Investigation The Effects Of Machine Parameters On Cutting Performance Of Diamond Wire Saw Machine In Cutting Of Marble Bench

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Abstract

Diamond wire saw machine is mainly used for bench cutting operation in marble at quarry site. Cutting performance of the diamond wire saw machine depends on non controllable parameters related to rocks characteristics and controllable parameters related to machine and operational aspects. Cutting rate and diamond beads wear rate are the two parameters for measuring cutting performance. The machine parameters like peripheral speed of diamond wire and thrust (pull back force) play an important role in cutting performance. To know the influence of these parameters, a detailed study was carried out in the marble area related to soft, medium hard and hard dolomitic marble. Optimum peripheral speed of diamond wire was determined for each category of marble by statistical analysis. Study also reveled that diamond beads wearing rate increases on increasing peripheral speed /thrust on diamond wire. Predicting equations for the wearing of diamond beads and cutting rate were developed based on regression models.

Keywords: Peripheral speed, Cutting rate, Wear rate, Thrust, Dolomitic marble

1. Introduction

The stone is quarried in block form and cut to specific dimensions for use in building construction and monuments. India is the largest producer of stones in the world accounting for over 30% of the world stone production including the marble. Marble reserves in India are 2216 million tonnes and out of these Rajasthan has 51.6 % share, accounting to 1144 million tonnes (Gupta and Kulveer, 2007). Out of 1144 million tonnes, about 800 million tonnes are of dolomitic variety and found in the Rajsamand district of the state (Jain et al., 2007).

In global competitive era, the ultimate objective of any stone operator is to produce good quality blocks at optimum cost with maximum recovery. To reduce the cutting cost with diamond wire saw machine, it is required to enhance the cutting performance of the machine. The cutting performance of diamond wire saw machine depends on rock parameters such as strength, hardness, texture, mineralogy; machine parameters such as machine power, peripheral speed, beads structure, wire construction, thrust and operational parameters such as size of bench cut, machine's position, operators' skill and quantity of water.

Wear of diamond beads during cutting operation is one main parameter in the economics of extraction of blocks in marble quarrying operation. Wearing of beads is affected by the engineering properties like mechanical, textural, mineralogical and petrographical (Ozcelik et al., 2002 & Ozcelik, 2005). The primary mode of diamond tool wear in sawing is diamond breakdown due to impact & fatigue, and the secondary mode being tool wear through abrasion of the matrix. With impregnated tools, continuous and efficient cutting can only be facilitated by compatible wear of the diamond particles and their bonding matrix (Wright et al., 2000 & Wright and Engels, 2003). The absence of quartz in carbonated rock generally gives high cut productivity with lower wire wear (Stellin et al, 2001). Cutting rate in marble quarrying is a function of both the peripheral velocity of diamond wire and the distribution of normal forces exerted on the rock by individual beads. Normal force distribution varies along the section of wire within the rock, tension applied to the system and curvature of the wire loop (Bortolussi et al., 1994). The application of greater

pull-back force increases the cutting rate and reduces wire productivity. However, no detailed field study was being conducted earlier to know the effect of machine parameters on cutting performance of diamond wire saw machine in marble.

The aim of this study was to investigate the effects of the machine parameters on the cutting performance of diamond wire saw machine on dolomitic marble. For this purpose, dolomitic marble having different mechanical properties in the field was cut vertically by using diamond wire saw machine. Physico-mechanical, textural and mineralogical properties were determined in laboratory of samples collected from field experiment locations.

Using the information obtained from field study, the statistical analysis was carried out to determine optimum peripheral speed of diamond wire in soft, medium hard and hard marble. Statistical models were developed and tested describing prime factor controlling the economy of diamond wire cutting i.e. beads wear rate and cutting rate during quarrying operation. The independent variables taken into consideration for modeling were rock shear strength parameter (X_1), peripheral speed (X_2) and thrust (X_3). Consequently, the numerical determination of the wearing in terms of rock and machine parameters is realized. The statistical evaluation was carried out using the SYSTAT 8.0.

2. Design of Experiment

Presently, fixed peripheral speed (27 m/s) machines are in operation in the study area irrespective of types of dolomitic marble. These machines have effect on diamond beads wearing rate and then life of diamond wire. Thus, to reduce the wear of diamond beads, it was decided that the study be conducted with variable speed diamond wire saw machine. In the study, experiments were designed in vertical cuts with variable speed diamond wire saw machine. Peripheral speed was controlled with the help of inverter and potentiometer. Field experiments were conducted on soft, medium hard and hard dolomitic marble, to know the influence of machine parameters on cutting performance. During all field experiments, diamond wire construction was kept uniform such as locking after every three diamond beads of sintered type of single company with 0.63 carat/bead and 30 beads / meter. The linear pressure calculated on diamond wire during the cut by dividing pull back force 930 N with contact length of wire, was 66.43 N/m.

Speed of diamond wire was kept low 20 m/s for initial and final stage of cut, for a duration of 30 minutes for each to increase the life of diamond beads from abrasive action of corners of the bench. The initial position of machine was kept away 4.0 m from bench cutting face at bottom for maintaining appropriate cutting angle. Three vertical cuts were observed in the field for each variable to measure cutting performance. All the cuts were made by same operators' skillness. Optimum water quantity was used for flushing or removing the cuttings from cut. Figure 1 shows the flowchart of study.

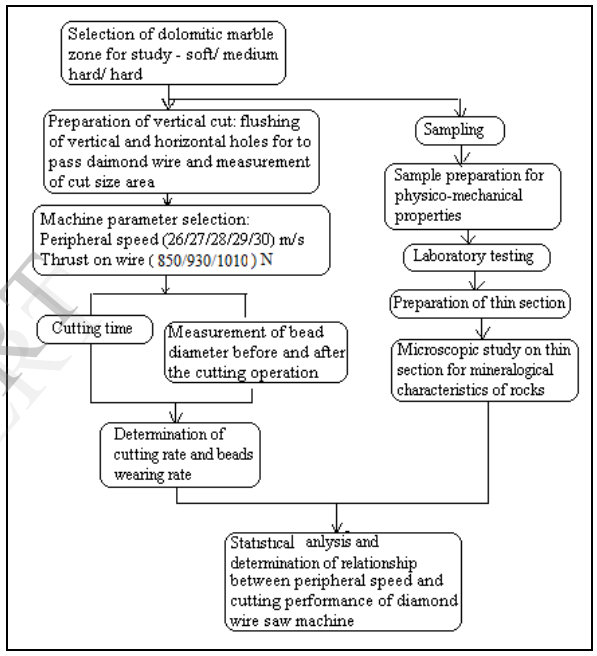


Figure 1 Flowchart of the study

The cutting performance was measured in the form of cutting rate and beads wear rate by varying the peripheral speed of diamond wire 26 to 30 m/s at various thrust levels 850/ 930/1010N, on three types of marble stone. The shear strength parameters of each sample were determined in the laboratory as per ISRM standard method. Thin sections were prepared from each type of dolomitic marble category to determine mineralogical and textural characteristics. After laboratory study and field observations, statistical analysis was carried out to determine relationship between machine parameters and cutting performance of diamond wire saw machine. Predictive equations were developed to know the relation between independent and dependent variables.

3. Laboratory and Field Investigations

Physico-mechanical, mineralogical and textural properties were determined in the laboratory of Mining Engineering Department, Maharana Pratap University of Agriculture and Technology. Field investigations were carried out at Morwad belt of dolomitic marble, situated at a distance of 90 km from Udaipur, Rajasthan, India.

3.1 Laboratory investigations

The shear strength parameters cohesion and angle of internal friction were determined by triaxial method after preparing the five samples of each variety of dolomitic marble from field and results obtained are given in Table 1-A. The result of shear strength parameters indicate increasing trend from soft to hard variety of dolomitic marble. The mineralogical and textural properties are given in Table 1-B. Soft dolomitic marble has coarse grained texture of calcite and grains of quartz, augite, pyroxene & muscovite. Figure 2 shows straight contact between calcite coarse grains. Medium to coarse grained texture of calcite with contact between coarse & fine variety of medium hard dolomitic marble was depicted in Figure 3. The hard dolomitic marble has fine to medium grained texture of calcite and high amount of quartz grains. The microphotograph of hard dolomitic marble in Figure 4, shows fine to medium grained calcite with subhedral grains of quartz, augite, pyroxene & muscovite.

Table 1-A Shear strength parameters of dolomitic marble

Type of dolomitic marble	Shear strength parameters	
	Cohesion; X_1 (C)	Angle of internal friction (Φ)
Soft	22.80	18
Medium hard	25.80	22
Hard	29.00	25

Table 1 (B) Mineralogical and Textural properties of dolomitic marble

Type of marble rock	Mineralogical and Textural properties
Soft dolomitic marble rock	Coarse grained texture of calcite with subhedral grains of quartz, augite, pyroxene & muscovite. Straight contacts between calcite grains are well visible and also isolated grains of sphene present.
Medium hard dolomitic marble rock	Medium to coarse grained texture of calcite. Small grains of quartz and fibrous tremolite are present as mineral impurities. The quartz grains are showing undolose extension with interlocking boundaries. Parallel arrangements of mineral like muscovite, amphibole & pyroxene are also present.
Hard dolomitic marble rock	Texture is fine to medium grained and high amount of quartz grains present. Quartz grains are sub angular with sutured contact and showing undolose extension. Grains of calcite along with amphibole and muscovite laths are also common mineral present and somewhere fibrous tremolite & muscovite are showing parallel elongation.

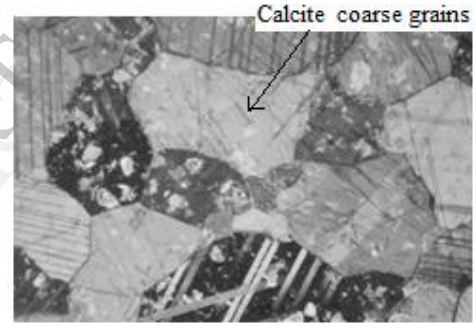


Figure 2. Soft dolomitic marble depicts straight contacts between calcite coarse grains. (Cross Nichols – 2.5x)

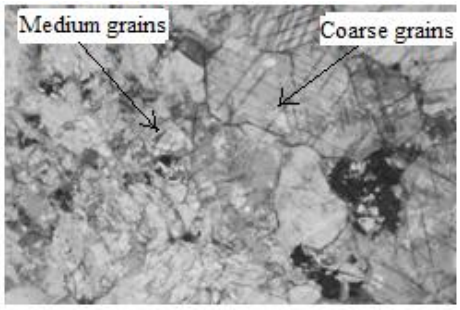


Figure 3. Medium hard dolomitic marble shows medium to coarse grained texture of calcite. (Cross Nichols – 2.5x)

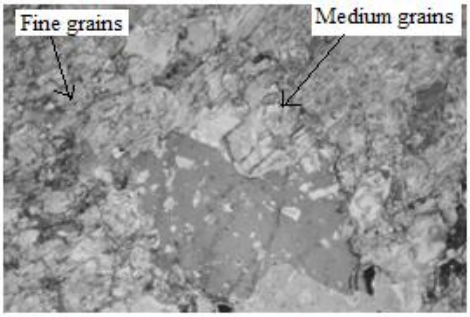


Figure 4. Hard dolomitic marble depicts fine to medium grained calcite with subhedral grains of quartz, augite, pyroxene & muscovite. (Cross Nichols – 2.5x)

3.2 Field investigations

Field investigations were conducted to determine the influence of machine parameters on cutting performance of diamond wire saw machine in soft, medium hard and hard dolomitic marble zones. Experiments were designed for vertical cuts and observations for three cuts were taken for each variable in bench cutting operation. In order to determine the amount of wearing on the diamond beads, beads diameter was measured by electronic digital caliper before and after completion of cut. Thereafter, cutting rate in m^2/h and beads wear rate in mm/m^2 were calculated. Cutting rate do not includes the initial and terminal phases of the cutting operation in the bench.

The influence of machine parameters on cutting performance of diamond wire saw machine was observed in soft dolomitic marble and given in Table 2. It has been found that the average cutting rates of diamond wire at peripheral speed 27 m/s in soft dolomitic marble were 4.26, 5.29 and 6.70 m^2/h at thrust levels 850 N, 930 N and 1010 N respectively. Cutting rates shows similar trends of increase in cutting rates at peripheral speed 28, 29 & 30 m/s for each thrust levels. The cutting rate found higher at peripheral speed of diamond wire 29 m/s for each thrust level. Beads wear rate shows increasing trend for increasing both machine parameters i.e. peripheral speed and thrust.

The results obtained to know the influence of machine parameters on cutting performance of diamond wire saw machine in medium hard dolomitic marble are given in Table 3. It has been observed that cutting rate was higher at peripheral speed of diamond wire 28 m/s for each thrust level. The average cutting rates at 27 m/s peripheral speed in medium hard dolomitic marble were 4.03, 4.86 and 6.50 m^2/h for thrust levels 850 N, 930 N and 1010 N respectively. Cutting rate shows similar trend of increasing for peripheral speed 28, 29 & 30 m/s. On increasing both peripheral speed of diamond wire and thrust, beads wear rate also increases.

Table 2. Influence of machine parameters on cutting performance in soft dolomitic marble

S. No	Diamond wire peripheral speed; X_2 (m/s)	Thrust / Load; X_3 (N)	Cut area (for three cuts) (m^2)	Machine run (for three cuts) (hours)	Cutting rate (Y_1) (m^2/h)	Beads wear rate (Y_2) ($\mu m/m^2$)
1	27	850	438.48	93.07	4.26	1.05
2	28	850	441.17	93.89	4.73	1.07
3	29	850	445.76	88.03	5.08	1.08
4	30	850	457.19	99.97	4.55	1.09
5	27	930	443.27	98.82	5.29	1.06
6	28	930	461.52	85.07	5.41	1.08
7	29	930	452.67	82.54	5.48	1.09
8	30	930	437.58	83.16	5.34	1.10
9	27	1010	448.62	66.92	6.70	1.14
10	28	1010	444.00	64.94	6.79	1.17
11	29	1010	452.88	63.61	7.23	1.19
12	30	1010	451.96	67.06	6.81	1.20

Table 3. Influence of machine parameters on cutting performance in medium hard dolomitic marble

S. No	Diamond wire peripheral speed; X_2 (m/s)	Thrust / Load; X_3 (N)	Cut area (for three cuts) (m^2)	Machine run (for three cuts) (hours)	Cutting rate (Y_1) (m^2/h)	Beads wear rate (Y_2) ($\mu m/m^2$)
1	27	850	414.85	103.47	4.03	1.16
2	28	850	425.59	95.96	4.44	1.18
3	29	850	420.13	97.93	4.30	1.19

4	30	850	421.79	101.13	4.18	1.20
5	27	930	418.22	86.06	4.86	1.17
6	28	930	418.49	79.86	5.23	1.19
7	29	930	423.57	82.85	5.11	1.20
8	30	930	423.27	87.29	4.86	1.21
9	27	1010	409.60	63.31	6.50	1.25
10	28	1010	415.05	61.97	6.71	1.28
11	29	1010	418.53	63.85	6.59	1.29
12	30	1010	421.86	65.50	6.44	1.30

Table 4 shows the cutting performance of diamond wire saw machine at different machine parameters for vertical cuts in hard dolomitic marble. Cutting rate found higher at peripheral speed of diamond wire 26 m/s for each thrust level. The cutting rates observed at 27 m/s peripheral speed in hard dolomitic marble were 3.86, 4.14 and 5.87 m^2/h for thrust levels 850 N, 930 N and 1010 N respectively. Similar trend for cutting rates found for peripheral speed 27, 28 & 29 m/s. Beads wear rate also increases on increasing both peripheral speed and thrust.

Table 4. Influence of machine parameters on cutting performance in hard dolomitic marble (X_1)

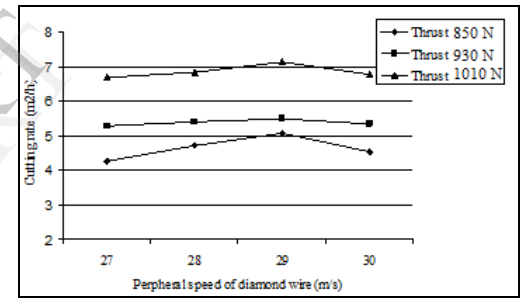
S. No	Diamond wire peripheral speed; X_2 (m/s)	Thrust / Load; X_3 (N)	Cut area (for three cuts) (m^2)	Machine run (for three cuts) (hours)	Cutting rate (Y_1) (m^2/h)	Beads wear rate (Y_2) (µm/m^2)
1	26	850	363.03	94.69	3.86	1.27
2	27	850	365.48	84.72	4.31	1.29
3	28	850	368.10	88.10	4.18	1.30
4	29	850	375.03	94.53	4.02	1.31
5	26	930	372.45	89.88	4.14	1.29
6	27	930	363.43	80.47	4.52	1.32
7	28	930	368.16	85.67	4.27	1.33
8	29	930	372.49	88.51	4.20	1.34
9	26	1010	368.65	62.43	5.87	1.38
10	27	1010	369.69	59.47	6.20	1.41
11	28	1010	365.63	60.70	6.02	1.42
12	29	1010	363.80	61.11	5.89	1.43

4. Results and Discussions

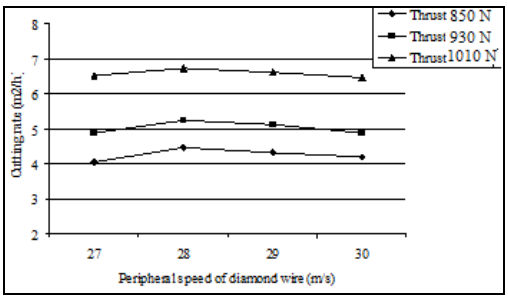
The machine parameters have influence on cutting performance of diamond wire saw machine in providing vertical cuts in bench cutting operation of dolomitic marble. Optimum peripheral speed varies according to physico-mechanical, textural & mineralogical characteristics of marble. It was also observed that the cutting rate increased on increasing thrust on diamond wire.

4.1 Peripheral speed and cutting rate relationships

Figure 5 (a), 5 (b) and 5 (c) shows the influence of peripheral speed on cutting rate in soft, medium hard and hard dolomitic marble respectively. It depicts that cutting rate is always increasing on increasing thrust on diamond wire from 850 N to 1010 N. Optimum peripheral speed was found to be 29m/s in soft, 28 m/s in medium-hard and 27 m/s in hard dolomitic marble due to their physico-mechanical, textural and mineral properties.



(a)



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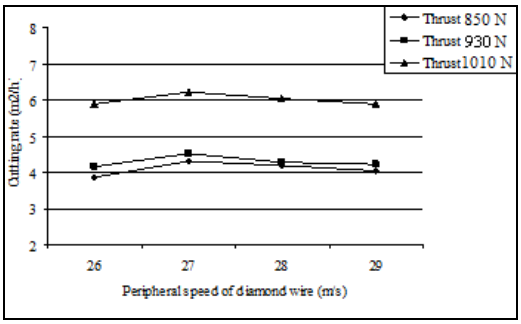

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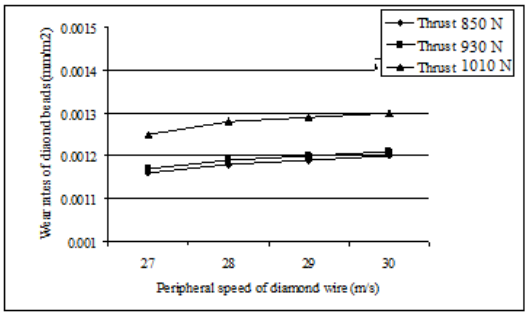
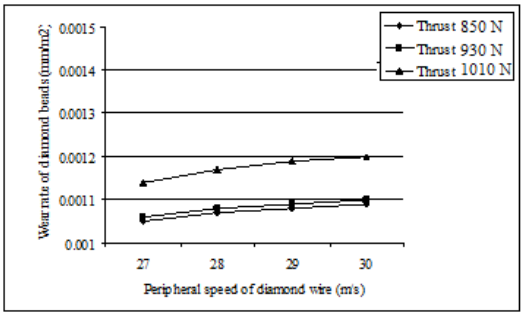


(b)

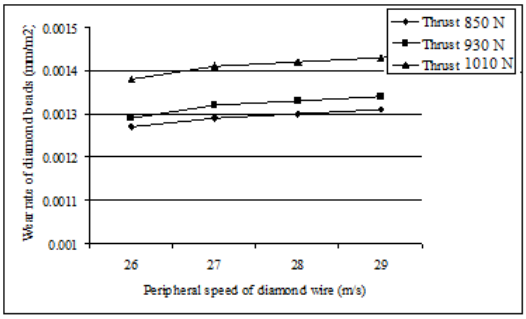
Figure 5. Relation between peripheral speed and cutting rate with diamond wire saw machine at different thrust levels in dolomitic marble (a) Soft (b) medium hard (c) Hard

4.2 Peripheral speed and wear of diamond beads relationships

The influence of peripheral speed of diamond wire on diamond beads wear rate in soft, medium hard and hard dolomitic marble at different thrust (load) level was analyzed here. Figure 6 (a), (b) & (c) shows the relationship between peripheral speed of diamond wire and diamond beads wear rate. It was observed in each category of dolomitic marble that the trend of diamond beads wearing rate was increasing on increasing peripheral speed. Diamond beads wear rate was much higher at thrust (load) 1010 N in comparison to other two thrust levels 850 N & 930 N. It was found that diamond beads wear rate was more in hard than soft and medium hard dolomitic marble. The wear rate of diamond beads varies from 0.93% to 1.88% on increasing peripheral speed from 26 m/s to 30 m/s. Diamond beads wear rate is 10.4% more in medium hard than soft dolomitic marble. Similarly, 13% more beads wear was observed in hard than medium hard dolomitic marble. It was because of fine to medium grained texture of calcite with more quartz in hard dolomitic marble.



(a)



(c)

Figure 6. Relation between peripheral speed and diamond beads wear rate at different thrust levels in dolomitic marble (a) Soft (b) medium hard (c) Hard

4.3 Regression models for cutting rate and diamond beads wear rate

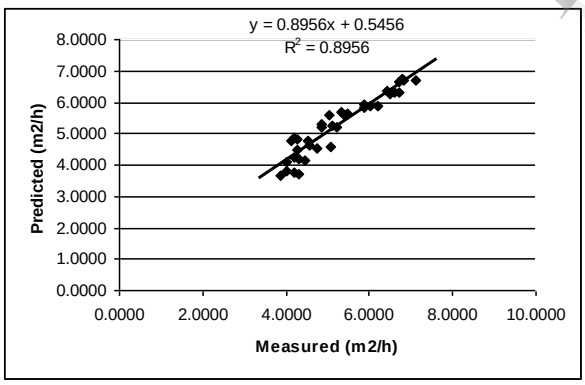
The complexity of most scientific mechanisms is such that in order to be able to predict an important response, a well known multiple regression models is needed. For predicting regression models, we have considered three independent variables i.e. shear strength parameter cohesion (X1), peripheral speed (X2) and thrust (X3) for each dependent variable i.e. cutting rate (Y1) and wear rate (Y2). During diamond wire cutting, marble is cut due to abrasive action of diamond beads on rock, and shear strength property of marble plays an important role in it. On the basis of observations given in above Tables 2, 3 & 4, regression models were derived using SYSTAT 8.0 program for vertical cutting and are given in Table 5. The factor coefficients show the effect of parameters on cutting rate and diamond beads wearing. The use of shear strength as relevant marble properties correlated to both cutting performance and wear rate seems to fit quite well in the model proposed for the three kinds of

marble taken into consideration. Shear strength parameter cohesion X1 plays a significant role as the amount of wearing calculated was 0.0395. Peripheral speed also plays a great role on both cutting as well as beads wearing rate.

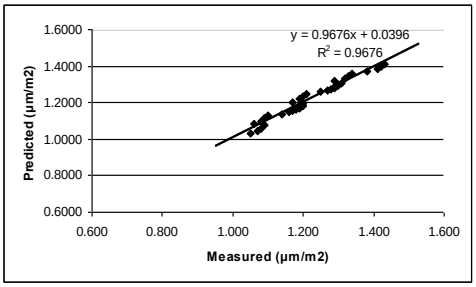
Table 5 Regression models derived for the result of vertical cutting in marble

S. No.	Models	Standard Error	Explanation (R^2)
1	Y_1= -4.9260-0.1268X_1+0.0345X_2+ 0.0134X_3	0.3397	0.8959
2	Y_2 = -0.8059 + 0.0395X_1 + 0.0139X_2+ 0.0007 X_3	0.0204	0.9676

The statistical validity of any regression model can be tested by variance analysis method. However, different approaches can also be used for this purpose. One of these methods can be used to demonstrate the differences between measures and predicted values with scattered graphs. Figure 7 (a) & (b) show the significant correlation between the results those obtained from field measurement and those predicted from the linear regression model for cutting rate and wear rate respectively. These models can be used to predict the cutting rate and wear rate for various marble and also to select appropriate diamond wire saw machine.



(a)



(b)

Figure 7. Validity of the model for (a) cutting rate and (b) wear rate in vertical cutting

4.4 Research application to other marble stones

The regression models shown may be applied to other marble stones based on shear strength parameter, peripheral speed and thrust parameters. This study may also be helpful for operators of the wire saw sector in quarrying operation of any marble deposits. They may determine the cutting rate and wear rate for diamond wire saw machine.

5. Conclusions

The optimum peripheral speed of diamond wire found based on cutting performance of diamond wire saw machine was 29 m/s in soft, 28 m/s in medium hard and 27 m/s in hard dolomitic marble. Regression models developed may be used to predict the cutting rate and wear rate for various types of marble deposit. Fixed speed diamond wire saw machine can be modified for adjusting the speed to the variable properties of marble of different areas. Diamond beads wear rate increases on increasing peripheral speed. Wear rate of diamond beads varies from 0.93% to 1.88% on increasing peripheral speed from 26 m/s to 30 m/s. Diamond beads wear rate observed was 10.4% more in medium hard than soft dolomitic marble. Similarly, 13% more beads wear found in hard than medium hard dolomitic marble.

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References:

[1] A . Bortolussi, R.Ciccu, P.P. Manca, and G. Massacci, Computer simulation of diamond wire cutting of hard and abrasive rock. Trans. Instn Min. Metal, May – August, 1994 pp A 124 to A128.

[2] R.K. Gupta, and K. Singh, Indian stone industry – An insight. 'Stonedge' Journal of Indian dimensional stone industry, February, 2007 pp 18-22

[3] S.C.Jain, S.S. Rathore, and S.N. Wahy, Performance of New Innovative Cutting Machines in Dolomitic Marble Mining. Journal of Rock Mechanics and Tunneling Technology, Volume 13, No.1, January, 2007 pp. 29-39.

[4] A. Kumar, and K. Singh, Indian stone industry – an insight. Conference Souvenir Stone Mart at Jaipur, Jan. 31 – Feb.4, 2003 pp 71-79.

[5] Y. Ozcelik, S. Kulaksiz, and M.C. Cetin, Assessment of the wear of diamond beads in the cutting of different rock types by the ridge regression. Journal of Materials Processing Technology, 127, 2002 pp 392-400.

[6] Y. Ozcelik, Effect of mineralogical and petrographical properties of marble on cutting by diamond wire. C*IM Bulletin*, 2005 Vol.98, No. 1085, pp 1-6

[7] A. Stellin, W.T. Hennies, L. Soares, and F. Fujimura, Dimensional stone block extraction by steel wire, *10th* Int.Symp. on Mine Planning and Equipment Selection, New Delhi, India, 19-21 Nov. 2001, pp. 215-221.

[8] D.N., Wright, W.R.J. Tagg, and P.R., Davis, The development of a rock classification system for use with diamond tools, Conference Souvenir Stonemart 2000, Feb 2-6, Jaipur, pp 109-128.

[9] D.N. Wright, and J.A. Engels, The environmental and cost benefits of using diamond wire for quarrying and processing of natural stone. Industrial Diamond Review, 2003, 4/03, pp 16-24.