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# ORIGINAL APPROACH FOR THE DRILLING PROCESS OPTIMIZATION IN OPEN CAST MINES; CASE STUDY OF KEF ESSENOUN OPEN PIT MINE NORTHEAST OF ALGERIA

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**Abstract:** The drill ability is a fundamental factor for bit penetration rate (PR) in mining engineering. The ability to predict the performance of rock drills is important for drilling operations. Not a single parameter defines the drill ability of a rock. For this task, a considerable amount of fieldwork must be done to provide the necessary data i.e.: rock properties and drilling technologies. The main purpose of this research is to conduct an experimental study under varying rotation and pressures on the drilling bit for different geological formations.
This paper presents a statistical analysis of process parameters of drilling in a phosphate mine in Jebel Onk, Tebessa, Algeria. Settings drilling parameters were determined by applying the design of experiments method. The level of importance of drilling parameters is determined by using analysis of variances. First, the teamwork determined the mathematical model for representative conditions of the phosphate mine of Jebel Onk. This mathematical model is a vital mathematical requirement for the operation engineers to deduce and determine the penetration rate according to the demands of work and to maximize the efficiency of the drilling machine and to minimize the bit wear in the abrasive layer.

***Keywords***: *statistical analysis, variance, design of experimental, Taguchi method, Phosphate mine.*

## INTRODUCTION

Drill ability is a term used to describe the influence of a number of parameters on the drilling rate and the bit wear of the drilling machine (Thuro, 1997). Penetration

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rate is the progression of the drilling bit into the rock in a specific period, expressed as m/min. According to the influential factors, penetration rate can be categorized as changeable and unchangeable factors (El Kacimi et al. 2017). A number of geoscientist have studied the relation between the penetration rate and the rock properties: Protodyakonov (1962) who developed drop tests and described the coefficient of rock strength (CRS) used as a measure of the resistance of rock by impact. Tandanand and Unger (1975), and Rabia and Brook (1981) thenmodified the Protodyakonov test. Paone et al. (1966), conducted research work on percussion drilling studies in the field. They concluded that the uni-axial compressive strength (UCS), tensile strength, shore hardness and static Young's modulus are correlated tolerably well with penetration rates of percussive drills in the mine- hard- abrasive rocks. Kahraman and Mülazımoğlu, (Bilim, 2011) developed penetration rate models for rotary, down the hole and hydraulic top hammer drills using multiple curvilinear regression analysis. Besides, for rotary drills uniaxial compressive strength, for drills Schmidt hammerrebound number and for hydraulic top hammer drills. The geological parameters will basically influence the drilling performance and the bit wear. The others such as machine and operating parameters can be variable and controllable. However, rock properties and geological conditions are uncontrollable parameters (Besteet al. 2007; Zahri et al. 2016). The strength characteristics of rocks have been used as drill ability criteria for a long time. Recent studies have shown that using strength features alone can be misleading. It is necessary that pressure, torque, rotation speed and impact frequency are applied as operational parameters according to the formation characteristics (Bilgin and Shahriar, 1986). The penetration rate increases with the thrust until a peak penetration rate value is reached. At the low thrust, the bit will not be in constant contact with the fresh rock surface at the bottom of the hole. An insufficient thrust results in lower penetration rates (Altındağ, 2003). The main objective of this study is to present a systematic relation between the PR and the rock properties in drilling blast holes, thus Kef Essenoun open cast mine is selected as a case study to optimize the process of blast holes drilling. The research passes through four steps: First step consists on the development of tests on the drilling machine in the different layers of geological formations; followed by data collection; then a statistical analysis of the data obtained is done; to achieve by a development of a representative mathematical model. The results expected from this work constitute an important mathematical tool for operation engineers to estimate the penetration rate according to the requirements of work, to maximize the efficiency of the drilling machine in, and to minimize the bit wear in the abrasive layer as well.

# GENERAL SETTINGS

## GEOGRAPHICAL BACKGROUND

Kef Essenoun phosphate mine is located on the southern flank of Jebel Onk Cretaceous anticline (34.726784 E, 7.895978 N). It is about 7 Km in the southeast of Bir el Ater city in the South of Tebessa province, and about 21 Km to the Algerian-Tunisian border (Fig. 1).

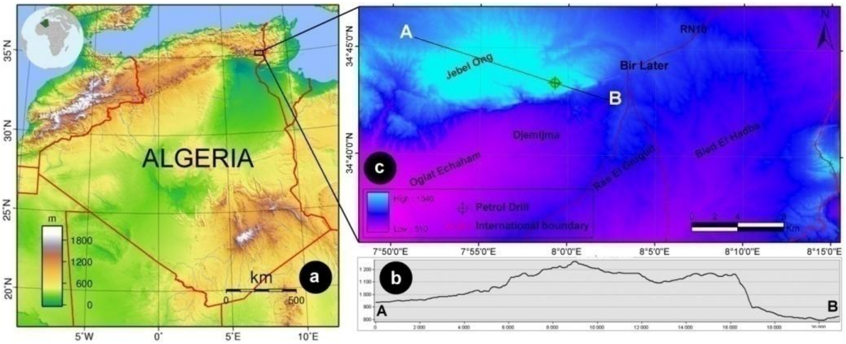


Fig. 1. Geographic location of the study area, b: Topography (DEM) of the study area; c: topographic cross section in the study area

## GEOLOGICAL CONDITIONS

The study site has an area of approximately 250 km$^2$ and belongs to the same mining basin rather than Metlaoui phosphate mine (SW Tunisia) (Mokadem et al. 2016). This mining site has been in operating for 40 years (with about 20–30% of $P_2O_5$ and 2–3.1% of MgO). It contains approximately the half of Algerian phosphate reserves estimated at two billion tons (Fredj et al. 2017). The mine of Jebel Onk aspires to be an economic hub and a center of development, exploitation, and transformation of phosphate (Panda et al.2016). The complexity of the structural directions that characterizes the study region is referred to two major compressive deformation phases: a post Eocene Atlases phase marked by (NW–SE) faults system and a post sub meridian tightening phase. The structural inversion and the quasi-vertical, relief of the southern edge of Jebel Onk area, reflect a sub-meridian tightening conditioned by a deep accident of the base (Gadri, et al. 2015) (Fig. 2).

The pit is excavated as benches with slope angles of 75° to 85°, 30 m in height, and 10 m in width. The depth of the base of the mine is 70 m. The thickness of the phosphate layer is about 50 m; the barren covering consists of a series of Ypersian dolomite limestone with silex, locally overcome with Lutetium limestone, Miocene sands, and Quaternary alluvium. The total thickness of covering varies from 40 to 198 m, indicating a ratio of 1.3 to 6 (Fig. 3), (Youbai, 2004; Hadji et al. 2013; 2017).

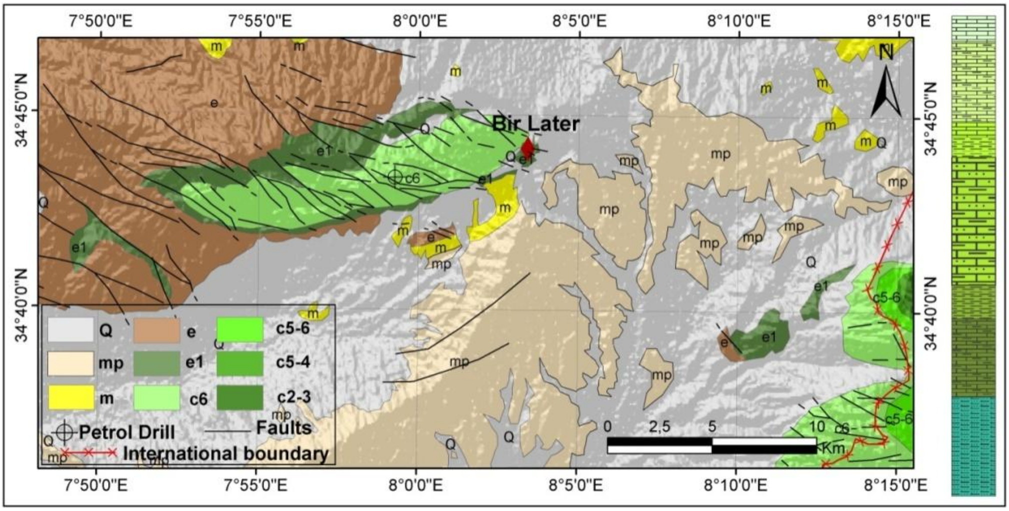


Fig. 2. Structural schema of the study region and its stratigraphic column. (Legend: Q = Quaternary; mp = Upper Miocene-Pliocene; m = Lower Miocene; e = Eocene with limestone and gypsuim; $e^1$ = Upper Maestrichtian-Meduim Paleocene; $C^6$ = Calcarous Maestrichtian; $C^{5-6}$ = Upper Campanian – Lower Maestrichtian; $C^{5-4}$ = Santonian-Lower to Middle Campanian; $C^{2-3}$ = Turonian-Coniacian)


Fig. 3. Lithological formations of Kef Essenoun Quarry

## DESIGN OF EXPERIMENTS (DOE)

The Optimization process has several control factors that directly decide the target or the desired value of the output. This involves determining the best control factor levels for the output either at the target value. Such is called "static problem".

The adopted statistical approach called Taguchi methodwas largely applied to engineering (Rosa et al. 2009), biotechnology (Rao et al. 2008), and industry (Karna et al. 2012). Our study uses it to describe the variation of the response function by a polynomial model. The controlled factors aredetermined by varying the push pressure PP **(**bar) and rotation pressure RP(bar), the penetration rate PR (m/min) in different layers. For this task we have make 80 blast holes in the different layers.

### MATHEMATICAL MODELING

The Taguchi matrix reduces the number of experimental configurations to be studied by Montgomery (1991). The effect of many different parameters on the performance characteristic in a process can be examined by using the orthogonal array experimental design proposed by Taguchi (Fraley et al. 2006). Once the parameters affecting a process that can be controlled have been determined, the levels at which these parameters should be varied must be determined. Determining what levels of avariable to test requires an in-depth understanding of the process, including the minimum, maximum, and currentvalue of the parameter. If the difference between the min and max value of a parameter is large, the values being tested can be further apart or more values can be tested. If the range of a parameter is small, then less value can be tested or the values tested can be closer together. The method of experimental designis simply explained in the flow diagram in figure 4.

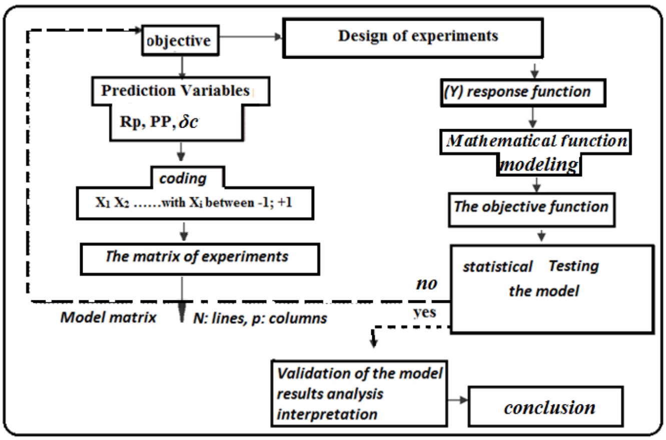


Fig. 4. Methodology of experimentaldesign

## LABORATORY TESTING AND IN SITU INVESTIGATIONS

Compressive strength is one of the most important mechanical properties of rock material used in drilling blast-holes. Compression testing machine (Controls device), (Fig. 5) was used to measure the universal compressive strength. In the phosphate open cast mine of jebel-Onk a lot of geological formations in work area. In different layers the drilling performance is taken as penetration rate of a blast hole. In each blast hole drillings, the net drilling time and penetration depth are reported. The penetration depth values are taken from digital panels of the drilling machine. Then, the penetration rates are calculated by using Eq.(1).

$$PR = \frac{H}{t} = \frac{\text{Blasthole Depth}}{\text{Net Drilling Time}} \qquad (m/min) \tag{1}$$

An Atlas- Copco ROC-L8 drilling machine was used during the drilling tests in the field. It was equipped by button bit with 160 mm diameter and drill tubes with an outer diameter of 70 mm. The drilling parameters of the machine were kept constant during drilling process. The depth of hole was collected from the machine digital indicator panel. The net drilling time was measured by using a chronometer. The drilling parameters of ATLAS-COPCO Rock L8 machine which we have taking in our studies the PP (30-110bar) and the rotation pressure RP(30-70 bar). The penetration rate was correlated with other parameters by using a method of least square regression $R^2$. The equation of the best-fit line and the correlation coefficient (r) were determined for each regression. A meaningful correlation between PR, PP and RP from the graphs was evident; it could be clearly observed that the increasing push pressure increases penetration rate. The results are summarised in table 01.
*Nb*: There is a correlation between PR and the drilling machine parameters in all layers except in the siliceous phosphate limestone layer by the presence of silex bolls.

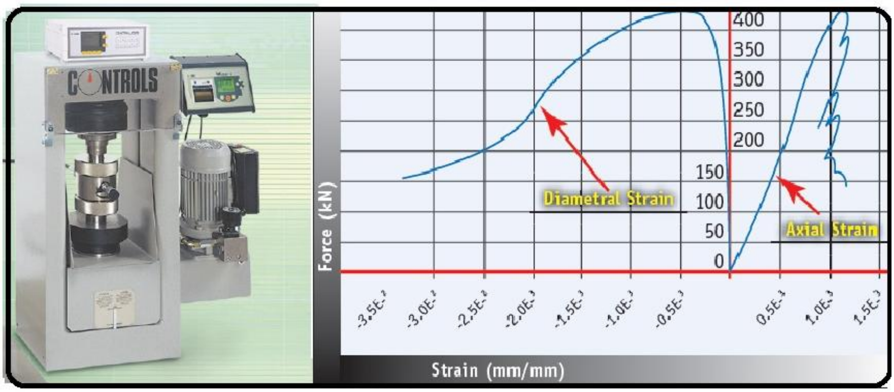


Fig. 5. The compression testing machine used for the study

Tab. 1. Laboratory and *in situ* tests (calculation of PR according to RP and PP of all studied layers)

| $\sigma_c$ Mpa | Calculation of PR (m/min), with variable RP and constant PP | Calculation of PR (m/min), with variable PP and constant RP |
|---|---|---|

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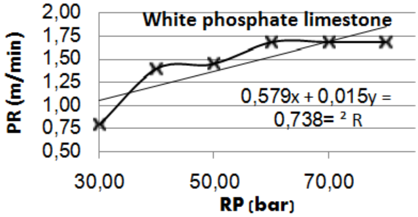


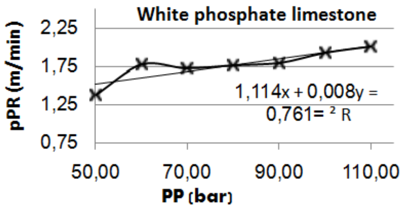


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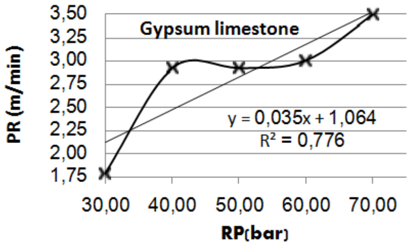


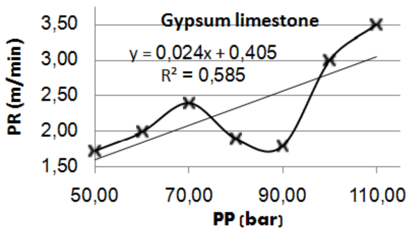


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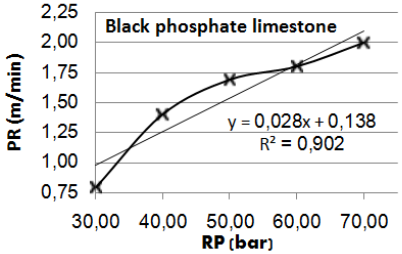


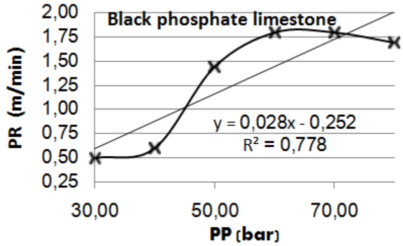


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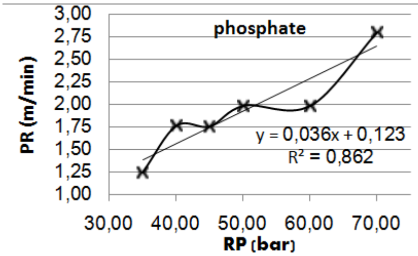


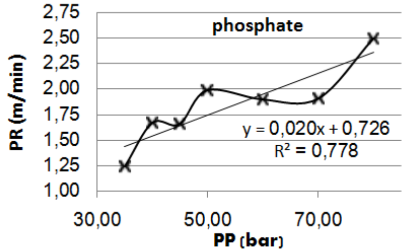


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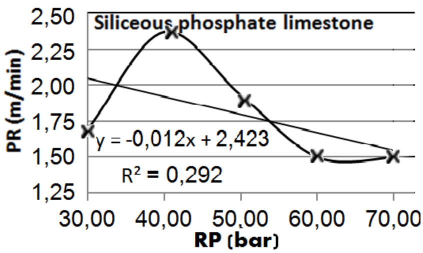


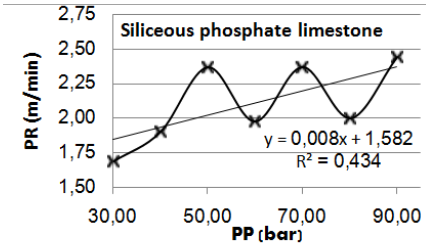

## MODELING USING THE EXPERIMENTAL DESIGN METHOD

The table (2) sum up all the tests. it consist of several columns the first identifies the tests . The following states indicate the states of the factors expressed in coded units whatever the factors replace natural variables with variable codes will make it possible to have for each factor the same rang of variation between +1 ,-1.

Each column being representative of a factor the last column shows the answers obtained for each test the blower lines recall the values of the level in natural units.

Tab. 2. Planification matrix (matrix of experiment of Taguichi)

| | | Factors | | | Interactions | | | | response Y | bi |
|---|---|---|---|---|---|---|---|---|---|---|
| N | $X_0$ | $X_1$ | $X_2$ | $X_3$ | $X_1.X_2$ | $X_1.X_3$ | $X_2.X_3$ | $X_1.X_2.X_3$ | | |
| 1 | +1 | –1 | –1 | –1 | +1 | +1 | +1 | –1 | 0.5 | 1.865 |
| 2 | +1 | +1 | –1 | –1 | –1 | –1 | +1 | +1 | 2.3 | 0.56 |
| 3 | +1 | –1 | +1 | –1 | –1 | +1 | –1 | +1 | 2.4 | 0.665 |
| 4 | +1 | +1 | +1 | –1 | +1 | –1 | –1 | –1 | 3.5 | –0.31 |
| 5 | +1 | –1 | –1 | +1 | +1 | –1 | –1 | +1 | 0.5 | –0.14 |
| 6 | +1 | +1 | –1 | +1 | –1 | +1 | –1 | –1 | 1.5 | –.165 |
| 7 | +1 | –1 | +1 | +1 | –1 | –1 | +1 | –1 | 1.82 | –0.11 |
| 8 | +1 | +1 | +1 | +1 | +1 | +1 | +1 | +1 | 2.4 | 0.035 |
| Level–1 | | 30 bars | 30 bars | 10 MPa | | | | | | |
| Level+1 | | 70 bars | 110 bars | 60 Mpa | | | | | | |

### MATHEMATICAL FUNCTION

$$y_{mod} = b_0 + b_1.x_1 + b_2.x_2 + b_3.x_3 + b_{11}.x_1.x_2 + b_{13}.x_1.x_3 \\ +b_{23}.x_2.x_3 + b_{123}.x_1.x_2.x_3$$

Objective function:

The response is well modeled by a linear function of the independent variables the expression of a polynomial model describing the variations of the response.

$$y_{mod} = 1.865 + 0.56.x_1 + 0.665.x_2 - 0.31.x_3 - 0.14.x_1.x_2 \\ -.165.x_1.x_3 \text{-} 0.11.x_2.x_3 + 0.035.x_1.x_2.x_3$$

### 5STATISTICAL ANALYSIS OF THE MODEL

### MODEL VALIDATION

#### STUDENT TEST

Student's t-test is a set of parametric hypothesis tests where the calculated statistic follows a Student's law when the null hypothesis is true. A t-test can be used in particular to statistically test the hypothesis of equality of two averages (Tab. 3).

$$t_{bI} = \frac{|b_I|}{S_{bI}} > t_{t(q,f)} \quad (2)$$

It is necessary that the condition of student is satisfied for all coefficients of the model to be significant

$$t_{bi} > t_{(q,f)} \quad (3)$$

$t_{(q,f)}$: Value taken from the student table.
$t_{bi:}$ Ratio between model coefficients and the dispersion of the model coefficients
$q = 0.05\%$;
$f$ : Degree of freedom.

Tab. 3. T-testof all confessants of the model

| Variables | effect | $t_{bi}$ $t_{(q,f)}$ | Result |
|---|---|---|---|
| | $b_0$=1.865 | 36.5981771>2.08 | Significant |
| $X_1$ | $b_1$=0.56 | 10.989265>2.08 | Significant |
| $X_2$ | $b_2$=0.665 | 13.0497522>2.08 | Significant |
| $X_3$ | $B_3$ =0.31 | 6.08334311>2.08 | Significant |
| $X_1X_2$ | $b_4$ =0.14 | 2.74731624>2.08 | Significant |
| $X_2X_3$ | $b_5$=0.165 | 3.23790843>2.08 | Significant |
| $X_1X_3$ | $b_6$=0.11 | 2.15860562>2.08 | Significant |
| $X_1X_2X_3$ | $b_7$=0.035 | 0.68682906<2.08 | Not significant |

The mathematical model satisfied the T-test and all coefficients $b_i$ are significant except $b_7$ witch is rejected from the mathematical model. The objective function in Jebel Onk mine conditions is as follows:

$$y_{mod} = 1.865+0.56.x_1 + 0.665.x_2 - 0.31.x_3 -0.14.x_1.x_2 - 0.165.x_1.x_3 -0.11.x_2.x_3 + 0.035.x_1.x_2.x_3 \quad (4)$$

FISHER TEST

The Fisher test helps us to find a relationship between the variation of the factors and the answers in the established model. So that the model is validated and the Fisher condition is confirmed.

$$F_{obs} < F_{tab} \quad (5)$$

$F_{obs} = 2.2$: Value calculated
$F_{tab} = 2.27$: Value taken from the fisher tableat $q = 0.05\%$

## STANDARDIZATION OF VARIABLES

The use of reduced centered variables has the advantage of being able to generalize the theory of experimental design (Tab. 4).

Tab. 4. Replacement of the values coded by physical values

| Coded Variables | | | Physical variables | | | reduced centered variables |
|---|---|---|---|---|---|---|
| Coded parameters | Min | Max | Physical parameters | Min (bar) | Max (bar) | $X_{i=}\dfrac{X_i - 0.5(X_{imax} + X_{imin})}{0.5(X_{imax} - X_{imin})}$ |
| $X_1$ | -1 | +1 | RP | 30 | 70 | $\dfrac{X_1 - 50}{20}$ |
| $X_2$ | -1 | +1 | PP | 30 | 110 | $\dfrac{X_2 - 70}{40}$ |
| $X_3$ | -1 | +1 | σc | 10 | 60 | $\dfrac{X_3 - 35}{25}$ |

Coded formula (mathematical model):

$$y_{\text{mod}}=1.865+0.56X_1+0.665X_2-0.31X_3-0.14X_1X_2-0.165X_1X_3-0.11X_2X_3 \qquad (6)$$

Replacing the variables coded by the reduced centered variables in the model formula.

Normalized formula (physical model):

$$\begin{aligned} \text{PR} = 1.865 + 0.56\left(\frac{1}{20}RP - 2.5\right) + 0.665\left(\frac{1}{40}PP - 1.75\right) \\ -0.31\left(\frac{1}{25}\partial c - 1.4\right) - 0.14\left(\frac{1}{20}RP - 2.5\right)\left(\frac{1}{40}PP - 1.75\right) \\ -0.165\left(\frac{1}{20}RP - 2.5\right)\left(\frac{1}{25}\partial c - 1.4\right)(\text{m/min}) \end{aligned} \qquad (7)$$

$$\begin{aligned} \text{PR} = -1.72425 + 0.05180\times RP + 0.029225\times PP + 0.01180\times\sigma c \\ -0.000175\times RP\times PP - 0.00033\times PP\times\sigma c - 0.00011\times RP\times\sigma c \ (\text{m/min}) \end{aligned} \qquad (8)$$

The equation (8) constitutes the main outcome of our study. The model satisfied the necessary statistical validation tests and can be used us a useful tool in the same conditions to predict the penetration rate. The necessity of optimizing time, costs and workmanship makes this design method an effective tool to implement experiments.

## VERIFICATION

The series of tests used to evaluate the proposed model, between the experimental results and the theoretical predictions. The residuals obtained by differentiating between the calculated and the measured value. If the residue is less than 30% the physical model is admissible (Seibi 2001). In our case residual is less than 6% so the model is a representative of Jebel Onk mine conditions except the siliceous phosphate limestone layer. Due to the random presence of the silex balls with great rigidity.

We return to the skill and experience of the operator in changing the appropriate Operating mode of the drilling machine according to needs of the work and the safety of the machine. We propose that this matter be the subject of future studies.

## CONCLUSION RECOMMENDATIONS AND PERSPECTIVES

This study presents a statistical analysis of the parameters of the drilling process in Jebel Onk phosphate mine. The teamwork conducted experimental studies applying varying rotational pressure and push pressure upon the drilling bit in different geological formation. Drilling parameter settings were determined using the method of design of experiments. The level of importance of the drilling parameters was determined using the analysis of the variance. Accordingly, the research team determined a representative mathematical model conditions for Jebel Onk field. This representative model is a necessary mathematical tool for operational engineers to predict the penetration rate. In addition, to adjust it according to the needs of the work to maximize the performance of the drilling machine, and to minimize the wear of the drilling tool by the employment of a suitable regime in the abrasive layer as well.

The Student test showed that all factor coefficients are significant with the exception of the interaction coefficient of the three factors together ($X_1X_2X_3$).

The final significant model is:

$$PR = -1.72425 + 0.05180\times RP + 0.029225\times PP + 0.01180\times \sigma c$$
$$-0.000175\times RP\times PP - 0.00033\times PP\times \sigma c - 0.00011\times RP\times \sigma c \quad (m/min)$$

The residual variance and the repeat variance are 0.13836 and 0.06232 respectively.

The Fischer test F = 2.22. The representativeness of the model is clearly satisfactory.

This work allowed the researchers to propose an acceptable and applicable a physical model in the conditions of Jebel Onk phosphate mine.

The prospects of this work indicate the demands to adopt a model with a polynomial tendency instead of a model with linear tendency and to associate numerical modeling

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