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Recovery of copper from printed circuit boards (PCBs) using shaking table

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Abstract: In recent years, there has been a growing focus on the reuse of metallic components from waste electrical and electronic equipment (WEEE) which refers to electrical and electronic equipment that has become obsolete, stopped working, or developed defects during production. In this research, shaking table was selected as a gravity concentration tool for the recovery of copper from the light components. The flowsheet included comminution, gravimetric concentration and physical/chemical characterization of feed material and products. The process parameters were deck angle (degrees), motion frequency (Hz), wash water rate (L/m) and particle size diameter. The Box Behnken Design (BBD) was used to optimize the performance of the wet shaking table and to identify the ideal combination of its operating parameters. By analysing the experimental design, it was found that the optimal settings for deck angle, motion frequency, wash water rate and particle size diameter were 2°, 50 Hz, 12 L/m, and –500+300 mm, respectively. These optimal settings were located near the central points of the experimental design, suggesting that the actual optimal point could be within the designed space.

Keywords: printed circuit boards; recycling; shaking table; copper; ANOVA.

INTRODUCTION

Several electrical and electronic equipment such as cell phones, computers, televisions, and printers that are obsolete, no longer work or had defects during their production are classified as waste electrical and electronic equipment. The re-utilization of WEEE components (printed circuit boards (PCBs), batteries, LCD, *etc*.) has received special attention in recent years because some of the metals (Cd, Pb, Hg, Br, Be and organics) have toxic effects on health and the environment. One of the most researched electronic parts, PCBs, are made of copper sheets laminated onto a non-conductive substrate used to support elec-

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tronic components mechanically and maintain the electrical connectivity of the circuits. Thin boards are composed of 28–32 % metallic components and 68 % non-metallic components that mainly include plastics, epoxy resin reinforced glass fibers and ceramics.[1,2] Metallic fraction includes Fe, Cu, Al, Pb, Sn, Pd, PGM, Zn and precious metals that are more than 10 times that of rich-content minerals. Typical metal contents are 10–27 % Cu, 2–8 % Al, 1–4 % Pb 1–8 % Fe, 1–6 % Sn and <0.1 % precious metals (Au; 10–1600 ppm, Ag: 20–200×10^3 ppm, Pd: 5–970 ppm).[3] There are: *i*) mechanical/physical,[4–7] *ii*) thermal[8,9] and *iii*) chemical,[10–14] *iv*) physicochemical techniques[15] and their combinations[16–18] applied to recover the targeted metallic fraction from PCBs. Physical methods include dismantling; screening; shape separation; flotation; jigging; air, electrostatic, magnetic, eddy current and density-based separation. These methods are generally used as pre-treatment methods to simplify the following metal recovery methods. Thermal recovery techniques having high operating costs with low-efficiency consist mainly of pyrolysis and combustion generating air pollution through the release of furans and dioxins. Chemical methods, hydro- and electrometallurgical techniques, provide high metal recoveries, while producing large quantities of waste acidic electrolytes which must be carefully handled.[5,19]

Among numerous recycling applications, more preferred process worldwide might be the mechanical/physical recycling techniques owing to a fact that valuable metals in PCBs are elementary substance.[20] Typical flow sheet starts with dismantling step to recover large iron, lead and aluminium parts and precious metal-concentrated parts separately. The target metal on the dismantled board is copper that is widely used in electrical circuits, machine, construction, defence industry and other fields.[21] However, the complex nature of the copper/other metals–epoxy resin–ceramic–glass fibre embedded board complicates the recycling process. Non-metallic fraction (1.1–2.5 g/cm^3) has lower densities compared to metallic fraction while metals have higher densities in the range of 7–21.4 g/cm^3. Thus, most of the time multiple steps are needed to recover pure metals.

Gravity concentration methods as an environmentally benign method to recover valuable metals from PCBs are the popular options for the pre-treatment steps. After sufficient liberation, metals and plastic fractions can be easily separated which can be supported by the concentration criteria ($CC = (\rho_{\text{heavy}}/\rho_{\text{fluid}})/(\rho_{\text{light}}/\rho_{\text{fluid}})$). The studies in the literature attempted to recover metallic contents by gravity methods are jigging, sorting on aero-tables, sink-float separation.[6,7,22–24] Bilesan *et al.*[7] used hydrocyclone to recover PMs and Cu and reported 72 % total separation efficiency of copper. In the other study[23] on pneumatic separation method followed by electrostatic/magnetic separation, copper recovery was 57 % for 0.3–0.6 mm size fraction. Das *et al.*[22] applied a multi-step process in which the table was used for two purposes: classification and pre-concentration. Copper grade in concentrate was 38 %. Total metal grade and recovery was 92 and 97 %, respectively, in the study of Duan *et al*.[6] in which Falcon concentrator was used. Similarly, Ma *et al*.[25] investigated heat-treated product grade after concentrating with Falcon and found product grades approximately 90 %. Burat and Özer[26] analysed the recovery of metals with shaking table-electrostatic/magnetic separators and obtained a heavy fraction with 41 % copper grade and 95 % copper recovery from the first process. The research on metal separation from PCBs by wet jigging and flotation processes gave as a result the metal product with 92.5 % grade at the size fraction of 0.59–1.68 mm.[1] In the Ventura *et al*. work,[27] physical processing alone as well as combined with thermal treatment (200–500 °C) has been performed to recover gold and copper. Physical treatment alone showed recoveries of 67 and 87 wt. % for gold and copper, respectively.

In this article, a shaking table was selected as a gravity concentration tool for the separation of the light material (plastic) from the heavier material (metal). The success of separation with concentrators depends on the selection of suitable design of variables and conditions. The effect of different operating and process parameters are crucial to understand and control the process.[25,28] However, it is very time consuming to test the influence of all factors on the process efficiency. Thus; a well-designed experimental test program should be followed to determine the response of the process to each parameter.[29–31] The objective of the present study was to determine the effect of the important operating variables of the shaking table using response surface methodology (RSM) in conjunction with Box Behnken method (BBM). The selective separation of heavy metals (copper, zinc, brass, gold, *etc*.) was not considered. It was intended to minimize the environmental drawbacks of electronic wastes and the effective recovery of metallic resources. The data collected from the experiments were analysed and the analysis of variance (ANOVA) of the model was performed using Design expert software version 9.0.2.0 from Stat Ease Inc., USA.

EXPERIMENTAL

In the present study, tests were implemented with the main PCBs from the same model/brand LED TVs after removal of electronic components (resistor, capacitor, diode, transistor, *etc*.) on the board (Fig. 1). The operations included comminution, gravimetric concentration and physical/chemical characterization of feed material and products.

In order to reduce the size effect in the concentration process, the components of PCB (epoxy resin, glass fibre cloth and copper) were liberated by two step-comminution. Dismantled PCBs were crushed in a shredder knife crusher with a 10 mm grid. In this type of crusher, hammers, which swing freely, are attached to rotating arms. The swinging hammer contacts the feed material at a high speed and imparts kinetic energy to fracture the feed. Pulse-jet bag filters are used to collect and recycle the dust throughout the comminution. In the second step, the particle size was reduced in closed circuit by a laboratory type ring mill up to –300 μm. Particle size measurement was applied using a vibratory laboratory sieve shaker. The microscope analyses were conducted to determine the copper liberation. Shaking table method was chosen to separate Cu from the PCBs.

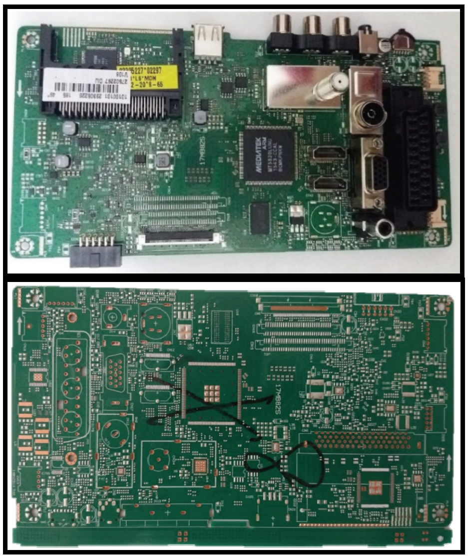

Fig. 1. PCB of LED TV original (top), dissembled board used for the experiments (bottom).

Experimental set-up

A Wilfley shaking table was used to recover the copper particles. It is an efficient technique to prevent the dust problem. It separates materials by particle density on inclined planes having smoothed/grooved shapes by the vibration of pulp material back and forth while wash water is flowing. Fig. 2 presents its schematic representation and the separation for WPCBs. The principle is based on the separation of rapid-moving coarse light particles from slower-moving small dense particles in the flowing water film with longitudinal vibration. Separation process starts: *i*) after feeding a 20–25 mass % pulp from the feed box which moves along the table with wash water; *ii*) continues with the diagonal movement of particles depends on their size and density by the vibration mechanism, using a slow forward stroke and rapid return; *iii*) ends by the collection of small-dense particles at the left end of table and large-lighter particles from opposite the feed box. The separation of metal and plastic materials can be conducted using a Wilfley model to the particle size from 100 μm to 1 mm.[32]

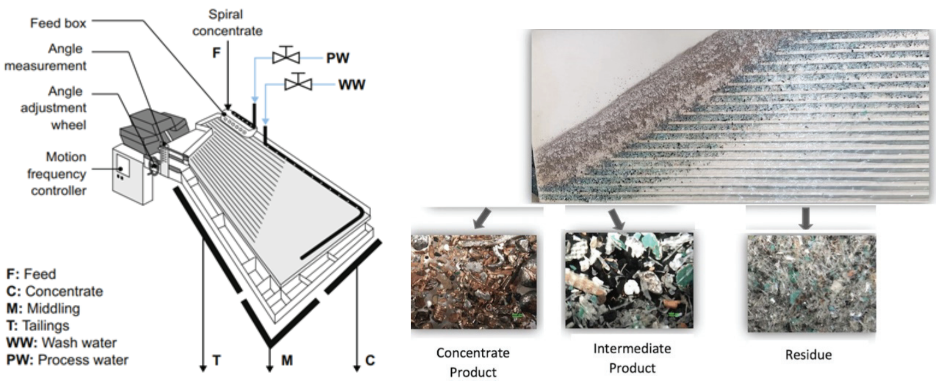

Fig. 2. Left: shaking tabletop view; right: WPCB separation.[33,34]

Response surface methodology (RSM) in conjunction with Box Behnken design (BBD)

BBD was developed by George E. P. Box and Donald Behnken in 1960.[35] The BBD of experiments offer modelling of the response surface methodology. The BBD make it possible to study sequentially the effect of the various factors of the design if, during the study of the first factors, the other factors are maintained at a constant level.[36] RSM and BBD are experimental design statistical tools used to evaluate complex multivariable systems, analyse the cause-and-effect relationship between true mean responses and input control variables, and optimize the response of multiple variable processes. The designs are not based on full or fractional factorial models.[37,38] It is specifically designed to fit a second-order model that is the primary interest in most RSM studies. To fit a second-order regression model (quadratic model), the BBD only needs three levels for each factor.[29,39] The BBD fixed a mid-level between the original low and high level of the factors, avoiding the extreme axial points and using face points. The addition of the mid-level point allows the efficient estimation of the coefficients of a second-order model.[40]

In the present study, the experiments are conducted using a BBD combined with RSM and the empirical relations are established for correlating the interactive and higher-order influences of various machining parameters on the laboratory type shaking table. Four different factors, particle size (mm); wash water flow rate (L/m); deck angle (°); motion frequency (Hz) and their influence on the copper grade and recovery of the concentrate were evaluated. 24 set of trials and four control experiments were conducted during the studies. The main advantage of the RSM–BBD methodology is the ability to perform analysis of several parameters with fewer experimental trials matched to other methods. 4 factors on 3 levels (low, medium and high) were assessed which were represented by a (−1), a (0) and a (+1) sign, respectively. The test variables chosen for the study are designated as particle size (*A*), wash water flow rate (*B*), deck angle (*C*) and motion frequency (*D*). These independent variables to predict responses, namely Cu grade and recovery of the shaking table separator, are named as *Y*1 and *Y*2, respectively. Variables (*A*, *B*, *C* and *D*) and their coded/actual levels used in this study are indicated in Table I.

TABLE I. Box Behnken design parameters and experimental conditions; –1: factor at low level; 0: factor at medium level; +1: factor at high level

Variable	Symbol	Coded variable levels		
		–1	0	+1
Particle size, mm	*A*	–300	500–300	+500
Wash water flow rate, L/m	*B*	6	12	18
Deck angle, °	*C*	1	2	3
Motion frequency, Hz	*D*	40	50	60

The mathematical model of second-order polynomial equations was used to predict the relationship between the four factors and the response. The Eq. (1) is shown by the second order polynomial:

$$Y_{1,2} = b_0+b_1A+b_2B+b_3C+b_4D+b_{12}AB+b_{13}AC+b_{14}AD+ b_{23}BC+b_{24}BD+b_{34}CD+b_{11}A^2+b_{22}B^2+b_{33}C^2+b_{44}D^2 \quad (1)$$

where *Y* is the predicted response, b_0 model constant; *A*, *B*, *C*, *D* independent variables; b_1, b_2 and b_3, b_4 are linear coefficients; b_{12}, b_{13}, b_{14}, b_{23}, b_{24} and b_{34} are cross product coefficients and b_{11}, b_{22}, b_{33} and b_{44} are the quadratic coefficients. Table I shows the experimental matrix design and the results of response variables considered. ANOVA for response surface quadratic model was applied on the results of beneficiation for the goodness of fit of the model and significance of each regression. 3D surface plots were generated using Design Expert 9.0.2 software.

RESULTS AND DISCUSSION

Physical and chemical characterization of PCBs

Particle size measurement of the ground PCBs was applied using a vibratory laboratory sieve shaker for 20 min. After agitation of sieve shaker PCBs collected on each sieve were weighted to calculate the particle size distribution. Wet chemical analysis was done to determine the Cu content of each different size fractions. Results are shown in Table II.

TABLE II. Size wise chemical analysis results of Cu from PCBs

Particle size, µm	Content, wt. %	Grade (Cu)
+500	41.3	12.50
–500+300	35.1	21.38
–300	23.6	11.29
Total	100	15.33

Wet chemical analyses in aqua region were performed to determine the metal content. The spectroscopic analyses of electrolyte solutions were carried out on Analytik Jena NovaA 300 AAS. The chemical composition of PCB is shown in Table III. A major component was copper. Thus, the remaining metallic elements (Fe, Sn, Al, Ca, *etc*.) were not traced for this study.

TABLE III. Chemical analysis of PCB of LED TV

Component	Cu	Sn	Al	Ni	Pb	Zn	Fe	Ca	Non-metals
Grade, %	15.37	3.72	3.22	2.10	1.45	1.04	0.09	6.42	66.31

Microscopic and mineralogical characterization of PCBs

The microscope analysis with the Nikon SMZ 1500 binocular microscope revealed that the copper liberation occurred under the particle sizes of 1 mm. The microscope pictures of all size fractions are given in Fig. 3. Three size fractions were selected to conduct the shaking table experiments: –1+0.50, –0.5+0.3 and –0.30 mm. X-Ray diffraction analyses of PCBs were performed using a Rigaku Miniflex II diffractometer with CuKα radiation. Qualitative XRD analysis of the head sample indicated the presence of polymer, ceramic and copper as major components and small amounts of tin and aluminium in the PCB.

Shaking table experiments

24 sets of trials and four control experiments were conducted to assess the effects of the four variables. The actual data achieved from the tests were also used

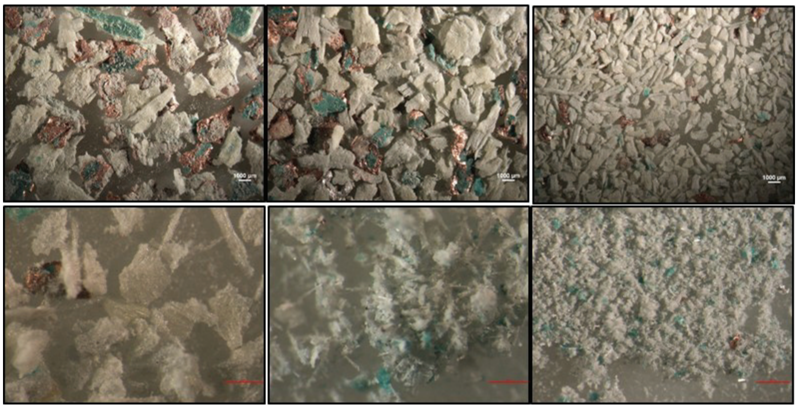

Fig. 3. Microscope analyses of ground sample (top left: –2+1, –1+0.5, –0.5+0.3 mm; bottom left: –0.3+0.2, –0.2+0.1, –0,1 mm).

to make the mathematical equation presenting copper grade and copper yield as a function of the independent variables. The experimental results of the design matrix along with their condition are presented in Table IV. The experimental programme provided a broad range of grade and recovery values which foresaw that the concentrate fraction had been enriched up to with an amount of 53.29 % Cu grade and 83.72 % Cu recovery whereas a maximum amount of 89.99 % Cu recovery (with content of 37.33 % Cu grade).

The experiments were carried out using the laboratory type-shaking table (gravity concentrator) to concentrate the copper particles. The regression coefficient values for the copper grade and copper yield are listed in Table V. The significance of each coefficient was determined by the Student's *t*-test. As it is shown, both independent variables and their interactions can affect the copper grade and yield of the PBCs. From Table V, the model *F*-value of implies that the model is significant for the Cu grade and yield, 98.60 and 19.51, respectively. There is only a 0.01 % chance that a "model *F*-value" this large could occur due to noise. Values of "*Prob* > *F*" less than 0.05 indicate model terms are significant. In this case A, B, A^2, B^2 are more significant model terms for grade. Values greater than 0.1000 indicate the model terms are not significant. The significance level of the coefficients is evaluated with the *F*-value. In other words, for the coefficient to be more significant, the *F*-value is expected to be large.

The response of yield (%) and grade (%) fitted to the second-order polynomial equations. The uncoded model equation for grade (Y_1) and recovery (Y_2) of the concentrate fraction of the shaking table is in Eqs. (2) and (3), respectively. A positive value of the parameter coefficients shows a direct effect on yield and copper content, while a negative sign indicates an adverse effect.

$$Y_1 = +53.27–6.30A+1.65B–0.59C–0.075D+0.13AB+1.48AC– –0.43AD–0.17BC+0.27BD+0.27CD–20.38A^2–5.37B^2–3.92C^2–3.47D^2 \quad (2)$$

$$Y_2 = +83.56–10.49A–1.75B–3.30C–1.91D+2.05AB+4.45AC+ 1.56AD–2.16B+0.014BD–2.57CD–4.66A^2–9.067B^2–7.15C^2–3.94D^2 \quad (3)$$

TABLE IV. RSM–BBD designed experimental results

Run number	Actual independent variables				Grade, Cu %		Yield, Cu %	
	A	*B*	*C*	*D*	Actual	Predicted	Actual	Predicted
1	300–500	12	2	50	52.63	53.27	84.95	83.56
2	300–500	12	1	60	47.22	46.12	77.95	76.43
3	300–500	18	2	60	45.44	46.28	64.04	66.92
4	500	18	2	50	23.68	23.00	60.44	59.66
5	300–500	18	2	40	47.35	45.88	72.76	70.71
6	300	12	1	50	38.26	37.33	91.92	89.99
7	300–500	12	2	50	53.02	53.28	82.19	83.56
8	300–500	12	2	50	53.96	53.27	83.40	83.56
9	500	6	2	50	20.42	19.44	59.93	59.06
10	500	12	1	50	22.69	21.77	62.60	60.11
11	300–500	18	3	50	46.22	44.87	62.90	60.15
12	300–500	12	3	50	32.65	33.18	71.38	74.50
13	300–500	12	1	40	46.91	46.81	71.82	75.10
14	300–500	6	2	40	44.35	43.13	76.45	74.23
15	300	6	2	50	31.42	32.29	82.74	84.14
16	500	12	3	50	23.02	23.56	59.82	62.41
17	300	18	2	50	34.16	35.33	75.06	76.55
18	500	12	2	60	22.24	22.61	63.43	64.12
19	300–500	12	3	60	45.2	45.48	67.35	64.69
20	300–500	6	2	60	41.35	42.43	67.68	70.39
21	300–500	6	1	50	41.19	42.74	68.80	70.24
22	300–500	12	3	40	43.8	45.09	71.52	73.65
23	300–500	6	3	50	43.21	41.91	70.43	67.97
24	300–500	12	2	50	53.45	53.29	83.72	83.56
25	300	12	2	60	37.53	36.06	84.10	81.99
26	500	12	2	40	21.94	23.61	63.99	64.82
27	300	12	2	40	35.53	35.36	90.90	88.92
28	300–500	18	1	50	44.89	46.39	69.88	71.07

Fig. 4 shows the solid linear relationship between the experimental and predicted values of the responses. The determination coefficients R^2 of 0.9907 and 0.9546 of grade and yield cupper content of PCBs, respectively, shows that the fit is reasonably good. The predicted R^2 values of grade and yield copper content of PCB 0.9475 and 0.9346, respectively, are reasonably consistent with the adjusted R^2 values 0.9806 and 0.9256, and the difference between these two values is less than 0.2 for both models, implying that the overall mean may be a better predictor of the response. The actual and predicted values of both the concentrate grade and yield obtained using model Eqs (2) and (3) are presented in Fig. 4a and b, respectively. The predicted values are in well agreement with the experimental values.

TABLE V. Regression coefficient values for the parameter and parameter interaction effects

Factor	Cu (%) grade			Cu (%) yield		
	Coefficient estimate	*F*-value	*Prob>F*	Coefficient estimate	*F*-value	*Prob>F*
Intercept	53.27	98.60	<0.0001	83.56	19.51	< 0.0001
A-particle size, mm	–6.30	215.92	<0.0001	–10.49	154.05	< 0.0001
B-wash water flow rate, L/m	1.65	14.83	0.0020	–1.75	4.28	0.0592
C-deck angle, °	–0.59	1.89	0.1930	–3.30	15.21	0.0018
D-motion frequency, Hz	–0.075	0.031	0.8638	–1.91	5.09	0.0419
AB	0.13	0.031	0.8637	2.05	1.95	0.1859
AC	1.48	4.00	0.0667	4.45	9.23	0.0095
AD	–0.43	0.33	0.5767	1.56	1.13	0.3069
BC	–0.17	0.054	0.8198	–2.16	2.18	0.1634
BD	0.27	0.13	0.7194	0.014	$8.675*10^{-5}$	0.9927
CD	0.27	0.13	0.7194	–2.57	3.09	0.1022
A^2	–20.38	1131.48	<0.0001	–4.66	15.17	0.0018
B^2	–5.37	78.44	<0.0001	–9.06	57.38	<0.0001
C^2	–3.92	41.83	<0.0001	–7.15	35.79	<0.0001
D^2	–3.47	32.78	<0.0001	–3.94	10.87	0.0058
Lack of fit		8.46	0.0526		8.36	0.0535

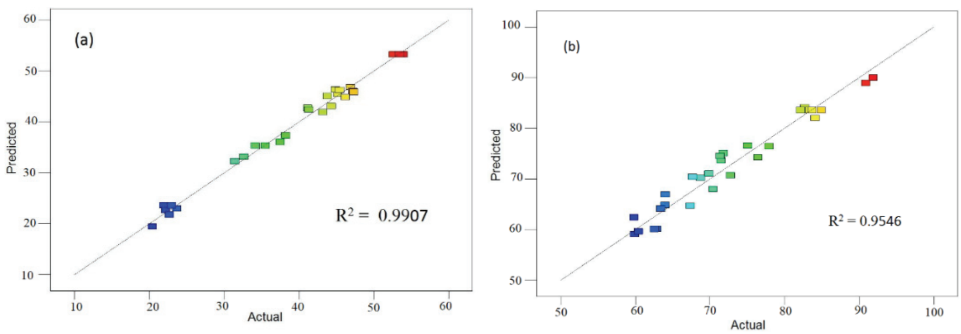

Fig. 4. Relationship between observed and predicted values (a: grade, b: recovery).

Table VI shows the analysis of variance of the developed models for the concentrate fraction of Cu grade and yield. Fisher's test with corresponding *P* values was used to study the effect of different parameters on two responses (grade and recovery) in the result analysis by ANOVA analysis model. The models are significant as the F-value is high, the *Prob*>*F* value is less than 0.05 and the standard deviation is very small 1.48 for the grade and 2.93 for the recovery.

TABLE VI. ANOVA for the parameters of RSM-BBD for the grade and yield models

Statistics	Source	
	Cu (%) grade model	Cu (%) yield model
Sum of square	3041.68	2342.52
Degree of freedom	14	14
Mean square	217.26	167.32
F-Value	98.60	19.51
Prob>*F*	<0.0001	<0.0001
Standard deviation	1.48	2.93
R^2	0.9907	0.9546

According to the results of the shaking table tests, which were divided into narrow sizes to obtain maximum grade and yield; the lowest grade value 20.42 %, the highest grade value 53.96 %, the lowest yield 59.82 % and the highest yield 91.92 % were found (Table VII).

TABLE VII. Statistical analysis for responses (grade and yield)

Variable	Unit	Type	Value		
			Std. Dev.	Low	High
Particle size	mm	Factor	0	–300	+500
Wash water flow rate	L/m	Factor	0	6	18
Deck angle	°	Factor	0	1	3
Motion frequency	Hz	Factor	0	40	60
Rrecovery of concentrate	%	Response	1.48	59.82	91.92
Grade (Cu)	%	Response	2.93	20.42	53.96

Effect of shaking table variables on concentrate grade

Due to the significant difference between the specific gravity of plastics and metals, PCB powder can be separated through low-cost gravity operations such as tabling. To provide the better understanding of the results, the predicted models are described in terms of three dimensional (3D) response surface plots which show the effect of process variables on grade and yield of Cu in concentrate fraction of shaking table. Fig. 5 explains the effect of the process parameters of Wilfley table on the grade of concentrate fraction and it shows the effects of particle size (A), wash water flow rate (B), deck angle (C) and frequency (D) on the grade of the concentrate fraction. It is observed that higher grade is obtained at lower level of wash water, flow rate and higher level of deck tilt angle, which is caused due to a decrease in the residence time of the gangue minerals and that results in the wash away of the low-density minerals to the tailing fraction. Also, it is observed that higher grade is obtained at 300–500 particle size range at level of wash water flow rate. When evaluating the effect of changes made among the *B*, *C* and *D* parameters on the grade, it was observed that the results showed relatively moderate values and there was not a significant difference. From the graphs and the equation obtained through ANOVA analysis, it is understood that the particle size has the greatest impact on the Cu % grade. The results depicted in Fig. 5 indicate that the highest copper grade, 53.96 %, is obtained at the centre level of the inclination and the wash water flow rate recovery is necessary. Therefore, the tabling stage serves a dual purpose as a classification and a pre-concentration operation. The process targets a high yield clean product with a middling stream having relatively lower purity, and a low-grade rejectable tailings stream.

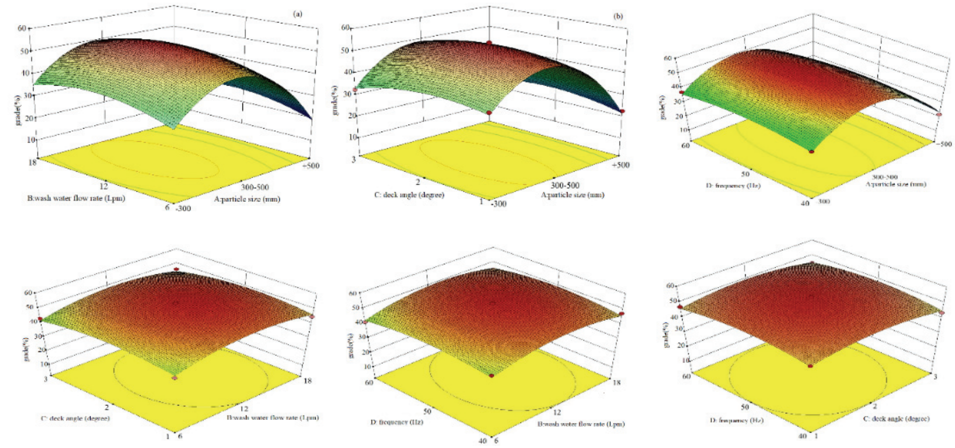

Fig. 5. Results of effecting variables on concentrate for Cu % grade.

Effect of of shaking table variables on concentrate yield

Based on the information provided, Fig. 6 shows the variables that affect the concentration of Cu % yield in a separation process. The relationship between these variables is complex, and the values of some parameters are dependent on the level of other parameters. Specifically, it has been observed that the effect of deck angle on the Cu % yield is dependent on the washing water flow rate. Increasing the deck angle level reduces the washing water flow rate, especially when the washing water flow rate is at its lowest level. Therefore, a moderate level of deck angle should be selected to increase the Cu % yield. Additionally, the results show that the Cu % yield increases when the deck angle and particle size are at their lowest, and the main effects of particle size, deck angle, square of wash water flow rate, and frequency have a significant impact on the separation process.

Among the interactional effects, the interactions between particle size, deck angle, and wash water flow rate have a considerable effect on the recovery of the concentrate fraction. However, the frequency and interaction between frequency and deck angle, as well as the interaction between wash water flow rate and frequency, are less significant. Empirical models were used to describe the effect of each variable at different combination variables on concentrate recovery in Fig. 6. Overall, understanding the relationships and interactions between these variables is critical to optimizing the separation process and achieving the desired Cu % yield.

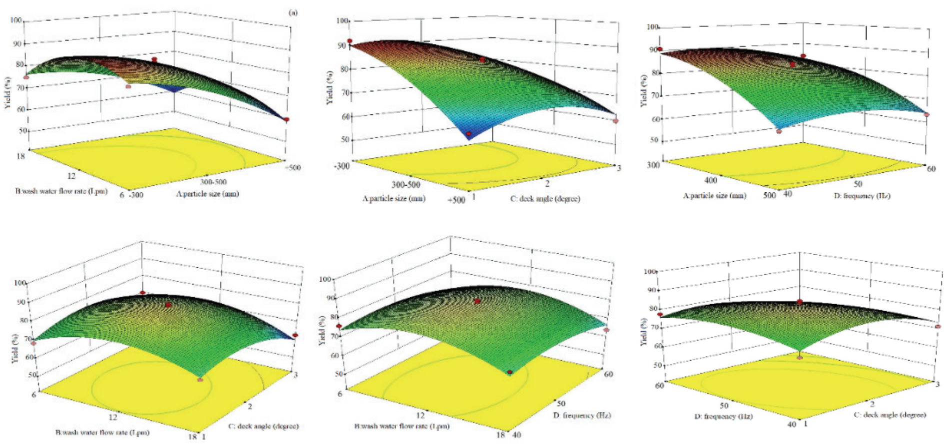

Fig. 6. Results of effecting variables on concentrate for Cu % yield.

Validation of the model

Grade and recovery are significant terms for evaluating the performance of any unit operation in mineral processing. In addition, the grade and recovery of any process are inversely related to each other. To validate the obtained model for predicting the grade and recovery of copper content in concentrate, several tests were conducted based on the empirical model. The observed and predicted results for both responses are illustrated in Fig. 7. Fig. 7 shows that the predicted values are in good agreement with the observed values, with R^2 values of 0.9525 and 0.9413 for grade and recovery of copper concentrates, respectively. Overall, this study provides valuable insights into the performance of the described unit operation for copper processing.

It was also found that the predicted values of the experimental values are in reasonably good agreement, with R^2 value for grade and recovery of the concentrate fraction of the laboratory shaking table is 0.9907 and 0.9806, respectively. According to the results of the ANOVA analysis, the particle size was found to be the most effective parameter in terms of both grade and metal recovery. The optimized values for the greatest grade and the recovery were 53.96 and 83.40 %, respectively.

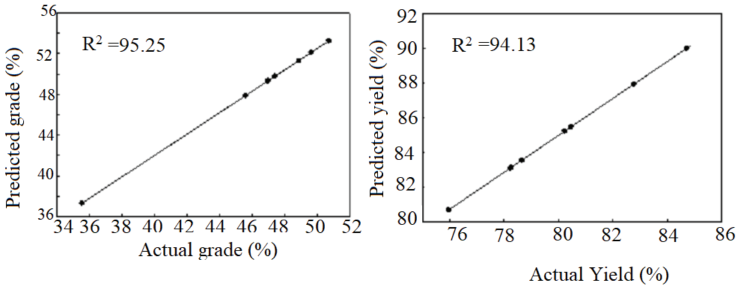

Fig. 7. Relationship between observed and predicted values for the grade and yield (% Cu).

CONCLUSION

In this study, the Box Behnken design was used to optimize the performance of the wet shaking table and to identify the ideal combination of its operating parameters. The four process parameters were investigated: deck angle, motion frequency, wash water rate, and particle size diameter. The mathematical models were developed for both grade and recovery of Cu in the concentrate fraction by using a set of experimental data and the mathematical software package Design Expert 9.0.2 software. The optimal settings were determined to be a deck angle of 2°, motion frequency of 50 Hz, wash water rate of 12 L/m, and particle size diameter of –500+300 mm. Optimal settings were determined to be near the central points of the experimental design, indicating that the true optimal point may lie within the designed space.

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ИЗВОД

ИЗВЛАЧЕЊЕ БАКРА СА ШТАМПАНИХ КОЛА (PCB) ПОМОЋУ ВИБРАЦИОНОГ СТОЛА

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У последњих неколико година расте заинтересованост за поновну употребу металних компоненти из електричне и електронске опреме отпадног порекла (WEEE), што се односи на електричне и електронске уређаје који су постали застарели, престали да раде или показали дефекте током производње. У овом истраживању као алат за гравитациону концентрацију за рециклажу бакра из лаких компонената изабран је вибрациони сто. Технолошки поступак је укључивао уситњавање, гравиметријску концентрацију и физичко–хемијску карактеризацију улазног материјала и продуката. Параметри процеса су били угао стола (у степенима), фреквенција покрета (Hz), брзина воде за испирање (L/m) и пречник честица. Бох Бехнкен (Box Behnken) дизајн (BBD) је употребљен за

оптимизацију перформанси мокрог вибрационог стола и идентификацију идеалне комбинације његових радних параметара. Анализом експерименталног дизајна утврђено је да су оптималне вредности за угао стола, фреквенцију покрета, брзину воде за испирање и пречник честица износили 2°, 50 Hz, 12 L/m и –500+300 mm, редом. Ове оптималне поставке биле су лоциране близу централних тачака експерименталног дизајна, што сугерише да се стварна оптимална тачка може налазити унутар одређеног простора.

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