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PERFORMANCE PREDICTION OF CHAIN SAW MACHINES USING SCHMIDT HAMMER HARDNESS

SCHMIDT ÇEKİCİ SERTLİĞİ KULLANILARAK ZİNCİRLİ KESME MAKİNELERİNİN PERFORMANS TAHMİNİ

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ABSTRACT

Schmidt hammer hardness (R_L) provides a quick and inexpensive measure of surface hardness that is widely used for estimating the mechanical properties of rock material such as strength, sawability, cuttability and drillability. In this study, R_L as predictors, which is thought to be a useful, simple and inexpensive test particularly for performance prediction of chain saw machine (CSM), is suggested. This study aims to estimate CSM performance from R_L values of rocks. For this purpose, rock cutting and rock mechanics tests were performed on twenty four different natural stone samples having different strength values. In this study, Chain Saw Penetration Index (CSPI) has been predicted based on R_L which is one of the two models previously used for performance prediction of CSMs. The R_L values were correlated with UCS, CSPI and SE using simple regression analysis with SPSS 15.0. As a result of this evaluation, R_L has a strong relation with UCS and SE. It is statistically proved that the model based on R_L for predicting CSPI is valid and reliable for performance prediction of CSM. Results of this study indicated that the CSPI of CSMs could be reliably predicted by empirical model using R_L.

Keywords:
Chain saw machines,
Specific energy,
Schmidt hammer hardness,
Rock cutting tests

ÖZ

Schmidt çekici sertliği (R_L) kayaların dayanım, kesilebilirlik (doğrusal ve dairesel) ve delinebilirlik gibi mekanik özelliklerini belirlemek için yaygın olarak kullanılan ucuz ve kolaylık sağlayan bir yüzey sertliği ölçüsüdür. Bu çalışmada, özellikle zincirli kesme makinesinin performans tahmininde, kullanışlı, basit ve ucuz bir test olan Schmidt çekici sertliği değişken olarak önerilmiştir. Bu çalışmada amaç, kayaların Schmidt sertliklerinden zincirli kesme makinelerinin performansını tahmin etmektir. Bunun için, farklı dayanım özelliklerine sahip 24 farklı doğal taş numunesi üzerinde kesme ve kaya mekaniği testleri yapılmıştır. Bu çalışmada, zincirli kesme makinelerinin performans tahmini için daha önce kullanılan iki modelden biri olan Zincirli Kesme Penetrasyon İndeksi (CSPI) R_L baz alınarak öngörülmüştür. R_L değerleri ile tek eksenli basınç dayanımı, zincirli kesme indeksi ve spesifik enerji değerlerinin korelasyonu SPSS 15.0 istatistik programı kullanılarak yapılmıştır. Bu değerlendirme sonucunda; R_L değerleri ile tek eksenli basınç dayanımı ve spesifik enerji değerleri arasında güçlü korelasyon olduğu belirlenmiştir. Buna göre; zincirli kesme indeksini tahmin etmek için R_L'ye dayanan modelin zincirli kesme makinesinin performans tahmini için geçerli ve güvenilir olduğu istatistiksel olarak kanıtlanmıştır. Bu çalışmanın sonuçları, zincirli kesme makinelerinin zincirli kesme indeksini, R_L değerleri kullanılarak oluşturulan görgül modeller ile güvenilir bir şekilde tahmin edilebileceğini göstermiştir.

Anahtar Sözcükler:
Zincirli kesme makineleri,
Spesifik enerji,
Schmidt çekici sertliği,
Kaya kesme deneyleri

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INTRODUCTION

CSMs are used for the extraction of natural (dimensional) stones such as travertine and marble. They are used for cutting low-to medium-abrasive and soft-to medium-strength natural stones in both underground and surface quarrying operations, as well as in squaring operations. They cut relatively thin slots vertically or horizontally and are usually used in combination with diamond wire-cutting machines (Primavori 2006). Adding only one chain saw to the equipment fleet, in addition to diamond wire-cutting machines, improves the overall performance of a midsize quarry by about 20% (Copur et al. 2006). They eliminate time losses and labor for drilling boreholes for wire insertion when using with diamond wire-cutting machines, especially in high benches more than 6-7 m (eliminate collimation problems). They reduce production and time losses due to their ability of sumping horizontally or vertically to enter a new bench. They result in a directly saleable stone. They create an excellent working environment (regular and planar surfaces) for quarrying. They produce less dust and waste material compared to diamond-wire cutting machines (Sariisik and Sariisik 2010). The basic limitation of these machines is that they cannot cut hard, abrasive, and fractured stone deposits.

CSMs produce an excellent working environment, produce less waste material and dust, eliminate collimation problems encountered with diamond wire cutting machines, reduce time and production losses to enter a new bench, and produce directly saleable blocks (Mancini et al., 2001; Copur et al., 2006; Copur et al., 2011a; Primavori, 2006).

There are a few studies in the literature related to performance prediction of CSMs. Mancini et al. (1992, 1994) tested the parameters affecting the performance of different chain saw machines, and simulated geostatistically the chain cutting, the results were compared with the field performances of different CSMs working in different conditions. Mancini et al. (2001) investigated in situ chain saw applications in terms of cutting rates and tool wear rates. Primavori (2006) tested the operational conditions of CSMs in order to understand the effective usage of these machines. Copur et al. (2007) performed linear cutting tests to analyze the cutting characteristics of CSMs. Copur et al. (2011a) suggested an empirical model based on CSPI for prediction of the areal net cutting rate (ANCR) of CSMs. In this model, UCS of the stones, useful cutting depth of the arms, and weight of the CSMs were used as predictors. Copur (2010) and Copur et al. (2011a, b) proposed another model based on the SE obtained from linear cutting tests in unrelieved cutting mode. Copur (2010) and Copur et al. (2011c) proposed a deterministic model in order to predict ANCR of CSMs. Sariisik and Sariisik (2013) analyzed the cutting performance of a CSM, and the results obtained from the field were compared with diamond wire cutting results. According to their study, block efficiency in natural stone quarries increased by up to 60-80 % with the use of CSM. Tumac (2014) suggested a model based on Shore hardness values and deformation coefficient for prediction of CSPI and ANCR of CSMs. The Shore hardness values have been used to improve two models previously developed based on the CSPI and SE.

This paper is concerned with establishing empirical prediction model for CSPI of CSM based on R_L values. The relation between Schmidt hardness, UCS and SE were investigated. For this purpose, rock cutting and rock mechanics tests were performed on twenty four samples representing marble, travertine and tuff, obtained from sites around Konya province. Two empirical models for prediction of the ANCR of the CSMs were developed by Copur et al. (2011a). One of the models is based on the CSPI, and uses the UCS values of the stone, weight of the CSM and useful cutting depth of the arm as predictor parameters. The other model is based on the results of linear cutting experiments performed in the unrelieved cutting mode with a standard chisel tool and uses SE as the predictor parameter. They suggested empirical models based on CSPI and linear cutting experiments are energy as the predictor parameter are also statistically verified and proved to be a very useful and reliable tool for prediction of ANCR of CSMs. In these models, they have been used six different rock samples including marble, travertine and overburden.

In this study, the CSPI model is revised using R_L values. To develop the proposed models, the database that is composed of R_L, UCS and also

SE values including unrelieved cutting modes were established using the dataset obtained from experimental studies. The model is based on a revised CSPI, which uses R_L, machine weight, and useful arm cutting depth as predictors. The R_L values were used for predicting of CSPI, UCS and SE. The CSPI model developed previously are improved by using R_L values for the prediction of chain saw machines. According to the regression analysis, the CSPI can be predicted through R_L values of rocks.

1. LABORATORY STUDIES

The testing program in this study included rock cutting and rock mechanics tests. Additionally, mineralogical and petrographic analyses were performed on rock samples. A total twenty-four different rock samples having different strength values representing marble, travertine and tuff collected from sites around Konya province of, Turkey for small-scale linear rock cutting and rock mechanics tests. Rock block samples were transported to the Rock Mechanics Laboratory in the Mining Engineering Department of Selcuk University. Cylindrical core specimens were prepared from block samples for rock mechanics tests and block samples were prepared for rock cutting tests. The standard testing procedures suggested by the ISRM (International Society for Rock Mechanics) for testing cuttability and mechanical properties of rocks.

1.1. Rock mechanics tests

All tests were carried out in the laboratory for determination of physical and mechanical properties of rock samples. Cylindrical core specimens NX (54 mm) in diameter were prepared from block samples by drilling in such a way that the drilling direction was perpendicular to the plane of the thin section. The standard testing procedures suggested by the ISRM for testing mechanical properties of rock were followed throughout the tests (ISRM 2007). The results of the tests related to the determination of the engineering properties of the samples are summarized in Table 1 and testing procedures are briefly given below. The tests were repeated at least ten times for each rock type and the average value was recorded.

The UCS values were determined on a hydraulic testing machine with a capacity of 3000 kN. The loading rate was applied within the limits of 2 kN/sec. Cylindrical specimens NX in diameter with a length to diameter ratio of 2.5:1 were used.

Schmidt hammer rebound tests were applied on the test samples having an approximate dimension of 30 x 30 x 20 cm^3. The tests were performed with a Proceq L-type digital Schmidt hammer with impact energy of 0.735 Nm. The hammer is equipped with a sensor that measures the rebound value of a test impact with high resolution and repeatability. Basic settings and measured values are shown on the display unit. The measured data can be transmitted easily by a serial RS 232 cable to a normal printer or to a PC with the appropriate software. All the tests were conducted with the hammer by holding vertically downwards and at right angles to the horizontal rock surface. In the tests, the ISRM (2007) recommendations were applied for each rock type. ISRM suggested that 20 rebound values from single impacts separated by at least a plunger diameter should be recorded, and the upper ten values averaged.

1.2. Rock cutting tests

The small-scale rock cutting test has been developed for the purpose of measuring direct cuttability of a given rock. The test rig which is a modified Kloop shaping machine having a stroke 450 mm and a power of 4 kW was used (Fig. 1). The rig which is similar to the one originally developed by McFeat-Smith and Fowell (1977, 1979) is located in the laboratories of the Mining Engineering Department at Selcuk University. In this study, rectangular blocks of rock samples of 30x30x10 cm were fixed in a table of a shaping machine and cut by a chisel pick having a rake angle of -5°, a clearance angle of 5°, and a tool width of 12.7 mm. The depth of cut was selected as 2 mm in unrelieved cutting mode. The cutting speed was around 36 cm/s and the data acquisition rate was 1,000 Hz. In this study, data collection system included two load cells (cutting and normal), a current and a voltage transducer, a power analyzer, an AC power speed control system, a laser sensor, a data acquisition card and a computer were used. During the rock cutting tests the tool forces in cutting directions are recorded by using platform type load cell with capacity of 750 kg, a data acquisition card and block diagrams in Matlab Simulink as illustrated in Fig. 2.

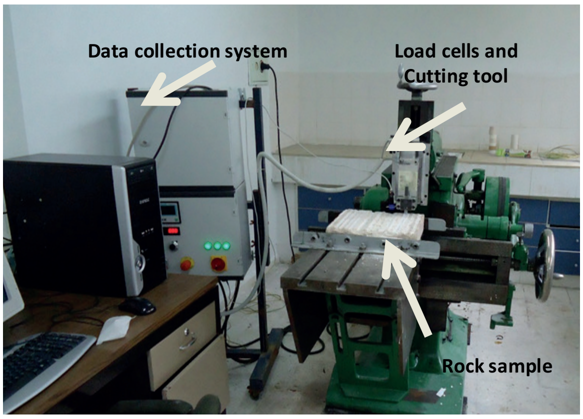

Figure 1. Small-scale rock cutting test rig (Dursun, 2012)

Three tests were carried out on each rock sample in which mean cutting forces were recorded. After each cutting test, the length of cut was measured and the rock cuttings for the cut were collected and weighed for determination of specific energy. Specific energy is calculated using the formula below:

$$SE = [(FC.L)/Q]x10^{-1} \qquad (1)$$

where SE is the specific energy in MJ/m^3 or kWh/m^3, FC the average cutting force acting on the tool in kN, L the cutting length in cm, Q the volume cut, in cm^3 (Q = Y/D), Y the yield in gr, D the density in g/cm^3.

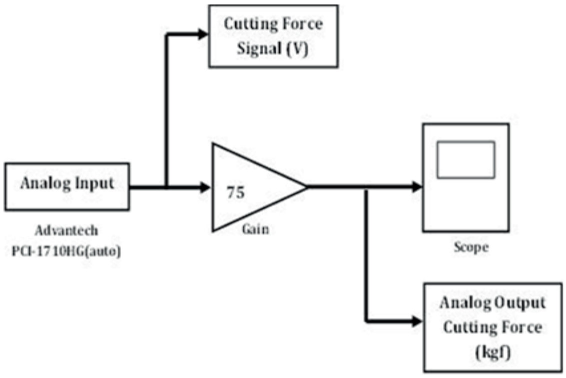

Figure 2. Block diagrams in Simulink for cutting forces

2. EVALUATION OF THE RESULTS

The average results of rock cutting and rock mechanics tests are given in Table 1. As shown in Table 1, the range varies from soft to hard rocks: UCS from 4.44 to 80.73 MPa, Brazilian tensile strength (BTS) from 1.05 to 6.88 MPa, P-wave velocity (Vp) from 1.88 to 6.58 km/s, R_L from 25.95 to 80.26, density (ρ) from 1.43 to 2.77 g/cm^3 and the SE values range from 1.58 to 17.63 kWh/m^3.

2.1. Prediction of UCS and SE from R_L values

The Schmidt hammer hardness value is one of the physico-mechanical properties of the rock. Schmidt hammer test is very simple and inexpensive test to conduct and the rebound value is a good indicator of mechanical properties of rock material (Bilgin et al., 2002).

Some researchers found strong correlations between Schmidt hardness value and the cutting rate of roadheaders, tunnel boring machines and impact hammers (Bilgin et al., 1996, 2002; Howarth et al., 1986; Poole and Farmer, 1978; Goktan and Gunes, 2005). Additionally, Schmidt hammer value is used in rock cutting applications and sawability for prediction of performance of the cutting process (Kahraman et al. 2004; Ersoy and Atici, 2005; Yurdakul and Akdas, 2012).

In this study, relations between R_L, SE and UCS was analyzed using regression analysis method with SPSS 15.0. The relation between UCS and R_L are presented in Fig. 3. According to the simple regression analysis for all data, the exponential function showed significant relation between UCS and R_L values of rocks. The estimation of the UCS from R_L is given in Eq. 2. The regression coefficient (R^2) for this equation is 0.891. The relation between SE and R_L are presented in Fig. 4. According to the simple regression analysis for all data, the power function showed significant relation between SE and R_L values of rocks. The estimation of the SE from R_L is given in Eq. 3. The regression coefficient (R^2) for this equation is 0.936. The equations of curves are given as follows:

$$UCS = 2.180e^{0.048RL} \qquad (2)$$

$$SE = 0.002R_L^{2.181} \qquad (3)$$

where UCS is uniaxial compressive strength in MPa, SE is specific energy in kWh/m^3 and R_L is Schmidt hardness value.

R_L has a meaningful correlation with UCS and SE, with a strong coefficient of determination and in these models.

2.2. Model development studies by using R_L values

Predicting performance of mechanical miners is very important for feasibility and planning purposes. There are some prediction models in the literature for performance prediction of mechanical miners. The model based on instantaneous cutting rate of mechanical miner developed by Rostami et al. (1994) has been more frequently used in these models. Net cutting rate, also called as instantaneous cutting rate, of a mechanical miner can be estimated by using Eq. (4).

$$NCR = kP/SE_{opt} \qquad (4)$$

where NCR is the net cutting rate in m^3/h, SE_{opt} is the optimum specific energy in kWh/m^3 obtained from linear cutting tests, P is the cutting power of the excavation machine in kW, and k is coefficient related to the transfer of cutting to the rock depending on the type of mechanical miner.

Limited researches have been performed for performance prediction of CSMs. Two empirical models were developed and used to predict the performance of CSM by Copur et al. (2011a). One of the models depends on the stone, machine and operational parameters as predictors, which are normalized as the CSPI. The other model depends on linear cutting tests and uses SE as the predictor. In this study, the CSPI has been improved by using the R_L values of rocks.

Table 1. Rock cutting and rock mechanics tests results

Rock Code Number	Rock Type	UCS (MPa)	BTS (MPa)	V_p (km/s)	R_L	ρ (g/cm^3)	FC (kN)	SE (kWh/m^3)
1	Travertine	18.56 ±2.57	1.75 ±0.23	4.03 ±0.17	47.78 ±4.49	2.16 ±0.05	1.12	8.26
2	Travertine	27.55 ±4.06	2.94 ±0.90	4.16 ±0.28	45.63 ±2.17	2.26 ±0.08	1.02	7.91
3	Travertine	30.69 ±5.19	2.96 ±0.57	4.70 ±0.21	53.30 ±2.15	2.36 ±0.10	1.47	10.05
4	Travertine	32.23 ±4.83	3.74 ±0.98	5.22 ±0.37	61.67 ±1.87	2.40 ±0.09	1.42	12.19
5	Travertine	25.95 ±8.60	2.86 ±0.71	4.88 ±0.28	52.71 ±3.15	2.33 ±0.03	1.51	7.97
6	Travertine	28.11 ±10.46	3.01 ±0.63	5.38 ±0.14	49.16 ±0.82	2.39 ±0.06	1.25	10.82
7	Travertine	14.82 ±3.84	2.96 ±0.31	4.57 ±0.18	48.05 ±1.02	2.24 ±0.04	1.39	9.01
8	Travertine	19.22 ±6.58	2.79 ±0.59	4.31 ±0.36	45.52 ±3.42	2.46 ±0.05	0.99	8.68
9	Travertine	22.45 ±6.02	3.44 ±0.86	4.19 ±0.19	51.29 ±1.51	2.48 ±0.06	1.50	9.67
10	Travertine	28.19 ±5.47	4.24 ±0.65	4.92 ±0.08	53.93 ±1.33	2.52 ±0.03	1.33	10.74
11	Travertine	43.95 ±8.45	4.83 ±1.25	4.12 ±0.06	53.52 ±1.93	2.48 ±0.06	1.30	9.00
12	Marble	71.98 ±11.41	6.51 ±1.29	6.58 ±0.15	70.14 ±1.23	2.71 ±0.03	2.15	17.63
13	Marble	80.73 ±25.88	4.43 ±0.55	6.54 ±0.03	65.49 ±1.80	2.70 ±0.07	1.81	17.28
14	Marble	56.16 ±12.77	6.04 ±0.63	5.98 ±0.44	69.63 ±2.19	2.66 ±0.01	1.99	17.41
15	Marble	54.63 ±8.61	4.22 ±0.89	6.26 ±0.30	61.44 ±1.33	2.74 ±0.06	1.90	11.71
16	Marble	58.87 ±12.98	4.76 ±1.61	4.22 ±0.34	70.50 ±1.95	2.77 ±0.06	1.74	13.26
17	Marble	71.18 ±9.79	6.88 ±1.21	6.39 ±0.16	80.26 ±2.86	2.77 ±0.03	1.68	16.69
18	Tuff	19.67 ±4.94	1.96 ±0.61	2.63 ±0.06	47.75 ±4.73	1.82 ±0.003	0.66	4.84
19	Tuff	4.44 ±1.18	1.05 ±0.09	1.88 ±0.08	26.66 ±0.92	1.43 ±0.02	0.20	1.58
20	Tuff	7.86 ±1.27	1.39 ±0.12	2.17 ±0.03	27.27 ±0.88	1.50 ±0,01	0.23	1.71
21	Tuff	11.86 ±0.79	1.52 ±0.14	2.28 ±0.03	33.79 ±0.87	1.67 ±0.01	0.45	3.08
22	Tuff	11.23 ±2.10	1.59 ±0.35	2.23 ±0.14	28.59 ±2.13	1.72 ±0.09	0.31	2.73
23	Tuff	8.23 ±1.72	1.19 ±0.46	2.21 ±0.05	30.21 ±2.18	1.66 ±0.03	0.32	2.84
24	Tuff	9.35 ±1.17	1.78 ±0.36	2.29 ±0.04	25.95 ±2.17	1.57 ±0.01	0.27	2.02

UCS: Uniaxial compressive strength, BTS: Brazilian tensile strength, Vp: P wave velocity, R_L: Schmidt hammer hardness, ρ: Density FC: Cutting force, SE: Specific energy.

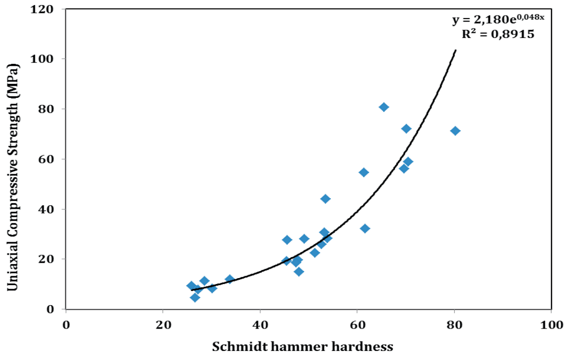

Figure 3. Relation between Schmidt hammer hardness and UCS values

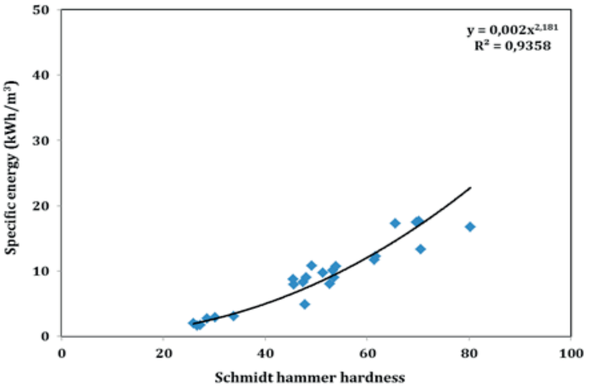

Figure 4. Relation between Schmidt hammer hardness and SE values

The CSPI is given in Eq. 5 (Copur et al. 2011a; Tumac, 2014):

$$CSPI = WH/UCS \tag{5}$$

where CSPI is the chain saw penetration index in m^3, W is the weight of chain saw machine in tons, H is the useful arm cutting depth in m, and UCS is the uniaxial compressive strength of the stone in MPa. The UCS can be estimated from relationship between UCS and R_L values given in Eq. 2 in order to determine the CSPI. This equation can be rewritten as the predicted chain saw penetration index ($CSPI_{pre}$), shown in Eq. 6:

$$CSPI_{pre} = \frac{WH}{2.180e^{0.048RL}} \tag{6}$$

where $CSPI_{pre}$ is the predicted chain saw penetration index in m^3, W is the weight of chain saw machine in tons, H is the useful arm cutting depth in m, e is the base of the natural logarithm, and R_L is the Schmidt hammer hardness value.

In this study, the performance prediction of a CSM based on CSPI were calculated for the tested stones using Eq. 5 and given in Table 2, which were developed by Copur et al. (2011a). This equation can be rewritten as the revised CSPI, given Eq. 6. This model was improved using Schmidt hardness value. The predictors used in these models such as machine weight (W), useful arm cutting depth (H) are assumed to be 5.5 tons, 2.6 m, respectively, which can be obtained from Copur et al. (2011a). Detailed field performances and technical features of chain saw machines can be seen in previous study performed by Copur et al. (2011a). Table 2 shows the predicted CSPI, UCS and SE based on R_L values using simple regression analysis with SPSS 15.0. The UCS requirement of the model developed by Copur et al. (2011a) needs core samples, and the sample preparation and tests take a long time; however, R_L values in the improved model is obtained from Schmidt hammer test, which is an easy, inexpensive and practical test.

A good correlation was found between the calculated CSPI using Eq. 5 developed by Copur (2011a) and predicted $CSPI_{pre}$ using Eq. 6 based on R_L values of rocks as seen in Fig. 5. The relation follows a power function with coefficient of determination (R^2) value was 0.892. In this model which revealed the regression equation, the regression parameters were all significant (p=0.000). The equation of the curve is:

$$\text{Model 1: } CSPI = 0.999CSPI_{pre}^{1.004} \tag{7}$$

where CSPI is the chain saw penetration index in m^3, $CSPI_{pre}$ is the predicted chain saw penetration index by using Eq. 6 in m^3.

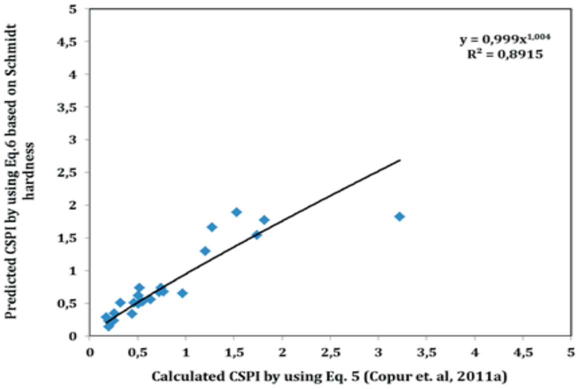

Figure 5. Relation between predicted and calculated CSPI

Table 2. Summary of the predictions of UCS, SE and CSPI based on R_L values

Rock Code Number	Rock Type	H* (m)	T* (m)	W* (tons)	$P_{cutting}$ *(kW)	Predicted UCS (Eq.2)	Predicted SE (Eq.3)	Calculated CSPI (Eq.5)	Predicted CSPI (Eq.6)
1	Travertine	2.6	0.042	5.5	11.4	21.29	9.07	0.77	0.67
2	Travertine	2.6	0.042	5.5	11.4	19.48	8.31	0.52	0.73
3	Travertine	2.6	0.042	5.5	11.4	28.16	11.67	0.47	0.51
4	Travertine	2.6	0.042	5.5	11.4	42.08	16.04	0.44	0.34
5	Travertine	2.6	0.042	5.5	11.4	27.37	11.39	0.55	0.52
6	Travertine	2.6	0.042	5.5	11.4	23.08	9.78	0.51	0.62
7	Travertine	2.6	0.042	5.5	11.4	21.88	9.31	0.96	0.65
8	Travertine	2.6	0.042	5.5	11.4	19.38	8.27	0.74	0.74
9	Travertine	2.6	0.042	5.5	11.4	25.57	10.73	0.64	0.56
10	Travertine	2.6	0.042	5.5	11.4	29.02	11.97	0.51	0.49
11	Travertine	2.6	0.042	5.5	11.4	28.45	11.77	0.33	0.50
12	Marble	2.6	0.042	5.5	11.4	63.18	21.24	0.20	0.23
13	Marble	2.6	0.042	5.5	11.4	50.54	18.29	0.18	0.28
14	Marble	2.6	0.042	5.5	11.4	61.66	20.90	0.25	0.23
15	Marble	2.6	0.042	5.5	11.4	41.61	15.91	0.26	0.34
16	Marble	2.6	0.042	5.5	11.4	64.29	21.47	0.24	0.22
17	Marble	2.6	0.042	5.5	11.4	102.70	28.49	0.20	0.14
18	Tuff	2.6	0.042	5.5	11.4	21.57	9.18	0.73	0.66
19	Tuff	2.6	0.042	5.5	11.4	7.84	2.58	3.22	1.82
20	Tuff	2.6	0.042	5.5	11.4	8.07	2.71	1.82	1.77
21	Tuff	2.6	0.042	5.5	11.4	11.04	4.32	1.21	1.30
22	Tuff	2.6	0.042	5.5	11.4	8.60	3.00	1.27	1.66
23	Tuff	2.6	0.042	5.5	11.4	9.29	3.38	1.74	1.54
24	Tuff	2.6	0.042	5.5	11.4	7.58	2.43	1.53	1.89

*The predictors of field performance of a chain saw machine used in this study were obtained from Copur et al. (2011a)

The predictive performances of the models were compared in order to determine the applicability of the models obtained. RMSE (Root Mean Square Error) (Eq. 8), coefficient of determination (R^2) and adjusted coefficient of determination (Adj. R^2) were used for the purpose of measuring the predictive performance of the models. A summary of the model generated for simple regression analysis is given in Table 3.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(o_i - t_i)^2} \qquad (8)$$

where o_i is the measured value, t_i is the predicted value and N is the number of the samples.

The performance indices above can be interpreted as follows: if the RMSE is low, then the model performs better also for a good predictive model, the value of R^2 and Adj. R^2 are expected to be close to 1 (Gokceoglu, 2002; Gokceoglu and Zorlu, 2004).

Table 3. Summary of the generated models for simple regression analysis

Model	R	R^2	Adj.R^2	RMSE	Std. Est	*p* value
1	0.946	0.892	0.890	0.32	0.261	0.00

CONCLUSIONS

This paper aims to develop easy and inexpensive prediction models to help performance prediction of

CSM. R_L value is used in rock cutting applications, the cutting rate of roadheaders, tunnel boring machines and impact hammers and sawability for prediction of performance of the cutting process. However, R_L has not been used for performance prediction of CSM. This is one of the research activities differentiating this research from similar previous work. Relatively few published studies are available on the relation between Schmidt hardness and performance prediction of CSM. The simple regression technique used in this paper demonstrated very satisfactory results in predicting CSPI. The aim of this study is to assess and discuss the efficiency of R_L values on the performance prediction of CSM. For this purpose, CSPI were calculated using equation developed by Copur et al. (2011a). The UCS requirement of the model developed by Copur et al. (2011a) needs core samples, and the sample preparation and tests take a long time; however, R_L values in the improved model is obtained from Schmidt hammer test, which is an easy, inexpensive and practical test. The empirical models based on R_L values are statistically verified and proved to be useful and reliable tool for prediction of CSPI. The R_L values are strongly correlated between UCS and SE obtained from linear cutting tests performed by using standard chisel tool in the unrelieved cutting mode. According to R^2, Adj. R^2 and RMSE values, it is thought that the proposed Schmidt hammer hardness test in this work may be used as a preliminary guide for performance prediction of chain saw machines, for cutting stone in the production of natural stone quarry blocks.

REFERENCES

Bilgin, N., Yazici, S., Eskikaya, S., 1996. A Model to Predict the Performance of Roadheader and Impact Hammers in Tunnel Drivages. In: Proc. Eurock ‘96 Rotterdam: Balkema*,* 715-720.

Bilgin, N., Dincer, T., Copur, H., 2002. The Performance Prediction of Impact Hammers from Schmidt Hammer Rebound Values in Istanbul Metro Tunnel Drivages. Tunnelling and Underground Space Technology, July 17 (3), 237-247.

Copur, H., Balci, C., Bilgin, N., Tumac, D., Feridunoglu, C., Dincer, T., Serter, A., 2006. Cutting Performance of Chain Saw Machines in Quarries and Laboratory. In: Proc. of the 15th Int. Symp. on Mine Planning and Equipment Selection, Turin, Italy, September, 1324-1329.

Copur, H., Balci, C., Bilgin, N., Tumac, D., Duzyol, I., 2007. Full-scale Linear Cutting Tests Towards Performance Prediction of Chain Saw Machines. In: Proc. of the 20th Int. Mining Congress Exhibition (IMCET 2007), Ankara, Turkey, June, 161-169.

Copur, H., 2010. Linear Stone Cutting Tests with Chisel Tools for Identification of Cutting Principles and Predicting Performance of Chain Saw Machines. Int. J. Rock Mech. Min. Sci., 47, 1, 104-120.

Copur, H., Balci, C., Tumac, D., Bilgin, N., 2011a. Field and Laboratory Studies on Natural Stones Leading to Empirical Performance Prediction of Chain Saw Machines. Int. J. Rock Mech. Min. Sci., 48, 2, 269-282.

Copur, H., Balci, C., Bilgin, N., Tumac, D., Avunduk, E., Demirel, S., Simsek, A., 2011b. An Empirical Model for Predicting the Performance of Chain Saw Machines. In: Proc. of the 3rd Mining Machinery Symposium, Izmir, Turkey, May, 55-65 (in Turkish).

Copur, H., Balci, C., Bilgin, N., Tumac, D., Avunduk, E., Saracoglu, M.A., Serter, A, 2011c. A Deterministic Model for Predicting and Optimizing Performance of Chain Saw Machines. In: Proc. of the 22nd World Mining Congress and Expo, Istanbul, Turkey, September, 175-181.

Dursun, A.E, 2012. Cuttability of Limestone Strata at North-West of Konya City. PhD. Thesis, The Graduate School of Natural and Applied Science, Selçuk University, Konya, Turkey, p.286 (In Turkish).

Ersoy, A., Atici, U., 2005. Specific Energy Prediction for Circular Diamond Saw in Cutting Different Types of Rocks Using Multivariable Linear Regression Analysis. J. Min. Sci., 41, 240-260.

Gokceoglu, C., 2002. A Fuzzy Triangular Chart to Predict the Uniaxial Compressive Strength of Ankara Agglomerates from Their Petrographic Composition. Eng Geol, 66, 39-51.

Gokceoglu, C., Zorlu, K., 2004. A Fuzzy Model to Predict the Uniaxial Compressive Strength and the Modulus of Elasticity of a Problematic Rock. Engineering Applications of Artificial Intelligence, 17 (1), 61-72.

Goktan, R.M., Gunes, N., 2005. A Comparative Study of Schmidt Hammer Testing Procedures with Reference to Rock Cutting Machine Performance Prediction. Int. J. Rock Mech. Min. Sci., 42, 466-477.

Howarth, D.F., Adamson, W.R., Berndt, J.R., 1986. Correlation of Model Tunnel Boring and Drilling Machine Performances with Rock Properties. Int. J. Rock Mech. Min. Sci., 23, 171-175.

ISRM, 2007. The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974–2006. In: Ulusay, R., Hudson, J.A. (Eds.), ISRM Turkish National Group, Ankara, Turkey.

Kahraman, S., Fener, M., Gunaydin, O., 2004. Predicting the Sawability of Carbonate Rocks Using Multiple Curvilinear Regression Analysis. Int. J. Rock Mech. Min. Sci., 41, 1123-1131.

Mancini, R., Cardu, M., Fornaro, M., Linares, M., Peila, D., 1992. Analysis and Simulation of Stone Cutting with Microtools. In: Proc. of the 3rd Int. GeoEngineering Conference, Torino, Italy, September, 227-236.

Mancini, R., Linares, M., Cardu, M., Fornaro, M., Bobbio, M., 1994. Simulation of the Operation of a Rock Chain Cutter on Statistical Models of Inhomogeneous Rocks. In: Proc. of the 3rd Int. Symp. on Mine Planning and Equipment Selection, Istanbul, Turkey, October, 461-468.

Mancini, R., Cardu, M., Fornaro, M., Toma, C.M., 2001. The Current Status of Marble Chain Cutting. In: Proc. of the 9th Int. Symp. on Mine Planning and Equipment Selection, New Delhi, India, November, 151-158.

McFeat-Smith, I., Fowell, R.J., 1977. Correlation of Rock Properties and The Cutting Performance of Tunneling Machines. In Proc. of a Conference on Rock Engineering, CORE-UK, The University of Newcastle upon Tyne, 581-602.

McFeat-Smith, I., Fowell, R.J., 1979. The Selection and Application of Roadheaders for Rock Tunneling. Proc. 4th Rapid Excavation and Tunnelling Conference, Atlanta, AIME, New York, 261-279.

Poole, R.W., Farmer, I.W., 1978. Geotechnical Factors Affecting Tunnelling Machine Performance in Coal Measures Rock. Tunnels and Tunnelling, 27-30.

Primavori, P., 2006. Uses for The Chain Saw. Marmo Mach. Int., 53, 80-102.

Rostami, J., Ozdemir, L., Neil, D., 1994. Performance Prediction, A Key Issue in Mechanical Hard Rock Mining. Mining Engineering, November, 1264-1267.

Sariisik, A., Sariisik, G., 2010. Efficiency Analysis of Armed-Chained Cutting Machines in Block Production in Travertine Quarries. The Journal of Southern African Institute of Mining and Metallurgy, 110:473–480.

Sariisik A., Sariisik G., 2013. Investigation of The Cutting Performance of the Natural Stone Block Production in Quarries with Armed Chain Cutting Machine. Proc. Inst. Mech. Eng. C. J. Mech. Eng. Sci. 227:155–165.

Tumac, D., 2014. Predicting The Performance of Chain Saw Machines Based on Shore Scleroscope Hardness. Rock. Mech. Rock. Eng., 47, 703-715.

Yurdakul, M., Akdaş, H., 2012. Prediction of Specific Cutting Energy for Large Diameter Circular Saws During Natural Stone Cutting. Int. J. Rock Mech. Min. Sci., 53, 38-44.