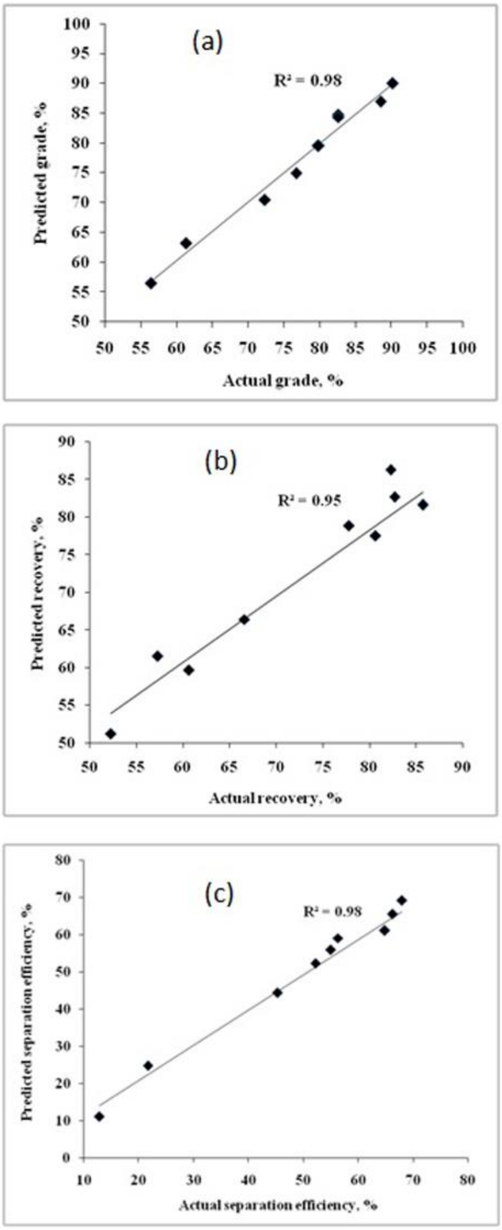

Figure 4. Relation between experimental and predicted values for (a) Grade, (b) Recovery and (c) Separation efficiency

3.3. Effect of variables on the responses

In order to gain a better understanding of the results, Figs. 5, 6 and 7 show 3D response surface plots, which describe the effect of grade, recovery and separation efficiency with change in variable parameters.

Fig. 5 shows the effect of grid gap and current on grade of ilmenite mineral. It is observed that higher grade is obtained at lower level of current and higher level of grid gap. It is because; the magnetic strength is increases with increase in grid gap at constant current. Thus, ilmenite is better magnetised at higher magnetic intensity. At constant current if grid gap increases then magnetic intensity of magnets decreases due to which the grade of ilmenite gradually falls down.

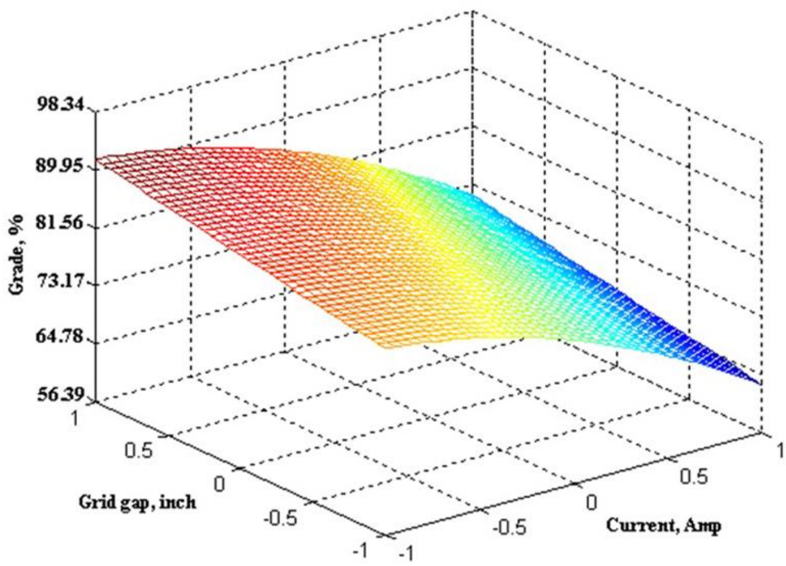

Figure 5. Response surface plot showing the effect of current and grid gap on the grade

Fig. 6 shows the effect of grid gap and current on recovery of ilmenite mineral from the mixture of garnet and other minerals. It is observed that higher recovery is obtained at centre level of current and lower level of grid gap. It is due to at lower grid gap the grade of ilmenite is decreases due to low magnetic intensity. Hence, decrease in grid gap increases the recovery where as at centre level of current the recovery of ilmenite is more.

Fig. 7 shows the effect of grid gap and current on separation efficiency of magnetic process. It is observed that separation efficiency is gradually falling down with increase in current where as it is increases with increase in grid gap.

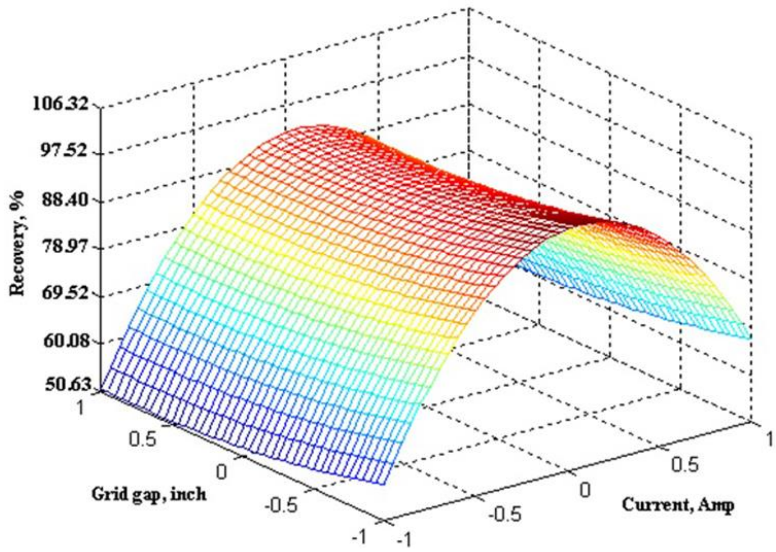

Figure 6. Response surface plot showing the effect of current and grid gap on the recovery

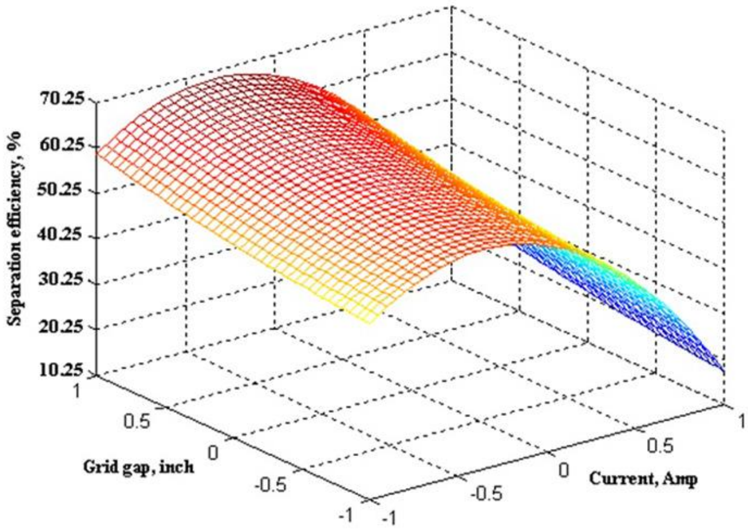

Figure 7. Response surface plot showing the effect of current and grid gap on the separation efficiency

3.4. Optimization

The objective of response surface optimization is to find a desirable location in the design space. This could be a maximum, a minimum, or an area where the response is stable over a range of factors. In this research, quadratic optimization technique was used for optimization of response equations using MATLAB 8.1 software. The results obtained by performing the above method are given in Table 4.

Table 4. Result of optimization by MATLAB

(a) Optimum conditions for grade

Variables	Optimum condition	Maximum grade, %
Current, Ampere*	3.5	87.9
Grid gap, inch	2	

(b) Optimum conditions for recovery

Variables	Optimum condition	Maximum recovery, %
Current, Ampere*	7	59.7
Grid gap, inch	1	

(c) Optimum conditions for separation efficiency

Variables	Optimum condition	Maximum separation efficiency, %
Current, Ampere*	7	44.3
Grid gap, inch	2	

*Magnetic intensity: Tesla (T)

It is observed that maximum grade of 87.9% is achieved at 3.5 amp current and 2 inch grid gap. Maximum recovery of 59.7% is achieved at 7 amp current and 1 inch grid gap. Similarly, maximum separation efficiency of 44.3% is achieved 7 amp current and 2 inch grid gap.

4. Conclusions

The following conclusions are drawn from the experimental and optimization studies carried out on red sediments for recovery of ilmenite mineral by optimizing different parameters of WHIMS.

(i) The two factorial central composite design with response surface methodology could employed successfully for modeling the WHIMS. Different equations are developed with varying three parameters such as grid gap and current.

(ii) In order to accomplish better understanding of the variables of the WHIMS on grade, recovery and separation efficiency (process and equipment) in magnetic fraction, the predicted model values could be presented as 3D response surface graphs.

(iii) The regression analysis gives very good result between observed value and predicted value such as, R2 value of 0.98 for grade, R2 value of 0.95 for recovery and R2 value of 0.98 for separation efficiency.

(iv) Using optimization study, it is observed that maximum grade of 87.9% is achieved at 3.5 amp current (0.53T) and 2 inch grid gap. It is as expected that at low magnetic intensity maximum amount of ilmenite minerals have been recovered. Maximum recovery of 59.7% is achieved at 7 amp current (1.08T) and 1 inch grid gap. It is because of that along with ilmenite other magnetic minerals such as garnet etc are also recovered and hence grade of ilmenite has fallen down and recovery is increases.

It is clear from this study that all the three responses such as grade, recovery and separation efficiency could be optimized using RSM and QP optimization techniques by which the plant performance could be improved.

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