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Controlling Grinding Process Parameters Using Central Composite Design to Reduce Slimes in Phosphate Ore Beneficiation

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Abstract

Ultrafine particles resulting from the grinding operations of phosphate ore cause problems of air pollution, and of the beneficiation plants particularly, flotation cells and filtration units. Particles of less than 38 μm are one of the undesirable consequences of the phosphate ore beneficiation stage, where fine or ultrafine powder accounts for 10–30 percent of phosphate quantities and is regarded as a loss. Furthermore, maintaining additional amounts of phosphate by reducing these particles will provide several benefits, including minimizing the environmental implications of slime disposal and enhancing the economic impact of the phosphate ore beneficiation process. This paper aims to maximize the useful phosphate particles and reduce the slime instead of doing even more work with traditional techniques. This goal might be attained by increasing the percent of particles of the desired size of the phosphate (Target) during the grinding process by determining the optimal operational conditions, that will reduce the amount of slime. The central composite design (CCD) is used to identify the number of experiments to be evaluated and to create a predictive model to be used for determining the optimal operation parameters. As a result of the optimization process, a maximum Target of 87.6% was obtained at grinding conditions t (5.1 min), v (42.6%), s (81.2%), and c (50.7%). Where t, v, s, and c stand for grinding time, occupied volume of ball, rotational speed percent from critical speed (%) and solid concentration by volume (%) respectively.

Keywords:
Phosphate slimes; ball mill; central composite design; optimization; grinding operation

1. Introduction

Slimes are phosphatic clays, which are ultrafine products with a mesh size of less than 150 mesh (< 0.1 mm) and are one of the undesirable consequences of the phosphate ore beneficiation process (**Abdel-Khalek et al., 2000; Zapata and Roy, 2004**). This is the case with sedimentary ores. Slimes (size <-38 microns) frequently contain phosphate ores which cause significant issues in mineral equipment, particularly in flotation and filtering units. Several beneficiation plants around the world, including Jordan (**Al-Thyabat et al., 2011**), Iran (**Pourkarimi et al., 2018**), India (**Pradip and Sankar, 1992**), China (**Liu et al., 2017**), Australia (**Teague and Lollback, 2012**), the United States (**Zhang and Bogan, 1995**), and Brazil (**Elves et al., 2017; Guimarães and Peres, 2002**) reported that phosphate ore possesses similar chemical and physical features as their slimes. Therefore, desliming is a common and important procedure in phosphate ore beneficiation plants. For successful concentration, it is necessary to lower the ultrafine feed in order to minimize unwanted impacts. Desliming is a frequent procedure and an important step in phosphate ore beneficiation plants for successful phosphate beneficiation by lowering the ultrafine feed to minimize unwanted impacts (**Matiolo et al., 2017; Guimarães and Peres, 2002**). However, the difficulty in processing ultrafine particles is due to their size, which is due to their small mass, large superficial area, and high superficial energy, as well as the fact that the slimes' fraction typically generates a large amount of clay minerals, which has a strong impact on the flotation process's beneficiation stage. These properties have a number of negative consequences, including a poor particle/bubble collision efficiency, high reagent consumption, slime coating, high pulp viscosity, and trouble breaking the energy barrier between particle/particle and particle/bub-

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ble, as well as froth rigidity (**Shahbazi et al., 2010; Sivamohan, 1990; Subrahmanyam and Forssberg, 1990**). As a result, column flotation, as used with Jordanian phosphate ore, is one option for phosphate slime flotation (**Al-Thyabat et al., 2011**). In fact, even after cleaning the rougher concentrate, using traditional froth flotation techniques will not result in such grades and recoveries (**Abdel-Khalek et al., 2000; Aleksandrova et al., 2020**). Another method for desliming is to employ a hydrocyclone, which is utilized either before or after flotation (**Sajid et al., 2021**).

The fines (slimes) are separated from the coarse phosphate particles using a Mozley rig hydrocyclone. An experiment was conducted to determine the influence of cyclone characteristics on phosphate desliming. In addition, two situations were used in the studies. The feed solids percent was gradually confirmed from 5 to 20% in the first scenario while maintaining a feeding pressure of 68.95 kPa (10 psi). In the second case, the feeding pressure was set at an optimal solid percent of the feed, which had been previously determined. A feed batch was prepared for each circumstance to ensure that the entire run was satisfied. The cyclone was fed at a constant pressure with dense phosphate pulp (20% solids by volume) in the first scenario. For the first experiment, 30 seconds of a sampling was taken from both cyclone products at the same time. For the second experiment, the same feed was diluted with enough water and circulated through the hydrocyclone for homogenization. The products were sampled for the same 30 seconds after homogenization by hydrocyclone. The solid content of the underflow and overflow samples, as well as the cut size, were analyzed (Analysett 22 laser particle size analyzer). Finally, the underflow and overflow products were collected and prepared for chemical and mass balance studies, with the underflow being kept for further flotation testing (**Ahmed, 2007**).

Furthermore, substantial advancements have been made in the Brazilian phosphate industry to improve strategies for recovering phosphates from slimes (**Matiolo et al., 2017; Guimarães and Peres, 2002**). Desliming is accomplished using hydrocyclones with diameters of 4 cm to remove particles smaller than 5–10 m, followed by a flotation section to remove the ultrafine powder. However, a comparison of the findings was produced from the Denver flotation cell's flotation process in the presence and absence of nanobubbles (**Pradip and Sankar, 1992**). The flotation results showed that the presence of nanobubbles has a favorable effect, with almost 90% of P_2O_5 with an assay of more than 40% recoverable in the presence of nanobubbles, but the P_2O_5 recovery was only 37% in the absence of nanobubbles under the same conditions. When compared to flotation without nanobubbles, the recovery of apatite by flotation in the presence of nanobubbles increased by around 30% (**Pourkarimi et al., 2018; Pradip and Sankar, 1992**). Screening before flotation was also used as a desliming procedure. The identical Fritsch shaker was used to test both dry and wet screening for phosphate desliming. Only the material flow rate changed, while the screening time and vibrating amplitude remained fixed at 10 minutes and 50 Hz, respectively. Phosphate was fed to the screen at different rates, ranging from a double layer to multiple layers. The number of particle layers present on the screen was computed by taking the average particle size of the feed and multiplying it by the overall area of the screen. Based on their sizes, there are two sorts of materials used to make screen products. As a result, there are two types of products: oversize flotation feed and undersize flotation feed (slimes.) Both were computed using percentages of weight and P_2O_5 and SiO_2 concentrations were evaluated. The efficacy of the desliming procedure was then assessed based on how the feed responded to flotation separation (**Ahmed, 2007; Ipek, 2000**). Furthermore, optimizing phosphate grinding settings will boost phosphate recovery to around 58 percent and reduce slimes (**Abdelhaffez et al., 2022; Abdelhaffez, 2020 and 2005; Boujlel et al., 2018**).

Recently, many statistical experimental design methods have been used in different industries for the optimization of process parameters. In the traditional technique, optimization of a multivariate system follows one factor at a time. Several trials are required for these techniques, and these methods do not represent the combined effect, which requires more data to determine the optimal level and takes a long time (**Omidbakhsh et al., 2012**). The design of experiments (DOE) is an efficient systematic method that can be used to determine the relationship between factors affecting a process and the output of that process, which could help in the optimization of experimental parameters and provide statistical models (**Montgomery, 2013**). DOE methods have been used extensively in investigating the significance of manufacturing process conditions on the process outputs, such as quality of machined surfaces (**Khashaba et al., 2020**), forming operations output (**Tahboub and Rawabdeh, 2004**), yield of chemical processing (**Lee et al., 2014**), and performance of the assembled product during production (**El-Midany et al., 2013**).

Factorial design was used to estimate the optimum conditions of nitric acid treatment used for the phosphogypsum beneficiation process (**Aliedeh and Jarrah, 2012**). The Taguchi method was used to find the optimal process variables for the extrusion of the Al 6061 alloy (**Rao and Krishna, 2012**). **Nezadi et al.** (**2021**) demonstrated that the Taguchi method was successfully applied to the optimization of electrospinning conditions for Thermoplastic Polyurethane nanofibers. The Box-Behnken design was used to determine the optimal conditions of the reductive leaching process of MnO_2 from manganese mine tailings (**Alaoui et al., 2015**). Also, this design was used to design the reverse flotation experiments integrated with nanobubbles to attain maximum Fe recovery at the optimal conditions (**Sobhy et al., 2021**). Response surface methodology (RSM) combined

Table 1: Chemical analysis of the Al-Nasr phosphate mine, Egypt

Oxide	P_2O_5	CaO	Fe_2O_3	SiO_2	Al_2O_3	Na_2O	K_2O	MgO	Cl−	CO_2−	SO_3−	F−
(%)	19.82	44.26	2.78	5.63	2.21	1.73	0.16	4.3	0.45	16.1	1.35	1.21

with central composite design (CCD) of experiments has been used to characterize the influential parameters on the flotation behaviour of a sulfurized mixed copper ore (**Azizi et al., 2020**). **Flores et al.** (**2020**) employed artificial neural networks to build a predictive model for copper recovery in leaching piles with low-grade material, using data from actual pile operation. A lot of research is combined with design experiment methods and neural networks to develop prediction models (**Abdelwahed et al., 2012; El-Midany et al., 2013; Kharwar and Verma, 2019**).

A lot of research investigated how to find the proper solutions for phosphate processing, and to mitigate the effect of the waste clay produced as a residue of phosphate ore processing, which poses severe environmental problems, as well economic loss (**Eskanlou and Huang, 2021; Yang et al., 2021**).

To improve the sustainability requirements, it is necessary to reduce phosphate losses in the slimes as much as possible at a low cost, with low energy consumption and low environmental impact, and without disrupting the beneficiation process. In a mineral processing plant, the work concept aims to gather with simplicity and efficiency, with the optimum grinding operation circumstances taken into account before any processing technology is applied. According to the knowledge of the author and literature review, the improved ball mill method outcomes in phosphate ore beneficiation by controlling the process parameters to reduce slimes, has not been thoroughly addressed. Therefore, the current paper aims to fill this gap. The number of experiments evaluated for enhancing desliming procedures utilizing the developed response surface model is determined using CCD.

2. Methodology of Experimental Work

2.1. Material preparation

200 kg of ROM typical samples of phosphate material were taken from the Al-Nasr phosphate mine in Egypt. All samples were ground to - 5 mm in a jaw crusher, sieved to get the size fraction of mill feed between (-5+3mm), and the samples were prepared for the test using the coning and quartering sampling technique. Following that, samples were sieved for the phosphate grinding procedure. The investigations were carried out using laboratory equipment from the Assiut University's mining and metallurgical department in Egypt. Slimes differ depending on the geological origin of the phosphate ores, whether sedimentary or igneous rocks, in terms of mineralogical composition, and most importantly, particle size. **Table 1** gives the chemical composition of the Al-Nasr phosphate mine in Egypt.

2.2. Equipment

A cylindrical ball mill, which has an inner diameter of 15 cm and a length of 30 cm and was designed by the Engineering Faculty at Assiut University, will be used. To eliminate vibration, the mill is supported on a metallic foundation that is fastened to the floor. The particle size distribution for the mill feed and product was determined using a sieve shaker.

2.3. Experimental procedures

The release of precious minerals from the gangue is usually the consequence of grinding the ore. Dry and wet grinding are the two types of grinding, with the latter using less energy (**Abdel-Hafeez, 2005**). The parameters will be examined under wet circumstances at various solid concentrations to ensure that they meet the industry standards for phosphate ore wet grinding. The purpose of these tests is to improve phosphate grain liberation, boost the obtainment of the desired size range of the needed fractions, and reduce slimes to lessen their negative impact on the next stage of production. This research will look into four operating parameters of a ball mill. The factorial design application will evaluate grinding time (t) ranging from (1-9 min). The percentage of the ball's occupied volume (v) will be tested (20-60%). The rotational speed will be checked on a scale of (65-95%) of critical speed. Solid concentration will be measured between 30% and 70%. The output of each test run will be kept in a furnace at 110°C for 24 hours until dry, then sieved for 10 minutes to determine the percentage of the size fraction of the concentrate between size fractions (-250 + 38 μm).

3. Results

3.1. Experimental Design

Minitab 19 was used to construct the experiment, run regression analysis on the experimental data, and draw a 3D representation of the response surface. To reduce the number of tests performed, the central composite design was utilized to plan the experiments (**Montgomery, 2013**). Grinding time (min), percent of occupied volume of ball (percent), rotational speed percent from critical speed (percent), and solid concentration by volume are all considered control elements in this study (percent). The experimental levels for the control factors are displayed in **Table 2**.

3.2. Statistical Analysis

To measure and evaluate the influence of the grinding operation parameters, the experimental data is statisti-

Table 2: Levels of the control factors

Control factor	Levels				
	-2	-1	0	1	2
t = Grinding time (min)	1	3	5	7	9
v = Occupied volume of ball (%)	20	30	40	50	60
s = Rotational speed percent from critical speed (%)	65	72.5	80	87.5	95
c = volumetric solid concentration (%)	30	40	50	60	70

cally examined. A second order polynomial function representing the correlation between the grinding operation parameters and the process target is developed according to the design shown in **Table 2**. This equation takes the following generic form, **Equation 1**:

$$Y = \beta_O + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_{11}X_1^2 + \beta_{22}X_2^2 + \\ + \beta_{33}X_3^2 + \beta_{44}X_4^2 + \beta_{12}X_1X_2 + \beta_{13}X_1X_3 + \beta_{14}X_1X_4 + \\ \beta_{23}X_2X_3 + \beta_{24}X_2X_4 + \beta_{34}X_3X_4 \quad (1)$$

Where Y represents the response, X_1, X_2, X_3, and X_4 represent the control variables, and β_s represents the constant and coefficients of variation resources of the prediction response model. R^2, a statistical measure, is used to evaluate the regression model's quality. **Table 3** shows how the desired particle size percent (*Target*) of the grinding operation output varies with different levels of grinding operation parameters.

3.3. Required size (Target) model construction

To understand the behaviour of the process and effect of its factors, an appropriate model should be selected. Hence, different models are fitted to the data of the grinding operation and evaluated by analysis of variance (ANOVA) in terms of the goodness and accuracy of the models fitted. The ANOVA was developed by Fisher to solve problems in the agricultural field. Its primary objective is to assess the influence of control factors on the outcome of an experiment. ANOVA is useful in the study of processing parameters with grained mineral properties (**Jamróz et al., 2020; Niedoba and Pięta, 2016**). From results of conducting the experimental CCD in **Table 3**, the second-order response function representing the percentage of the target of size fraction range can be expressed as a function of the four parameters of a grinding operation. The quadratic model was found to adequately predict the process outcome (*Target* %) given by the following equation:

$$\textit{Target},\ \% = -772.249 + 23.333t + 6.255v + \\ + 14.001s + 3.976c - 2.207t2 - 0.071v2 - \\ - 0.086s2 - 0.041c2 + 0.013t \times v - 0.017t \times s - \\ - 0.004v \times s + 0.003s \times c \quad (2)$$

The high value of coefficient of determination (R^2 = 0.9615), shown in **Table 4**, indicates that the suggested quadratic model is capable of representing the production process under the given experimental domain.

3.4. ANOVA results

The primary objective of using ANOVA is to investigate the significance of the grinding operation conditions (t, v, s and c) affecting the grinding outcome. The contribution percentage of each operation parameter on the total variation indicates its effect on the yielded outcome. The significance of the effect of the grinding parameters on the response can be measured by the P-value. For most experimental work, a P- value less than 0.05 indicates the significance of the related factor for the response. The results of the ANOVA applied to the CCD are summarized in **Table 4**.

Table 3: Central composite design (CCD) matrix and the results of experiments

Std	*t* (min)	*v* (%)	*s* (%)	*c* (%)	*Target* %	Std	*t* (min)	*v* (%)	*s* (%)	*c* (%)	*Target* %
1	3	30	72.5	40	55.12	15	3	50	87.5	60	68.11
2	7	30	72.5	40	58.23	16	7	50	87.5	60	70.79
3	3	50	72.5	40	63.19	17	1	40	80	50	50.05
4	7	50	72.5	40	65.87	18	9	40	80	50	49.53
5	3	30	87.5	40	60.24	19	5	20	80	50	50.01
6	7	30	87.5	40	62.85	20	5	60	80	50	64.03
7	3	50	87.5	40	67.31	21	5	40	65	50	68.00
8	7	50	87.5	40	69.08	22	5	40	100	50	64.00
9	3	30	72.5	60	55.94	23	5	40	80	30	66.50
10	7	30	72.5	60	57.17	24	5	40	80	70	71.00
11	3	50	72.5	60	61.89	25	5	40	80	50	86.79
12	7	50	72.5	60	67.78	26	5	40	80	50	85.39
13	3	30	87.5	60	61.25	27	5	40	80	50	87.84
14	7	30	87.5	60	63.06	28	5	40	80	50	88.09

Table 4: ANOVA results of the quadratic model of CCD

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	12	2954.3	96.15%	2954.3	246.19	31.21	0.000
Linear	4	387.13	12.60%	387.13	96.78	12.27	0.000
t	1	19.58	0.64%	19.58	19.58	2.48	0.136
v	1	324.14	10.55%	324.14	324.14	41.09	0.000
s	1	36.26	1.18%	36.26	36.26	4.6	0.049
c	1	7.15	0.23%	7.15	7.15	0.91	0.356
Square	4	2563.11	83.42%	2563.11	640.78	81.23	0.000
t*t	1	1037.63	33.77%	1869.84	1869.84	237.03	0.000
v*v	1	744.06	24.22%	1202.33	1202.33	152.41	0.000
s*s	1	369	12.01%	560.57	560.57	71.06	0.000
c*c	1	412.43	13.42%	412.43	412.43	52.28	0.000
2-Way Interaction	4	4.06	0.13%	4.06	1.01	0.13	0.970
t*v	1	1.13	0.04%	1.13	1.13	0.14	0.710
t*s	1	1.02	0.03%	1.02	1.02	0.13	0.724
v*s	1	1.2	0.04%	1.2	1.2	0.15	0.702
s*c	1	0.71	0.02%	0.71	0.71	0.09	0.769
Error	15	118.33	3.85%	118.33	7.89		
Lack-of-Fit	12	113.8	3.70%	113.8	9.48	6.28	0.078
Pure Error	3	4.53	0.15%	4.53	1.51		
Total	27	3072.63	100.00%	**R^2 = 0.9615**			

Accordingly, the largest contribution in the obtained model is of the *v* and v^2 (10.55% and 24.22% respectively), followed by the *t* and t^2 (0.64% and 33.77% respectively), then by the lowest contribution of the *s* and s^2 (1.18% and 12.01% respectively), while the contribution of the c^2 is 13.42% and the main factor *c* does not have a significant effect. Absolute values of the standardized effects from the largest to the smallest effect are illustrated in the half-normal probability plot of the effects shown in **Figure 1**. The factor of the occupied volume of the ball (*v*) has the most significant linear effect among the all-operation parameters studied here, while grinding time squared (t^2) has the most significant effect among all the sources of variation in the predictive model. The correlation coefficient between the measured *Target* percent values and that are predicted by the pro-

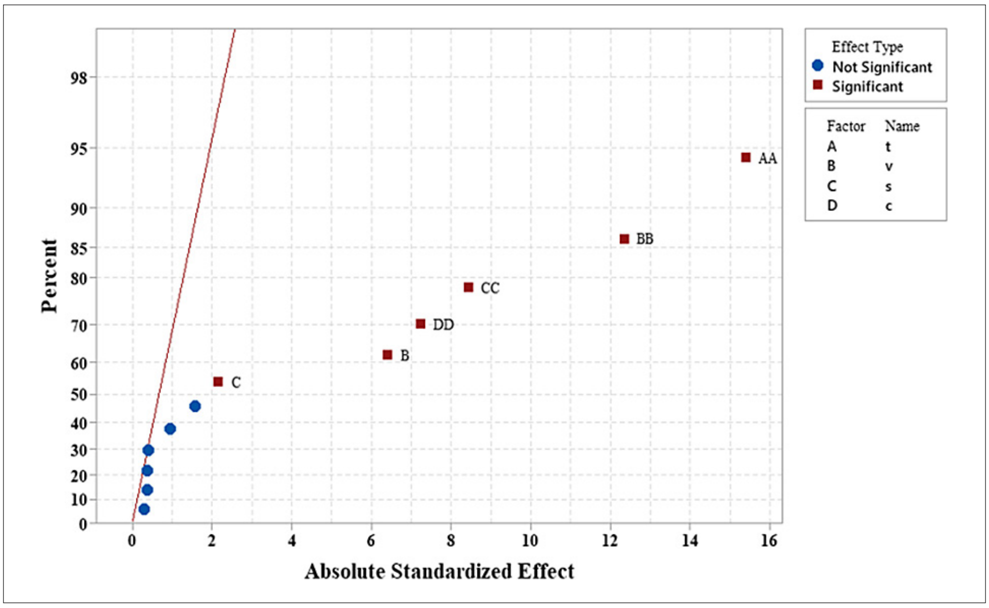

Figure 1: Half-normal probability plot of the effects

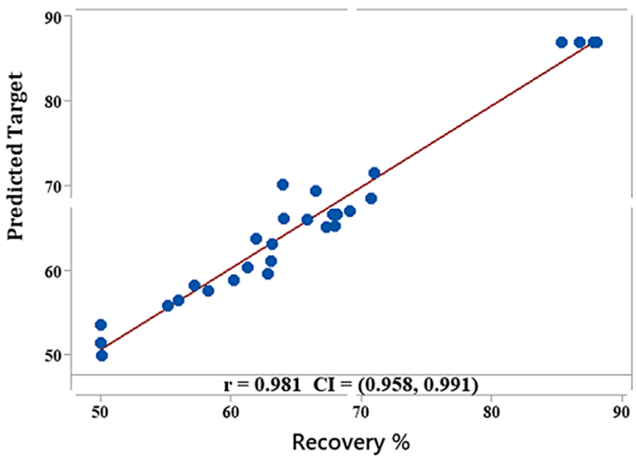

Figure 2:The plot of correlation between measured and predicted values of Target percent (95% CI for Pearson Correlation)

3.5. Factors influence on process response

Figure 3 depicts the normal probability of residuals. From ANOVA analysis in **Table 4**, it is clear that, there are no significant interaction effects. **Figure 4** shows the main effect plots of the investigated grinding process. The plotted data reveals that the all-factor curves have a curvature. With all factors, the *Target* increases from the low level to the centre points and decreases again towards the high level. 3D surface and contour plots of the grinding process response versus different operation parameters are plots that can easily indicate the worst and optimal conditions for the predicted outcome. For example, at a ball volume of 30% the critical *Target* value was observed at a time of 3 min, as shown in **Figure 5**. Likewise, optimum conditions can be inferred as will be described in the next section.

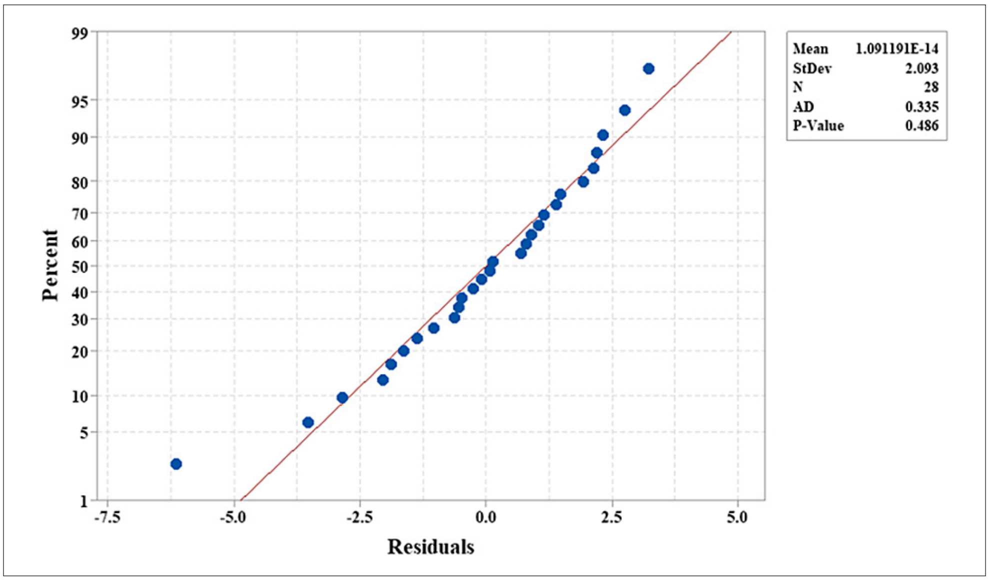

Figure 3: Normal probability plot of residuals

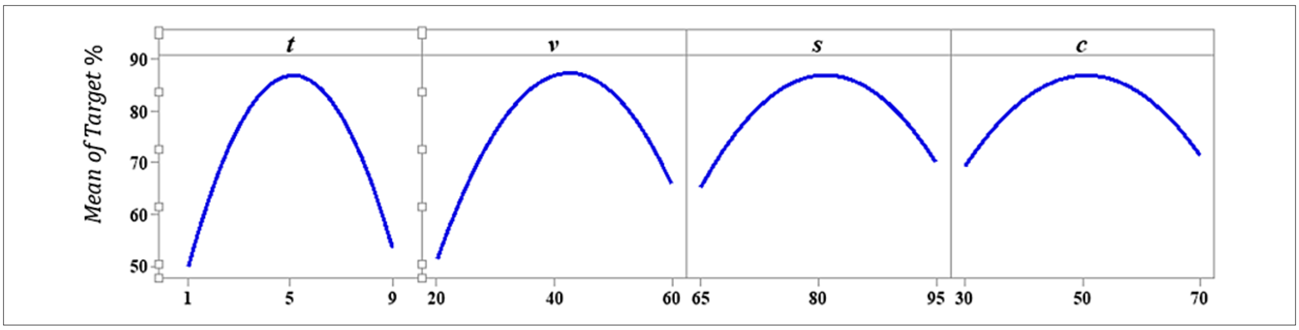

Figure 4: Main effect plot

posed quadratic model above are shown in **Figure 2**. Adequate precision measures the signal to noise ratio, which is desirable if it is greater than 4. In this study, it was of 19.39, indicating that the obtained model can be used to navigate the experiment design space.

3.6. Grinding process optimization

The grinding process parameters were optimized using the Design-Expert software package and the goal function of maximization for the *Target* % of required size within the range of experiment. **Figure 6** depicts the maximum target that can be obtained on a 3D plot using a predictive model, suggested by software, between *v* and *t* at the optimal value of *s* and *c*. The results of the optimization step shown in **Figure 7** elucidate the optimal operational conditions obtained from the software. It is found that the maximum *Target* of about 87.61% can be obtained at desirability level of 0.98. The optimal operating conditions suggested were *t* (5.1 min), *v* (42.58 %), *s* (80.89 %) and *c* (50.69 %.).

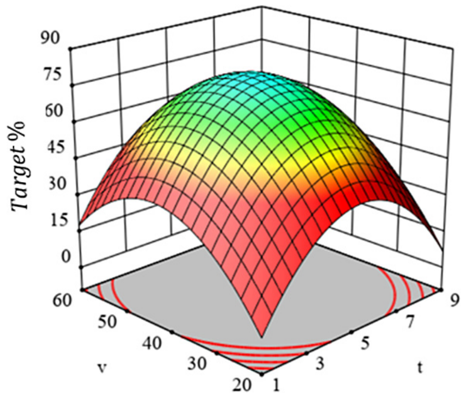

Figure 5: 3D response surface plot of combined effect of time and ball volume percent at s=72.5% and c= 60%

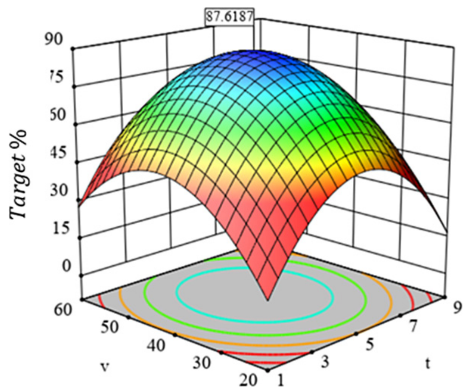

Figure 6: 3D plot with contour plot of optimal conditions suggested using the proposed predictive model at s=80.89% and c= 50.690%

4. Discussions

This part will go through the previous experimental data and the results of statistical analysis. The best *Target* % of necessary size (-250+38 microns) produced by the ball mill method is obtained using the constructed multivariant regression model determining which parameters are more significant in grinding phosphate ore and under what operating conditions. The grinding time appears to be a significant factor in the grinding process, based on the findings, there is direct proportionality from the lowest level up to the central level at which the proportionality is inversed even at the highest level. With an increase in time, the particle size decreases. And this relation is within the desired range even near the centre point. After that, particle size becomes less than the lower limit of the desired range of size (38 µm). For obtaining the maximum *Target*, the optimal grinding time is 5.1 minutes. Through the grinding process results, the percentage of ball-occupied volume has the most significant effect of variation source of square and the second in linear effect. *Target* increases from the lowest level of ***v*** up to the centre point to attain the maximum value. In our design space, the optimal percentage of ball-occupied volume was about 42.6%. The reduction of particle size inside the mill depends on the potential impact between the media of grinding and the ore

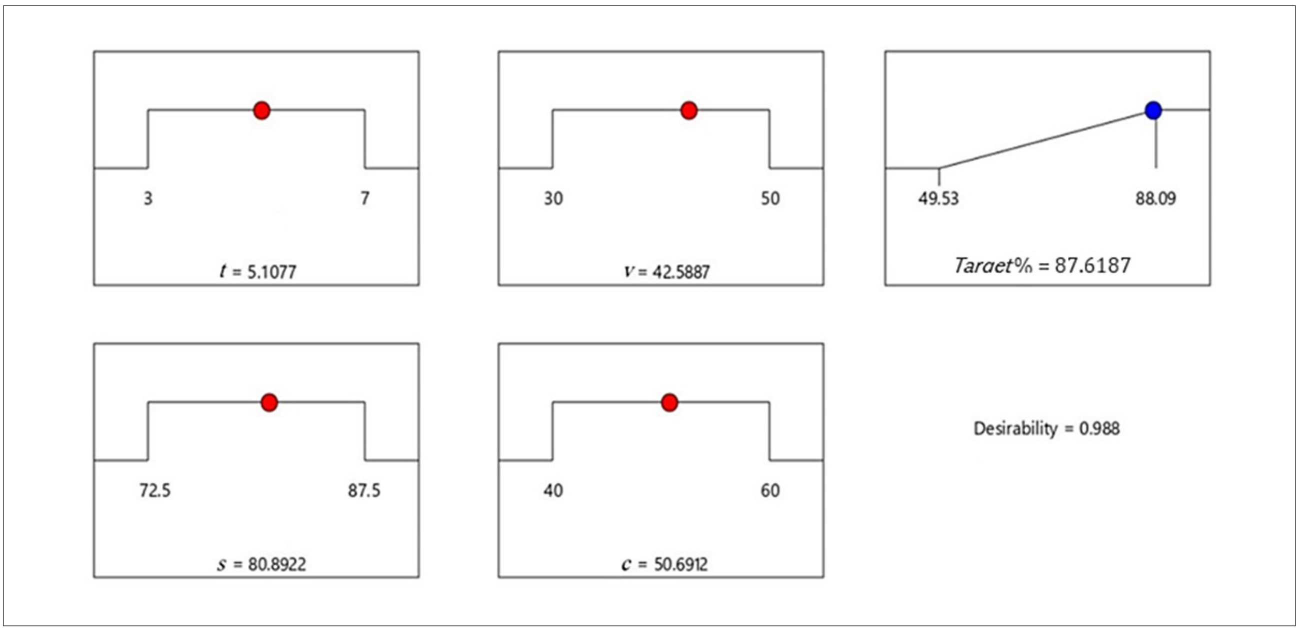

Figure 7: Optimal values of process parameters to maximize the Target

particles. It is attributed that the collision possibility increases with the optimum percentage occupied volume by balls (**Abdel-Hafeez, 2005**). As shown in ANOVA results, the effect of the rotation speed of mill (*s*) between 72.5% - 87.5% of critical speed is significant, the speed increases the motion of the charge inside the mill towards the mill wall. It is the centrifugal motion where the rotation speed is critical. This parameter contributes to the variation in the model by 1.2% and 13% of s and s^2 respectively. The solid concentration (*c*) role in the grinding could not be ignored. Although factor c is insignificant in the obtained model, c^2 is significant and contributes by 13.42% to the model effects as elucidated in **Table 4**. As indicated in the main effect plot in **Figure 4**, with low percentages of ore, the *Target* of desired size particle range was at its lowest value. While the solid percent increased close to 50%, *Target* % was at its highest around 86% attaining an improvement of about 20% at optimal values of the rest of the parameters. Then, when the solid concentration rises, the *Target* % drops to around 60% at 65% solid concentration.

5. Conclusions

Slimes differ depending on the geological origin of the phosphate ores, whether sedimentary or igneous rocks, in terms of mineralogical composition, and most importantly, particle size. Slimes (e.g. size < -38 microns) frequently contain phosphate ores, causing significant problems in mineral processing equipment, particularly flotation and filtering units. Thus, the aim of this research was to reduce the amount of slime produced during the grinding stage of phosphate ore processing. CCD of experiments was used to apply the response surface modelling to optimize and evaluate the effects of grinding time, percentage of ball-occupied volume, the rotation speed of the mill and solid concentration on the desired size percentage. ANOVA and response surface and contour plots were utilized in investigating the *Target* percent obtained. The findings revealed that all grinding operation parameters have a substantial impact on the *Target* percent, or the amount of slimes produced during grinding. Among the all-operation parameters analyzed here, the factor of occupied volume of ball (*v*) has the most significant linear effect, whereas grinding time squared (t^2) has the most significant effect among all sources of variation in the prediction model. The proposed strategy aids in the control of slime in the phosphate grinding process and maximizes the desired size utilizing the current manufacturing technology. Finally, we found that the maximum *Target* of about 87.61% can be obtained at a desirability level of 0.98 with the suggested optimal operating conditions *t* (5.1 min), *v* (42.6%), *s* (81.2%) and *c* (50.7%). Finally, in order to take advantage of this experimental work, the results may be transferred into the industrial environment to calibrate the current state applied to stand at the best grinding parameters. In future research, the particle size distribution of the ground product and the percentage of P_2o_5 in various size fractions will be taken into account to enhance and possess the investigation and results.

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SAŽETAK

Kontroliranje parametara procesa mljevenja korištenjem centralno kompozitnoga plana za smanjenje mulja u oplemenjivanju fosfatne rude

Vrlo sitne čestice koje nastaju u procesu mljevenja fosfatne rude uzrokuju probleme onečišćenja zraka, a posebno probleme u samome radu oplemenjivačkih postrojenja, flotacijskih ćelija i filtracijskih jedinica. Čestice manje od 38 µm jedna su od nepoželjnih posljedica faze oplemenjivanja fosfatne rude, gdje sitni ili vrlo sitni prah čini 10 – 30 posto količina usitnjene fosfatne rude i smatra se gubitkom. Nadalje, održavanje dodatnih količina korisnoga fosfatnog proizvoda smanjenjem tih čestica pružit će nekoliko prednosti, uključujući minimiziranje utjecaja odlaganja mulja na okoliš i povećanje ekonomskoga učinka procesa oplemenjivanja fosfatne rude. Cilj je ovoga istraživanja povećati udio korisnih čestica fosfata i smanjiti udio mulja, umjesto ulaganja dodatnoga napora u postojećim postupcima. Taj se cilj može postići povećanjem udjela fosfatnih čestica željene veličine (u izlazu) tijekom procesa mljevenja, određivanjem optimalnih radnih uvjeta koji će smanjiti količinu jalovinskoga mulja. Centralno kompozitni plan (*Central Composite Design* – CCD) koristi se za utvrđivanje broja pokusa koji se trebaju evaluirati te za izradu modela predviđanja koji će se koristiti za određivanje optimalnih vrijednosti radnih parametara. Kao rezultat procesa optimizacije maksimalni udio čestica željene veličine u izlazu od 87,6 % dobiven je pri uvjetima mljevenja: t = 5,1 min, v = 42,6 %, s = 81,2 % i c = 50,7 %, gdje t, v, s i c predstavljaju vrijeme mljevenja, volumen koji kugle zauzimaju u mlinu, postotak brzine rotacije u kritičnoj brzini (%) i volumnu koncentraciju krutih čestica (%).

Ključne riječi:
fosfatni mulj, kuglični mlin, centralno kompozitni plan, optimizacija, postupak mljevenja

Author's contribution

Gamal Abdelhaffez (Associate professor of Mineral Processing) gathered rock samples, collaborated on all experimental work with **Mohamed Abdelwahed** (Assistant professor of mechanical engineering at King Abdulaziz University in Saudi Arabia) and **Mohammed Hefni** (Associate professor of mining engineering at King Abdulaziz University in Saudi Arabia), and evaluated the results. The entire work was written collaboratively by the authors.