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PREDICTION OF PERFORMANCE OF DIAMOND WIRE SAW WITH RESPECT TO TEXTURE CHARACTERISTICS OF ROCK

PROGNOZOWANIE WYDAJNOŚCI PRACY STRUNOWEJ PIŁY DIAMENTOWEJ W ODNIESIENIU DO CHARAKTERYSTYKI TEKSTURY SKAŁ

In this study, prediction of production rate in diamond wire saw has been investigated. Performance measurements of diamond wire saw carried out in 7 different quarries of carbonate rocks in Iran. For determination textural properties, rock samples were collected from these quarries. At first, a thin section was prepared for each rock and then 5 digital photographs were taken from each section. After this, all images were digitized using AutoCAD software. Then, area, perimeter, longest diameter and shortest diameter were assigned. According to these parameters, all of the other textural characteristics and texture coefficient were determined too. The correlation between sawing rate and textural characteristics were evaluated using multiple and simple regression analyses. Then developed model was validated by P-value test. It was concluded that area, perimeter, diameter equivalent and index of grain size homogeneity are very effective on production rate. Production rate using diamond wire saw can reliably be predicted using developed model.

Keywords: Diamond wire saws, production rate, texture coefficient

W pracy prognozowano wydajność pracy strunowej piły diamentowej. Badania wydajności prowadzono w 7 kamieniołomach na terenie Iranu, w których wydobywane są skały węglanowe. W celu określenia tekstury skał zebrano próbki wszystkich skał wydobywanych w kamieniołomach. Przygotowano zgłady i wykonano 5 fotografii cyfrowych każdej analizowanej próbki. Uzyskane obrazy poddano następnie obróbce cyfrowej przy użyciu oprogramowania AutoCAD. Określono następujące parametry: powierzchnia, obwód, najdłuższa i najkrótsza średnica. W oparciu o powyższe parametry przeprowadzono analizę tekstury i wyznaczono odpowiednie współczynniki. Korelację pomiędzy wydajnością pracy piły a właściwościami powierzchni (teksturą) określono przy użyciu prostej regresji liniowej oraz regresji wielokrotnej. Otrzymany model poddano następnie walidacji przy pomocy odpowiednich testów statystycznych. Stwierdzono, że pole powierzchni, obwód, równoważne średnice oraz wskaźnik jednorodności uziarnienia mają wpływ na wydajność pracy piły. Opracowany model może być skutecznie wykorzystywany dla wiarygodnego prognozowania postępu prac prowadzonych z wykorzystaniem piły diamentowej.

Słowa kluczowe: strunowa piła diamentowa, wydajność pracy, tekstura

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1. Introduction

There are several methods for block production in carbonate rocks. Nowadays, diamond wire cutting is a widely used method in carbonate rocks. It is very important that extraction is carried out at minimum cost and high yield of good quality blocks. Therefore prediction of rock sawability is significant in the cost estimation and rate of production. Diamond wire is rotated with the drive wheel movement. Required tension and rotation force for cutting is provided by the movement of a diamond wire saw machine away from the cut surface on the rail. Water is applied with spin direction of the wire as a coolant and as a means of removing the participles. Diamond wire is simply a steel cable on which small beads bonded with abrasive are mounted at a regular interval with spacing material placed between the beads (Figure 1).

There are several parameters affecting on diamond wire cutting operation. These parameters are given in Table 1. The beads provide the actual cutting action in diamond wire saw operation. The important point efficient usage of diamond wire cutting is to produce blocks at minimum cost by adjusting to effective cutting parameters adequately. Non-controlled parameters such as physical, mechanical and textural properties should be determined before cutting operation. After determination of non-controlled parameters, it should be possible that efficient cutting should be achieved with adjusting of partially-controlled parameters under consideration of non-controlled (Ozcelik, 2004).

Up to now, any serious study has not been done on relation between textural properties and production rate of diamond wire saws. In rock engineering, selection of optimum machine and operation technique mostly depend on textural and mechanical properties. The textural characteristics of rocks significantly affect the mechanical behavior, performance of cutting and drilling equipments. The main textural properties are grain size, shape and orientation, proportion of grain and matrix material. These features resulted in a texture coefficient represented by a single number for each rock specimen (Ersoy, 1995). Rock texture has been defined as “the degree of crystalline, grain size or granularity and the fabric or geometrical relationship between the constituents of a rock” (Williams et al., 1982). In this study, effects of textural properties on production rate in diamond wire saws were investigated.

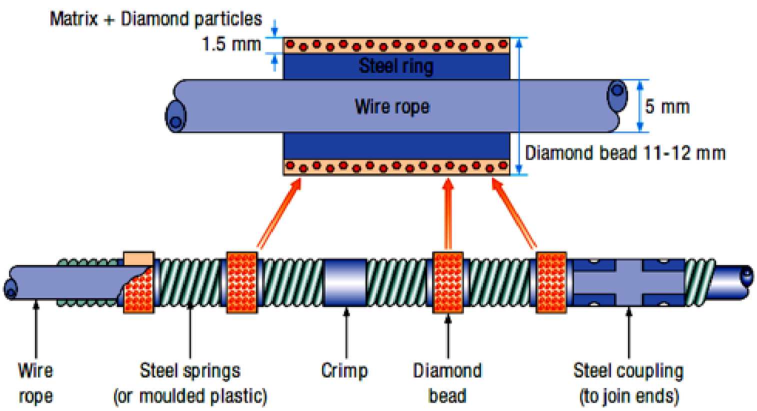

Fig. 1. Typical illustration of diamond wire and cross-section of diamond bead (Ozcelik, 2004)

TABLE 1

Parameters affect cutting efficiency in diamond wire cutting method (Ozcelik, 2004)

Non-controlled parameters	**Partially-controlled parameters**	
Rock properties	Cutting machine properties	Operating condition
• Rock hardness • Rock strength • Water content • Degree of alteration • Discontinuities • Mineralogical composition and texture	• Machine power • Wire speed • Structure of diamond bead • Dimension of block • Geometry of wire during cutting • Vibration of machine • Water consumption	• Technical personal • Used techniques

2. Quantitative analysis of rock texture

To study of texture rock, a thin section is prepared and digital photographs are taken from each sample. Individual analysis consisted of selecting a reference area or observation window, containing a number of grains which depend on the size of the grains in rock. Quantitative analysis of texture of rock is done by following parameters:

- **Area (A_i):** It is simplest parameter to evaluate texture of rock. Observed area of each grain in thin section is grain`s area.
- **Perimeter (L_p):** It is showing length of boundary of grain in rock. In fact it is perimeter of grain.
- **Maximum and minimum diameter:** these parameters are so useful that they are always used to study texture of rock. Length and breadth have been defined as being maximum and minimum diameter. These parameters represent the perpendicular distance between two parallel outer tangents to an object. The longest distance is defined as maximum diameter and the shortest distance is defined as minimum diameter.
- **Diameter equivalent:** This parameter introduces grain size. It is obtained by below equation (Petruk, 1986):

$$D_{equi} = \sqrt{\frac{4A_i}{\pi}} \qquad (1)$$

where,

D_{equi} — Diameter equivalent (mm),

A_i — Area of grain (mm^2);

- **Compactness:** This parameter is as shape of section in grain. It is calculated by below equation:

$$C = \frac{L_p^2}{A_i} \qquad (2)$$

where,

C — compactness,

L_p — Perimeter of grain (mm),

A_i — Area of grain (mm^2);

- **Shape factor:** At textural observations this parameter is as amount of round of section in grain. It is calculated by below equation:

$$SF = \frac{4\pi A_i}{L_p^2} \tag{3}$$

where,
SF — Shape factor,
A_i — Area of grain (mm^2),
L_p — Perimeter of grain (mm);

- **Aspect ratio:** It is obtained by dividing maximum diameter to minimum diameter.

$$AR = \frac{D_{\max}}{D_{\min}} \tag{4}$$

where,
AR — Aspect ratio,
$D_{\max}$ — Maximum diameter (mm),
$D_{\min}$ — Minimum diameter (mm);

- **Interlocking index:** at first, this index was presented by Dreyer in 1973. In fact this parameter shows relation between area of grain and part of perimeter that is neighbor with other grain. Actually this index explains complexity of relation between grains. To obtain this index, below equation was presented:

$$g = \frac{1}{n} \cdot \sum \frac{L_{pi}}{\sqrt{A_i}} \tag{5}$$

where,
g — Interlocking index,
n — Number of grains,
L_{pi} — Length of grain that is neighbor with other grains (mm),
A_i — Area of grain (mm);

- **Grain size homogeneity index:** This index was presented by Dreyer in 1973. It is introduced as explanation of distribution grain packing in texture of rock. Below equation was presented to obtain index of grain size homogeneity:

$$t = \frac{A_{avg}}{\sqrt{\sum (A_i - A_{avg})^2}} \tag{6}$$

were,
t — Grain size homogeneity index,
A_{avg} — Average of area of grains (mm^2),
Ai — Area of grain (mm^2);

- **Texture coefficient**: The method of quantitative analysis of geometrical properties of rock particles or rock texture comprises the following component:
  a. To measure and analyze grain shape.
  b. To measure and analyze grain elongation (to calculate shape factor and aspect ratio).

c. To measure and quantify grain angle (orientation).
d. To calculate total grain area to total references area (including matrix) or weighting factors based on the degree of grain packing.

The results can be derived from the following formula which was suggested by Howarth and Rowlands in 1987:

$$TC = AW\left[\left\{\frac{N_0}{N_0 + N_1} \times \frac{1}{FF_0}\right\} + \left\{\frac{N_1}{N_0 + N_1} \times AR_1 \times AF_1\right\}\right] \tag{7}$$

where,

TC — texture coefficient,
N_0 — Number of grains with aspect ratio less than 2,
N_1 — Number of grains with aspect ratio greater than 2,
FF_o — Arithmetic mean of shape factor of all N_0 grains,
AR_1 — Arithmetic mean of aspect ratio of N_1 grains,
AF_1 — Angle factor orientation which were computed for all N_1 grains,
AW — Area weighting (grain packing density), which calculated:

$$AW = \frac{\textit{Total grain area within reference are boundary}}{\textit{Total area enclosed by the reference area boundary (including matrix area)}}$$

Angle factor is defined as angle between the maximum diameter and horizon. The maximum value of angle is 180°. Angular orientation of grains was quantified by the development of the angle factor. This factor was only calculated for elongated grains where their aspect ratio was greater than 2. The angle factors AF_1 has been calculated by a class weighted system applied to the absolute, acute angular differences ($0° < \beta < 90°$), between each and every elongated grain (Howarth & Rowlands, 1987). Therefore, for a group of N grains the number of unique angular difference is:

$$(N-1) + (N-2) + \ldots + 2 + 1 = \frac{N(N-1)}{2}$$

Thus, four grains will have: 3 + 2 + 1 = 6 unique angular difference (β). The angular differences are grouped into nine classes, each of which is weighted (Table 2).

TABLE 2

Classes and weighting for absolute, acute angular differences (Ersoy, 2004)

Number	**Class range (β°)**	**Weighting (i)**
1	$0 < \theta_{DMAX} \leq 10$	1
2	$10 < \theta_{DMAX} \leq 20$	2
3	$20 < \theta_{DMAX} \leq 30$	3
4	$30 < \theta_{DMAX} \leq 40$	4
5	$40 < \theta_{DMAX} \leq 50$	5
6	$50 < \theta_{DMAX} \leq 60$	6
7	$60 < \theta_{DMAX} \leq 70$	7
8	$70 < \theta_{DMAX} \leq 80$	8
9	$80 < \theta_{DMAX} \leq 90$	9

The angle factor has been calculated by summing of the class weighting and fractions of the total number of angular differences in each class.

$$AF = \sum_{i=1}^{n} \left[\frac{X_i}{\frac{N(N-1)}{2}} \right] \tag{8}$$

where,

AF_1 — Angle factor,
N — Total number of elongated grains,
X_i — Number of angular differences in each class,
i — Weighting factor and class number.

3. Field studies

During the field study, 7 marble quarries in West of Iran were visited and the sawing performances of diamond wire saws on their different carbonate rocks were measured. In Iranian mines, usually very similar machines are used. Therefore in the studied quarries many technical features of wire saws machines were nearly same. In this paper properties of wire saws machine are considered to be constant and were not used in the prediction model. Characteristics of wire saws machines which were usually used in Iranian quarries are shown in Table 3.

TABLE 3

Operational parameters of wire saws machine

Parameter	Description
Main motor power (KW)	45
Length of wire (m)	65-80
Linear speed (m/s)	30-35
Rotator diameter (cm)	60
Beads per meter	33-36
Bead type	Special for soft rocks

4. Laboratory studies

The most important parameters of rock are its textural characteristics. In this study, in order to evaluation of the effects of texture on production rate in diamond saws wire, a thin section was prepared for each rock and then digital photographs were taken from each section. Then, all images were digitized using Auto CAD software Fig 2. Then area, perimeter, longest diameter and shortest diameter were assigned. After all above stages, relationships between textural characteristics and production rate of rocks have been evaluated and the related mathematical equations have presented. In all sections, basic information has been determined. Table 4 shows them. In respect to basic information, other textural parameters have been determined. Results are shown

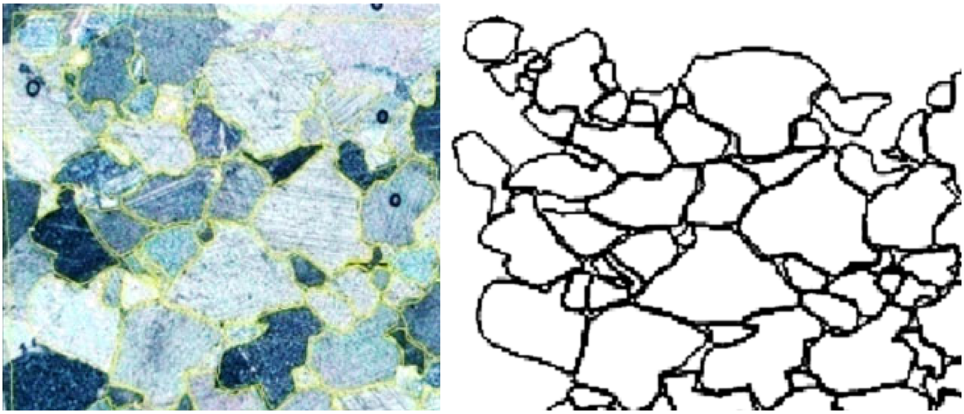

Fig. 2. Digital format of thin section

in Table 5. The results of performance studies (record rates) are given in Table 6. Parameters relevant to texture coefficient have been calculated and results are given in Table 7.

TABLE 4

Mean of basic textural information

Mine name	**Perimeter (mm)**	**Area (mm^2)**	**Maximum diameter (mm)**	**Minimum diameter (mm)**
Bad bad gharbi	1.208	0.107	0.430	0.324
Bad bad sharghi	1.792	0.226	0.664	0.441
Jushan rood	1.733	0.213	0.620	0.387
Cheshme haji	0.742	0.038	0.259	0.170
Madan sanj	0.946	0.067	0.342	0.210
Ordode gharbi	0.896	0.053	0.302	0.185
Ordode kargahe 4	0.699	0.031	0.240	0.154

TABLE 5

Textural characteristics for samples

Mine name	***g***	***t***	***SF***	***C***	***Dequi***	***AR***
Bad bad gharbi	3.89731	0.2032	0.83461	15.2291	0.350332407	1.406
Bad bad sharghi	3.9662	0.2885	0.80719	15.78	0.50870009	1.56747
Jushan rood	4.03215	0.32354	0.7793	16.2942	0.486971772	1.69236
Cheshme haji	3.97667	0.09612	0.76986	16.6513	0.206019827	1.61035
Madan sanj	4.13094	0.11657	0.74797	17.152	0.260747698	1.69829
Ordode gharbi	4.48402	0.09286	0.65484	20.4716	0.226568328	1.75954
Ordode kargahe 4	1.61462	0.187554301	0.73074	0.09288	4.18597	

TABLE 6

The result of performance studies

Mine name	Production rate (m^2/h)
Bad bad gharbi	10
Bad bad sharghi	6
Jushan rood	6.2
Cheshme haji	10
Madan sanj	10.6
Ordode gharbi	9.7
Ordode kargahe 4	9.3

TABLE 7

Texture coefficient derivation determined for rocks

Mine name	AW	$\frac{N_0}{N_0+N_1}$	$\frac{N_1}{N_0+N_1}$	$\frac{1}{FF_0}$	AR_1	AF_1	TC
Bad bad gharbi	0.8	0.95	0.04	1.18	3.13	0.6	0.97
Bad bad sharghi	0.88	0.76	0.24	1.18	2.3	0.67	1.12
Jushan rood	0.76	0.75	0.25	1.24	2.47	0.88	1.12
Cheshme haji	0.61	0.86	0.13	1.27	2.34	0.78	0.82
Madan sanj	0.61	0.84	0.15	1.32	2.55	0.89	0.89
Ordode gharbi	0.6	0.77	0.22	1.11	2.62	0.65	0.9
Ordode kargahe 4	0.7	0.88	0.11	1.35	2.38	0.77	0.98

5. Statistical analysis

5.1. Simple regression analysis

Performance results and textural characteristics were analyzed using the method of least squares regression. Hourly production values were correlated with the corresponding textural characteristic values. Linear, logarithmic, exponential and power curve fitting approximation equation with the highest correlation coefficient (R^2) was determined for each equation (Fig. 3-11).

A strong correlation between texture coefficient and production rate was found (Fig 2). The relation follows an exponential function. Hourly production decreases with increase texture coefficient. The equation of curve is:

$$P_h = 54.78e^{-1.9TC} \qquad R^2 = 0.82 \tag{9}$$

where P_h is production per hour (m^2/h), and TC is texture coefficient.

A strong correlation between area of grain and production rate was found (Fig. 3). The relation follows an exponential function. Hourly production decreases with increase area of grain. The equation of curve is:

$$P_h = 11.47e^{-2.7A} \qquad R^2 = 0.84 \tag{10}$$

where P_h is production per hour (m^2/h), and A is area of grain.

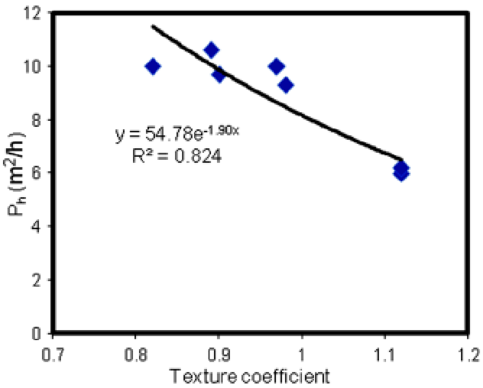

Fig. 3. Relation between production rate and texture coefficient

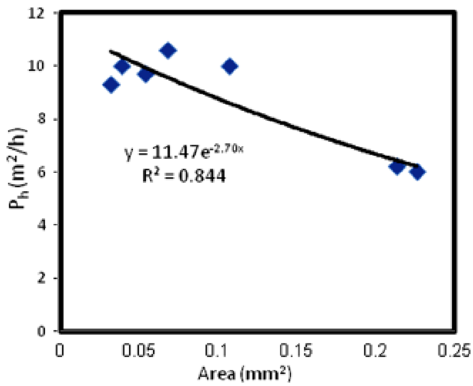

Fig. 4. Relation between production rate and Area of grain

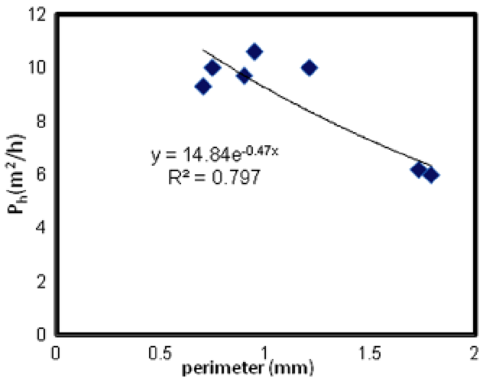

Fig. 5. Relation between Production rate and Perimeter of grain

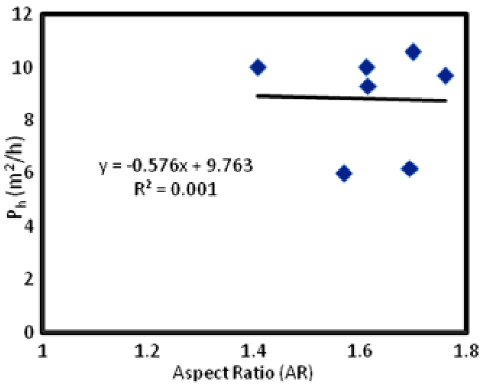

Fig. 6. Relation between production rate and Aspect Ratio

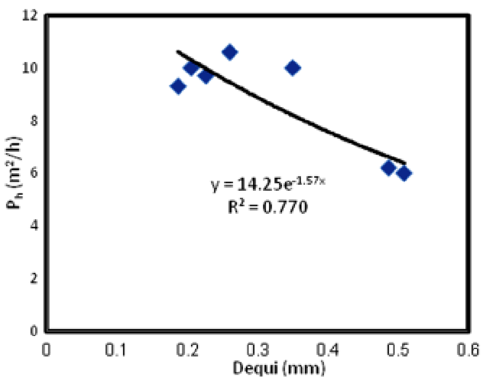

Fig. 7. Relation between production rate and Diameter equivalent

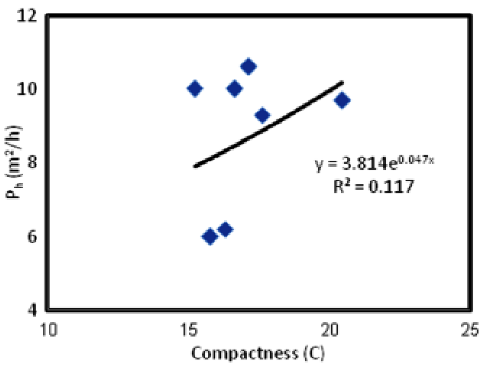

Fig. 8. Relation between production rate and Compactness

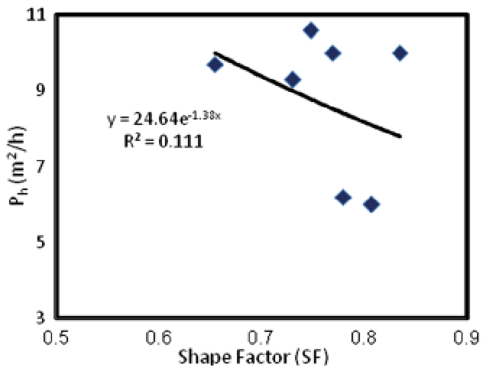

Fig. 9. Relation between production rate and texture coefficient

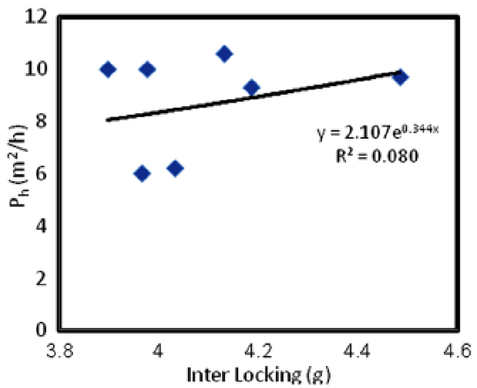

Fig. 10. Relation between production rate and texture coefficient

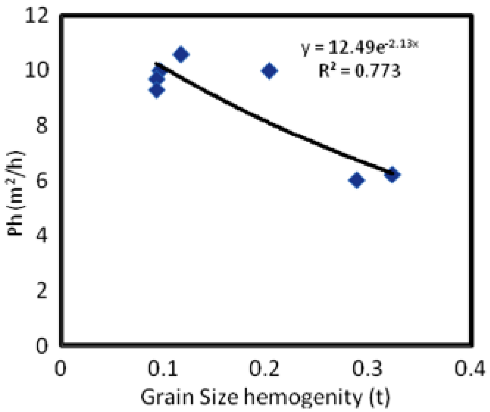

Fig. 11. Relation between production rate and texture coefficient

A strong correlation between perimeter of grain and production rate was found (Fig. 4). The relation follows an exponential function. Hourly production decreases with increase perimeter of grain. The equation of curve is:

$$P_h = 14.84e^{-2.7L_p} \qquad R^2 = 0.79 \qquad (11)$$

where P_h is production per hour (m^2/h), and L_p is perimeter of grain.

A strong correlation between diameter equivalent and production rate was found (Fig. 6). The relation follows an exponential function. Hourly production decreases with increase diameter equivalent. The equation of curve is:

$$P_h = 14.25e^{-1.5D_{equi}} \qquad R^2 = 0.77 \qquad (12)$$

where P_h is production per hour (m^2/h), and D_{equi} is diameter equivalent.

A strong correlation between grain size homogeneity and production rate was found (Fig. 10). The relation follows an exponential function. Hourly production decreases with increase grain size homogeneity. The equation of curve is:

$$P_h = 12.49e^{-2.13t} \qquad R^2 = 0.77 \tag{13}$$

where P_h is production per hour (m^2/h), and t is grain size homogeneity.

Correlations between textural traits are given in Table 8. Respect to this Table, multiple regressions have been done for parameters that have well correlation (more 0.5) at single regression and also correlation between them in above table is less 0.9. Therefore multiple regressions have been done for texture coefficient with area, perimeter, and diameter equivalent and grain size homogeneity.

TABLE 8

Correlation between textural traits

	TC	**Area**	**Perimeter**	***AR***	D_{equi}	***C***	***SF***	***g***	***t***	***Pr***
TC	1									
Area	0.89	1								
Perimeter	0.88	0.99	1							
AR	0.15	–0.14	0.15	1						
D_{equi}	0.87	0.99	0.99	0.21	1					
C	–0.41	–0.52	–0.52	0.74	–0.56	1				
SF	0.41	0.53	0.53	0.81	0.59	–0.98	1			
g	–0.3	–0.44	–0.42	0.74	–0.49	0.98	–0.97	1		
t	0.89	0.97	0.97	0.23	0.98	0.6	–0.61	–0.53	1	
Pr	–0.91	–.091	–0.88	0.3	–0.86	0.23	0.31	0.26	–0.86	1

5.2. Multiple regression analysis

To present more significant and more practical equation, multiple regression analysis was performed. The regression models including two and three independent variables are shown in Table 9. Equation 6 has the highest determination coefficient and it is the best model to predict production rate.

TABLE 9

Results of the multiple regression models

Model		R^2
1	**2**	**3**
Equ. 1	+ 17.97	0.86
Equ. 2	+ 20.23	0.84
Equ. 3	+ 20.73	0.82
Equ. 4	+ 20.73	0.82

1	2	3
Equ. 5	$Pr = -94.32A - 6.1TC + 14.63L_p + 7.94$	0.94
Equ. 6	$Pr = -87.44A - 5.24TC + 44.83D_{equi} + 8.89$	0.97
Equ. 7	$Pr = -23.47A - 9.25TC + 11.76t + 18.25$	0.88
Equ. 8	$Pr = -10.2L_p - 9.41TC + 29.24D_{equi} + 20.36$	0.87
Equ. 9	$Pr = -2.19L_p - 10.46TC + 3.88t + 20.83$	0.85
Equ. 10	$Pr = -4.10D_{equi} - 10.19TC + 0.1t + 20.47$	0.84
Equ.11	$Pr = 36.01D_{equi} - 5.1TC + 4.99L_p - 100.48A + 7.26$	0.96
Equ.12	$Pr = 6.47t - 6.79TC + 13.75L_p - 96.28A + 7.26$	0.94
Equ.13	$Pr = -7.43t - 8.34TC - 11.54\mathrm{L} +38{,}37D_{equi}$ 19.24 0.1t	0.86

6. Model validation

Validation of model was carried out by considering the determination coefficient, the t-test, F-test and the plot of observed production versus predicted production. The statistical result of model for Equ. 6 is given in Table 10. The determination coefficient (R^2) of the model is higher than 0.95. This value is good, but it does not necessarily identify the valid model. To test the significance of the regressions, analysis of variance was employed. This test follows an F-distribution for the model. In this test, a 95% level of confidence was chosen. If the computed F-value is greater than the tabulated F-value, the null hypothesis is rejected that there is a real relationship between dependant and independent variables. Since the computed F-value is greater than tabulated F-value for the model, the null hypothesis is rejected. Therefore it is concluded that the model is valid. The predicted and observed production values for all data are given in Table 11. The predicted production values for these data were plotted against the observed production values and are shown in Fig. 12. The error in predicted values is represented by the distance that each data point plots for the diagonal line. A point lying on the line indicates an exact prediction. In the plots for the model, the points are scattered uniformly about the diagonal line, suggesting that the model is good. It is concluded that the sawing speed for carbonate rocks using diamond wire saws can reliably be predicted using the developed model.

TABLE 10

Statistical results for model of Equ. 6

Model	**Independent variables**	**Coefficient**	**Standard error**	**Standard error of estimate**	***t*-value**	***F* ratio**	**Tabulated *F* ratio**	**R^2**	**Adjusted R^2**
Equ. 6	constant	8.89	4.1	0.45	2.16	34.25	9.28	0.97	0.94
	A	–87.44	24.11		–3.62				
	TC	–5.24	3.68		–1.42				
	D_{equi}	44.83	13.8		3.24				

TABLE 11

The predicted and observed values for all data (Equ. 6)

Mine Name	Observed production (m^2/h)	Predicted production (m^2/h)
Bad bad gharbi	10	10.14
Bad bad sharghi	6	6.05
Jushan rood	6.2	6.19
Cheshme haji	10	10.43
Madan sanj	10.6	9.97
Ordode gharbi	9.7	9.62
Ordode kargahe 4	9.3	9.37

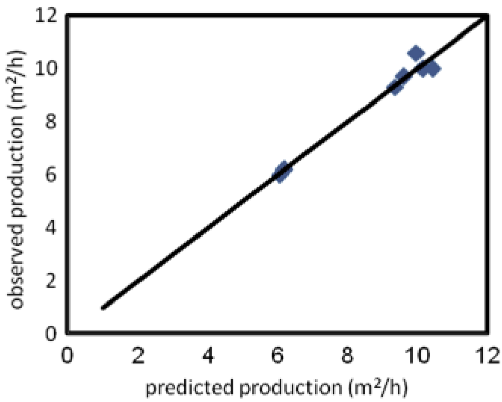

Fig. 12. The predicted production values VS the observed production values for Equ. 6

7. Conclusion

The diamond wire saw is one of the important machines used in carbonate stones extraction. Performance prediction of these saws is important in the cost estimation and the planning of the quarries. A correct estimation of saw ability helps to make the stone sawing more efficient. In this paper the relationship between production rate and textural traits was evaluated using multiple linear regression analysis and estimation model was developed. Are, diameter equivalent and texture coefficient are suggested for the estimation of the saw ability in carbonate rocks. The result shows that production rate has a strong relationship with area of grain, diameter equivalent and texture coefficient. It was concluded that the sawing rate of carbonate rocks using diamond wire saw can reliably be predicted using the developed model.

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