BİLİMSEL MADENCİLİK DERGİSİ
SCIENTIFIC MINING JOURNAL
TMMOB Maden Mühendisleri Odası Yayını / *The Publication of the Chamber of Mining Engineers of Turkey*

Orijinal Araştırma / *Original Research*

PREDICTION OF SPECIFIC ENERGY USING P-WAVE VELOCITY AND SCHMIDT HAMMER HARDNESS VALUES OF ROCKS BASED ON LABORATORY STUDIES

LABORATUVAR ÇALIŞMALARINA BAĞLI OLARAK KAYAÇLARIN P-DALGA HIZI VE SCHMIDT ÇEKİCİ SERTLİĞİ DEĞERLERİ KULLANILARAK ÖZGÜL ENERJİNİN TAHMİNİ

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Geliş Tarihi / *Received* : 21 Kasım / *November 2018*
Kabul Tarihi / *Accepted* : 27 Haziran / *June 2019*

Keywords:
Specific energy,
P-wave velocity,
Schmidt hammer hardness,
Rock cutting tests,
Statistical analysis.

ABSTRACT

Specific energy has been widely used to assess the rock cuttability for mechanical rock excavation. In mechanical rock excavation processes, engineers need to predict, of machine performance based on specific energy using easy applicable, more economical and simple sample preparation methods. In this study, P-wave velocity (V_p) and Schmidt hammer hardness (R_L) tests are used as predictors for prediction of specific energy, which are thought to be a practical, simple and inexpensive test. For this purpose, rock cutting and V_p and R_L tests were performed on 24 different rock samples. The V_p and R_L values were correlated with specific energy values using simple and multiple regression analysis with SPSS 15.0. As a result of this evaluation, there is a strong relation between specific energy, V_p and R_L values of rocks. According to the statistical analyses, specific energy values can be reliably predicted by using V_p and R_L values of rocks based on laboratories studies.

Anahtar Sözcükler:
Spesifik enerji,
P dalga hızı,
Schmidt çekici sertliği,
Kaya kesme deneyleri,
İstatistiksel analiz.

ÖZ

Spesifik enerji değeri mekanik kayaç kazısında kayaçların kesilebilirlik özelliklerini belirlemek için yaygın olarak kullanılmaktadır. Mekanik kayaç kazısı işlemlerinde mühendisler, spesifik enerji değerine bağlı olarak makine performansını tahmin etmek için kolay uygulanabilir, daha ekonomik ve basit örnek hazırlama yöntemlerinin kullanıldığı yöntemlere ihtiyaç duyarlar. Bu çalışmada, spesifik enerjinin tahmini için pratik, basit ve ucuz bir test olduğu düşünülen kayaçların P-dalga hızı (V_p) ve Schmidt çekici sertlik (R_L) değerleri değişken olarak önerilmiştir. Bu amaçla 24 farklı kaya numunesi üzerinde kaya kesme ile V_p ve R_L testleri yapılmıştır. Elde edilen V_p ve R_L ile spesifik enerji değerleri SPSS 15.0 programı kullanılarak basit ve çoklu regresyon analizi ile değerlendirilmiştir. Bu değerlendirme sonucunda kayaçların spesifik enerji, V_p ve R_L değerleri arasında güçlü bir ilişki olduğu belirlenmiştir. İstatistiksel analizlere göre, laboratuar çalışmalarına bağlı olarak kayaların V_p ve R_L değerleri kullanılarak spesifik enerji değerleri güvenilir bir şekilde tahmin edilebilir.

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INTRODUCTION

Specific energy is a commonly accepted measure of cutting efficiency and when obtained under a standardized condition, provides a realistic and meaningful measure of rock cuttability. Specific energy is defined as the energy required to cut a unit volume of rock, being an important indicator of rock cuttability (Rostami et al., 1994; Fowell and McFeat-Smith, 1976; McFeat-Smith and Fowell, 1977; 1979; Copur et al., 2001; Balci et al., 2004; Balci and Bilgin, 2007; Dursun, 2012; Dursun and Gokay, 2016).

Many prediction models have been developed for specific energy using some rock properties. Several rock properties such as, uniaxial compressive strength, Brazilian tensile strength, P-wave velocity, Schmidt hammer hardness, shore hardness, cone indenter hardness, static and dynamic elastic modulus, rock quality designation, point load strength, brittleness index, and density have been used for prediction of specific energy in many studies up to present (Rostami et al., 1994; Fowell and McFeat-Smith, 1976; McFeat-Smith and Fowell, 1977; 1979; Copur et al., 2001; Altindag, 2003; Balci et al., 2004; Tiryaki and Dikmen, 2006; Balci and Bilgin, 2007; Tumac et al., 2007; Copur, 2010; Copur et al., 2011; Dursun, 2012; Comakli et al., 2014; Tumac, 2014; Dursun and Gokay, 2016) In these models, V_p and R_L values of rocks have been used as predictors fewer than the other properties of rocks for prediction of specific energy.

Determination of specific energy values of rocks, prediction of excavation performance and physical and mechanical properties of rocks are very important for the studies of mine or tunnel projects. In the rock excavation technology, project engineers need to consider specific energy value and physical and mechanical properties of rocks to determine the relation between these properties of rocks and cutting machine performance. So, determination of specific energy values and physical and mechanical properties of rocks becomes a necessity for developing performance prediction models in rock excavation process.

Specific energy value is usually determined with the aid of laboratory cutting equipment which needs highly sophisticated instrumentation (Bilgin et al., 1997a; 1997b) and research engineers are always interested in finding a method to predict specific energy from one of the simple rock properties. Since sound velocity and Schmidt hardness tests can be applied both in laboratory and in the field and these techniques are nondestructive and easy to apply, these methods are frequently used by engineers working in mining, and construction industries. Especially in mining, V_p value have increasingly been used to determine the dynamic properties of rocks in rock mechanics tests and mining applications due to easy applicable, simple sample preparation and more economical experimental studies (Brich, 1960; Thill and Bur, 1969; Inoue and Ohomi, 1981; Kopf et al., 1985; Young, et al., 1985; Gaviglio, 1989; King et al., 1995; Apuani et al., 1997; Chrzan, 1997; Boadu, 2000; Kahraman, 2001; Kahraman, 2002a; 2002b; Kahraman et al., 2005; Karakus and Tutmez, 2006; Kahraman, 2007; Cobanoglu and Celik, 2008; Kahraman and Yeken, 2008; Vasconcelos et al., 2008; Khandelwal and Singh, 2009; Yagiz, 2011; Altindag, 2012). As for R_L value is a quick and inexpensive measure of rock hardness, which may be widely used for estimation of mechanical properties of rock materials such as strength, cuttability, sawability, and drillability (Schmidt, 1951; Kidybinski, 1968; Tarkoy and Hendron, 1975; Poole and Farmer, 1978; Farmer et al., 1979; Howarth, et al., 1986; Shahriar, 1988; Bilgin et al., 1990; Kahraman, 1999; Kahraman et al., 2000; Bilgin et al., 2002; Kahraman et al., 2003; Aydın and Basu, 2005; Goktan and Gunes, 2005; Karakus and Tutmez, 2006).

Predicting specific energy is a crucial issue for the accomplishment of mechanical tunnel projects, excavating tunnels and galleries for the purpose of mining and civil projects. Many models and equations have previously been introduced to estimate specific energy based on properties of rock using various statistical analysis techniques. In the related literature, properties of rock are the most widely parameters used for prediction of specific energy. Because, mechanical excavators are excavated efficiently and economically based on properties of rocks.

Schmidt hammer rebound hardness and seismic velocity tests are very simple and inexpensive test to conduct, R_L and V_p values are good indicator of mechanical properties of rock material (Bilgin et al., 2002). Schmidt hardness value is widely used in determining the performance of tunnel boring machines, impact hammers, roadheaders, and it is generally very successful in rock cutting applications for predicting the performance of the cutting process (Poole and Farmer, 1978; Howarth, et al., 1986; Bilgin et al., 1990; Bilgin et al., 2002; Aydın and Basu, 2005; Tuncdemir, 2008).

In the past, some prediction models for specific energy based on laboratory studies were developed for particular rock conditions which involved rock properties as predictors. However, literature surveys revealed that V_p and R_L values of rocks have been used less than the other properties of rocks for prediction of specific energy. This paper is concerned with correlation between V_p, R_L and specific energy values of rocks obtained from sophisticated laboratory equipment and developed a new specific energy prediction methods. This study is aimed to investigate using V_p and R_L values which can be applied easily and economically to determine specific energy value by using linear regression analyses.

In the first stage of this study, through the rock cutting tests performed in unrelieved cutting mode, the specific energy values have been calculated by two different methods. One of these methods is mechanical specific energy (SE_{Mec}) calculated from cutting forces and the other is electrical specific energy (SE_{Elec}) calculated from electrical parameters such as current and voltage values in the cutting tests. This study is different from the similar work done in the past because of these research activities. The second stage of this study was prediction of specific energy using V_p and R_L values of rocks based on statistical analysis.

1. LABORATORY STUDIES

The testing program in this study included rock cutting, sound velocity and Schmidt hardness tests. A total of 24 different natural stones including travertine, marble, and tuff were collected from different quarries around Konya, Turkey. The standard testing procedures suggested by the ISRM (International Society for Rock Mechanics) were applied for rock cutting, sound velocity, and hardness testing (Ulusay and Hudson, 2007). Cylindrical core specimens were prepared from block samples for rock mechanics tests and block samples were prepared for rock cutting tests. According to thin sections, the marble samples are composed of calcite minerals. Granoblastic texture has been created with re-crystallization of calcite minerals. The travertine samples are composed of high fossil recorder and calcite crystals. The matrix of rocks has been created completely from carbonates. The tuff samples are composed of quartz, biotite and feldspar minerals, different rock fragments and pumice grains. The groundmass of rocks is composed of volcanic glass.

1.1. Sound Velocity Tests

Sound velocity tests were performed on cylindrical core specimens NX (54 mm) in diameter which were prepared from block samples by drilling in such a way that the drilling direction was perpendicular to the plane of the thin section. And then end surfaces of the core samples were cut and polished sufficiently smooth plane to provide good coupling. V_p values of rocks were determined using the MATEST test equipment and two transducers (a transmitter and a receiver) having a frequency of 55 kHz on core samples and having both surfaces parallel to each other (Figure 1).

Figure 1. Sound velocity test equipment

During the tests, both surfaces of the core samples were applied with gel as a coupling agent in this study. After the applying gel the core samples were placed between the transducers. And the transducers were pressed to either end of the sample and the pulse transit time was recorded. V_p values were calculated by dividing the length of core to the pulse transit time as (Equation 1) The V_p values of the rocks were summarized in Table 1.

$$V_p = d/t \tag{1}$$

where V_p is the P-wave velocity in km/sec, d the length of core in cm, t the pulse transit time in sec.

1.2. Schmidt Hammer Hardness Tests

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 (Figure 2). 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 (Ulusay and Hudson, 2007) recommendations were applied for each rock type. ISRM has suggested that 20 rebound values from single impacts separated by at least a plunger diameter should be recorded, and the upper 10 values were averaged. The R_L values of the rocks were summarized in Table 1.

Figure 2. Schmidt hammer hardness test equipment

1.3. Rock Cutting Tests

Small-scale rock cutting test machine has been developed for the purpose of calculating specific energy values of rocks in the laboratory. Small-scale rock cutting test machine which is a modified Klopp shaping machine having a stroke 450 mm and a power of 4 kW was used in this study for measuring of cuttability of rocks (Figure 3). The rock cutting machine is similar to the one originally developed by Fowell and McFeat-Smith (1976), McFeat-Smith and Fowell (1977; 1979). It is suggested as a standard linear laboratory rock cutting test machine by the ISRM to measure rock cuttability. It was originally designed for core cutting in diameter of 76 mm by standard chisel tool for performance prediction of roadheaders and calculation of specific energy value in laboratory.

Rock cutting tests were carried out using standard cutting picks on blocks of rock samples with depth of cut 2 mm, cutting speed 36 cm/sec, rake angle -5°, clearance angle 5°, pick width 12.7 mm and data sampling rate 1000 Hz.

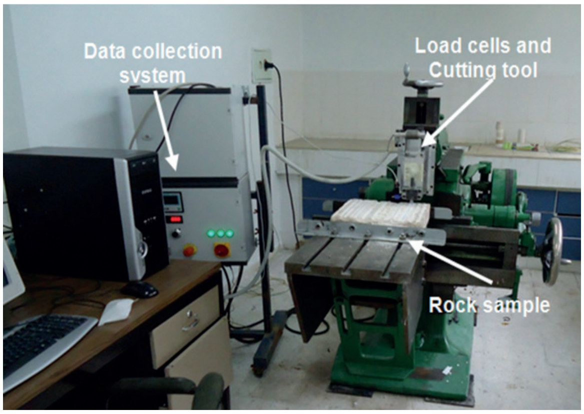


Figure 3. Small-scale rock cutting test machine

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. Block diagrams were prepared in Matlab Simulink for obtained the electrical and mechanical data during the cutting tests.

The data collection phase of this study included two parts: the electrical data was obtained from by using current and voltage transducer and the mechanical data (tool forces) was obtained from by using platform type load cell with capacity of 750 kg. Three tests were carried out on each rock sample in which cutting forces, electrical current, and voltage were recorded in unrelieved cutting mode. After each cutting test, the length of cut was measured and the rock cuttings by cut was collected and weighed for determination of specific energy. The electrical parameters in the cutting such as current and voltage values were recorded by current and voltage transducer which are located on the power line that transfers electric to the shaping machine. Additionally, during the time the chisel tool cut, the rock sample, the electrical data were recorded by using laser sensor which is located between current transducer with power line. And, when the chisel tool got through the cutting operation, the laser sensor finished to collect the electrical data. In this way, the data were obtained more sensitively and in a shorter time for data processing. Specific energy is defined as the amount of energy required to excavate unit volume of rock and it is one of the most important factors in determining the efficiency of a cutting system and optimum cutting geometry, and estimating net cutting rates. The specific energy values are calculated by using the (Equations 2 and 3).

$$SE_{Mec} = \left[\frac{(F_c * L)}{V}\right] * 10^{-1} \tag{2}$$

$$SE_{Elec} = \left[\frac{(P * h)}{V}\right] * 3{,}6 \tag{3}$$

where SE_{Mec} is the mechanical specific energy in MJ/m^3, SE_{Elec} is the electrical specific energy in MJ/m^3, F_C the average cutting force acting on the tool in kN, L the cutting length in cm, P the average net power in kW, ($P=\sqrt{3}IV\cos\phi$), I the average current during the cutting in A, V the average voltage in V, h the cutting time in sec, V the volume cut, in cm^3 (V= Y/D), Y the yield in gr, D the density in gr/cm^3. The small-scale rock cutting test results are given in Table 1.

2. EVALUATION OF THE RESULTS

The average results of rock cutting, sound velocity, Schmidt hardness, uniaxial compressive strength (UCS), and density (ρ) values of rocks 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, ρ from 1.43 to 2.77 g/cm^3, V_p from 1.88 to 6.58 km/s, R_L from 25.95 to 80.26, and the SE_{Mec} from 5.68 to 63.45 and SE_{Elec} values range from 8.22 to 60.13 MJ/m^3.

In this study, the rock cutting tests were performed using small-scale linear rock cutting test machine and amount of energy required to cut a unit volume of rock was calculated by using mechanical and electrical method for selected rock samples. In rock cutting tests, the tool forces and the energy consumption of cutting machine was measured and the specific energy values of the rocks was calculated in unrelieved cutting mode and 2 mm depth of cut. During the cutting tests, cutting forces were measured by load cells and electrical parameters such as current and voltage values were measured by current-voltage transducer. While measuring these values, they had been automatically saved on computer safely by using a digital data acquisition card. Relations between these two methods were evaluated using linear regression analysis with SPSS 15.0. The correlation between SE_{Mec} and SE_{Elec} values are given in Figure 4. The analysis results shown that very strong correlation was found between SE_{Mec} and SE_{Elec} and R^2 value is 0.977. It is concluded that there is a strong relation between these two methods which may be used to predict the rock cuttability. The data obtained in this study were evaluated with bivariate correlation and linear regression analyses. This methods were employed in determining the relation between specific energy values SE_{Mec} and SE_{Elec}, V_p and R_L values of rocks.

Results of the basic descriptive statistical analysis performed on input parameters are given in Table 2. First, the correlation matrix was obtained as a result of applying the bivariate correlation technique to the test data. Pearson's correlation coefficients (r-values) between specific energies (SE_{Mec}, SE_{Elec}), V_p and R_L values are given in Table 3. As shown in Table 3, very strong correlations were found between specific energies (SEMec, SEElec), V_p and R_L values of rocks. According to the correlation analysis, V_p and R_L are the most significant property affecting on specific energy. Correlation coefficients between specific energies, V_p and R_L are greater than 0.90 at 99% confidence level, which shows the strong relation between these three parameters.

Table 1. Rock cutting and rock mechanics tests results

Rock Code Number	Rock Type	V_p (km/s)	R_L	UCS (MPa)	ρ (g/cm^3)	SE_{Mec} (MJ/m^3)	SE_{Elec} (MJ/m^3)
1	Travertine	4.03 ±0.17	47.78 ±4.49	18.56 ±2.57	2.16	29.75	30.06
2	Travertine	4.16 ±0.28	45.63 ±2.17	27.55 ±4.06	2.26	28.48	26.15
3	Travertine	4.70 ±0.21	53.30 ±2.15	30.69 ±5.19	2.36	36.17	32.52
4	Travertine	5.22 ±0.37	61.67 ±1.87	32.23 ±4.83	2.40	43.89	39.70
5	Travertine	4.88 ±0.28	52.71 ±3.15	25.95 ±8.60	2.33	28.68	30.13
6	Travertine	5.38 ±0.14	49.16 ±0.82	28.11 ±10.46	2.39	38.95	38.70
7	Travertine	4.57 ±0.18	48.05 ±1.02	14.82 ±3.84	2.24	32.45	26.44
8	Travertine	4.31 ±0.36	45.52 ±3.42	19.22 ±6.58	2.46	31.24	25.98
9	Travertine	4.19 ±0.19	51.29 ±1.51	22.45 ±6.02	2.48	34.81	34.85
10	Travertine	4.92 ±0.08	53.93 ±1.33	28.19 ±5.47	2.52	38.65	33.10
11	Travertine	4.12 ±0.06	53.52 ±1.93	43.95 ±8.45	2.48	32.40	34.54
12	Marble	6.58 ±0.15	70.14 ±1.23	71.98 ±11.41	2.71	63.45	59.02
13	Marble	6.54 ±0.03	65.49 ±1.80	80.73 ±25.88	2.70	62.19	55.07
14	Marble	5.98 ±0.44	69.63 ±2.19	56.16 ±12.77	2.66	62.68	60.13
15	Marble	6.26 ±0.30	61.44 ±1.33	54.63 ±8.61	2.74	42.15	40.91
16	Marble	4.22 ±0.34	70.50 ±1.95	58.87 ±12.98	2.77	47.75	41.66
17	Marble	6.39 ±0.16	80.26 ±2.86	71.18 ±9.79	2.77	60.08	58.43
18	Tuff	2.63 ±0.06	47.75 ±4.73	19.67 ±4.94	1.82	17.42	17.70
19	Tuff	1.88 ±0.08	26.66 ±0.92	4.44 ±1.18	1.43	5.68	11.08
20	Tuff	2.17 ±0.03	27.27 ±0.88	7.86 ±1.27	1.50	6.15	11.65
21	Tuff	2.28 ±0.03	33.79 ±0.87	11.86 ±0.79	1.67	11.07	11.20
22	Tuff	2.23 ±0.14	28.59 ±2.13	11.23 ±2.10	1.72	9.84	11.83
23	Tuff	2.21 ±0.05	30.21 ±2.18	8.23 ±1.72	1.66	10.24	12.34
24	Tuff	2.29 ±0.04	25.95 ±2.17	9.35 ±0.36	1.57	7.27	8.22

Table 2. Basic descriptive statistics for test data

	Minimum	Maximum	Mean	Standard deviation	Number of samples (N)
SE_{Mec} (MJ/m^3)	5.68	63.45	32.560	18.475	24
SE_{Elec} (MJ/m^3)	8.22	60.13	31.309	16.138	24
V_p (km/s)	1.88	6.58	4.256	1.536	24
R_L	25.95	80.26	49.998	15.449	24

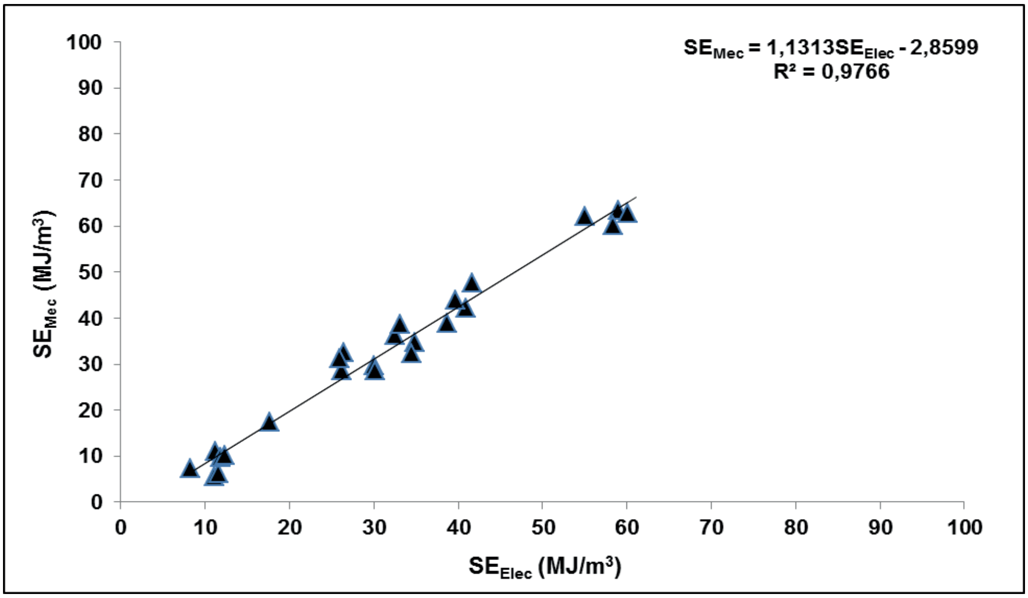


Figure 4. Relation between SE_{Mec} and SE_{Elec} obtained from unrelieved cutting mode

Table 3. Pearson's correlations between specific energies, V_p and R_L values of rocks

Independent variables		SE_{Mec}	SE_{Elec}
V_p	Pearson Correlation (*r*)	0.947**	0.939**
	Sig. (2-tailed)	0.000	0.000
	N	24	24
R_L	Pearson Correlation (*r*)	0.953**	0.947**
	Sig. (2-tailed)	0.000	0.000
	N	24	24
** Statistically significant at 0.01 level (2-tailed).			

Results of the basic descriptive statistical analysis performed on input parameters are given in Table 2. First, the correlation matrix was obtained as a result of applying the bivariate correlation technique to the test data. Pearson's correlation coefficients (r-values) between specific energies (SE_{Mec}, SE_{Elec}), V_p and R_L values are given in Table 3. As shown in Table 3, very strong correlations were found between specific energies (SE_{Mec}, SE_{Elec}), V_p and R_L values of rocks. According to the correlation analysis, V_p and R_L are the most significant property affecting on specific energy. Correlation coefficients between specific energies, V_p and R_L are greater than 0.90 at 99% confidence level, which shows the strong relation between these three parameters.

2.1. Prediction of SE_{Mec} Values

In this study, both single and multi-variable regression analyses were used to investigate relation between V_p, R_L and specific energy values of rocks and finally to develop empirical equations. The SPSS 15.0 was used for the regression analyses in order to determine the relation between the dependent variable, SE_{Mec}, SE_{Elec} and the independent variables; V_p and R_L values of rocks.

The enter method feature of SPSS 15.0 was used for the multiple linear regression analysis in order to determine the relation between the dependent variables are SE_{Mec}, SE_{Elec} and the independent variables are V_p and R_L values of rocks.

In the first stage of regression analyses, specific energy values SE_{Mec} and SE_{Elec} obtained from unrelieved cutting were analyzed with simple and multiple regression analysis techniques depending on V_p and R_L values of rocks. The models developed for the SE_{Mec} estimation are given in (Equations 4-6).

Model 1: $SE_{Mec} = 11.395V_p - 15.935$ (4)

Model 2: $SE_{Mec} = 1.140R_L - 24.441$ (5)

Model 3: $SE_{Mec} = 5.696V_p + 0.634R_L - 23.357$ (6)

In these models, R^2 values are 0.898, 0.909, and 0.954 respectively. In these models, which revealed the regression equation, the regression parameters are all considered as significant (p = 0.000), (Figure 5). According to the correlation coefficients obtained, these models predicting the SE_{Mec} value were strong and reliable. A summary of the models generated for regression analysis is given in Table 4, ANOVA results are given in Table 5 and signifiance of model components are given in Table 6.

Table 4. Summary of the generated models for linear regression analysis of SE_{Mec}

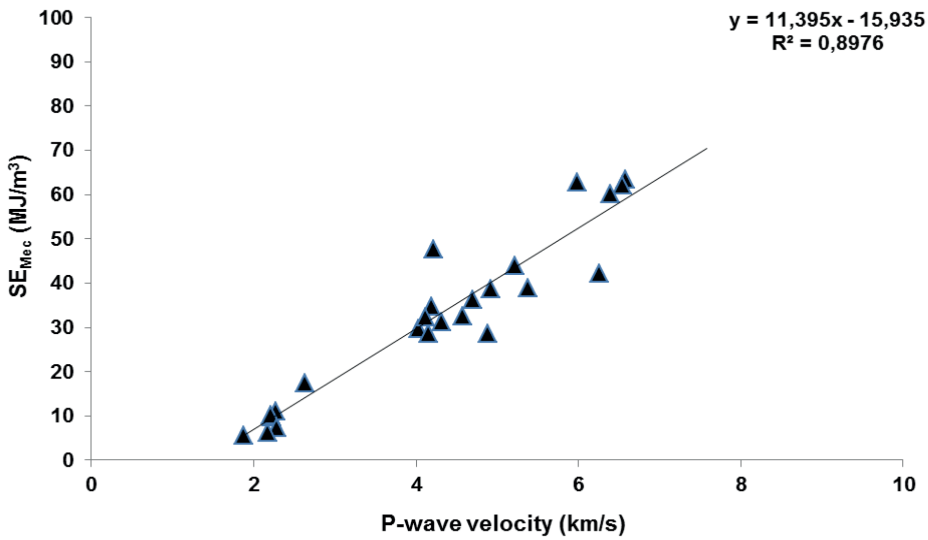
Model	Predictors	R	R^2	Adjusted R^2	Std Error of the estimate
1	V_p	0.947	0.898	0.893	6.04476
2	R_L	0.953	0.909	0.905	5.70206
3	V_p, R_L	0.977	0.954	0.949	4.15752

Table 5. ANOVA results for SE_{Mec}

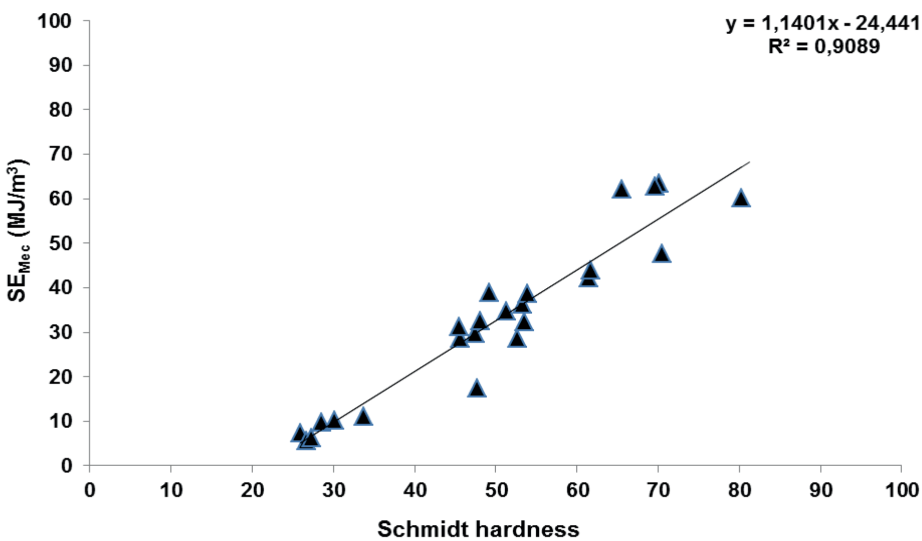
Model	Predictors	Sum of squares	df	Mean square	F	Signifiance of F	
1	V_p	regression	7046.325	1	7046.325	192.843	0.000
		residual	803.861	22	36.539		
		total	7850.186	23	-		
2	R_L	regression	7134.888	1	7134.888	219.444	0.000
		residual	715.297	22	32.514		
		total	7850.186	23	-		
3	V_p, R_L	regression	7487.202	2	3743.601	216.582	0.000
		residual	362.984	21	17.285		
		total	7850.186	23	-		

Table 6. Signifiance of model components and confidince intervals for SE_{Mec}

Regression models	Unstandardized coefficients	Standardized coefficients	t	Significance of t	95% Confidence interval for B		
	B	Std. error	Beta			Lower bound	Upper bound
1 (Constant)	-15.935	3.704	-	-4.302	0.000	-23.616	-8.254
V_p	11.395	0.821	0.947	13.887	0.000	9.693	13.097
2 (Constant)	-24.441	4.020	-	-6.080	0.000	-32.778	-16.104
R_L	1.140	0.077	0.953	14.814	0.000	0.980	1.300
3 (Constant)	-23.357	2.941	-	-7.942	0.000	-29.474	-17.241
V_p	5.696	1.262	0.474	4.515	0.000	3.072	8.320
R_L	0.634	0.125	0.530	5.050	0.000	0.373	0.894



(a)



(b)

Figure 5. Prediction of SE_{Mec} using P-wave velocity (a) and Schmidt hardness (b) values of rocks

2.2. Prediction of SE_{Elec} Values of Rocks

The models developed for the SE_{Elec} estimation are given in (Equations 7-9). In these models, R^2 values are 0.882, 0.898, and 0.904 respectively. In these models, which revealed the regression equation, the regression parameters all significant ($p = 0.000$), (Figure 6). According to the correlation coefficients obtained, these models predicting the SE_{Elec} value were strong and reliable. A summary of the models generated for enter regression analysis is given in Table 7, ANOVA results are given in Table 8 and signifiance of model components are given in Table 9.

Model 4: $SE1_{Elec} = 9.866V_p - 10.678$ (7)

Model 5: $SE1_{Elec} = 0.990R_L - 18.171$ (8)

Model 6: $SE1_{Elec} = 4.816V_p + 0.561R_L - 17.255$ (9)

Table 7. Summary of the generated models for linear regression analysis of SE_{Elec}

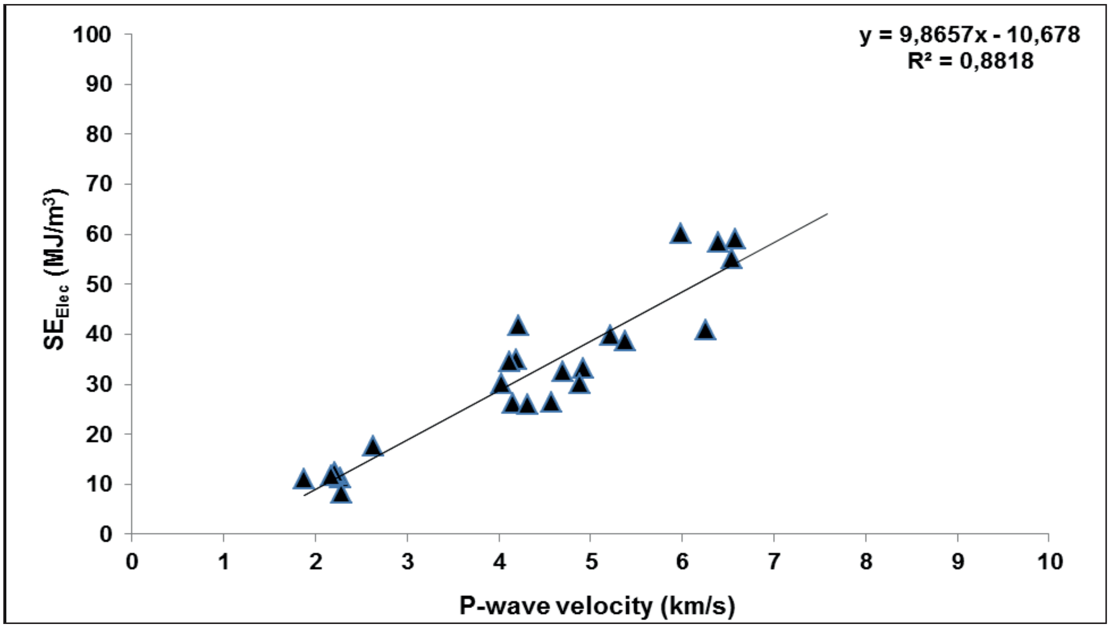
Model	Predictors	R	R^2	Adjusted R^2	Std Error of the estimate
4	V_p	0.939	0.882	0.876	5.67319
5	R_L	0.947	0.898	0.893	5.28167
6	V_p, R_L	0.969	0.940	0.934	4.15112

Table 8. ANOVA results for SE_{Elec}

Model	Predictors	Sum of squares	df	Mean square	F	Signifiance of F	
4	V_p	regression	5281.914	1	5281.914	164.111	0.000
		residual	708.072	22	32.185		
		total	5989.986	23	-		
5	R_L	regression	5376.274	1	5376.274	192.725	0.000
		residual	613.713	22	27.896		
		total	5989.986	23	-		
6	V_p, R_L	regression	5628.101	2	2814.051	163.298	0.000
		residual	361.885	21	17.233		
		total	5989.986	23	-		

Table 9. Signifiance of model components and confidince intervals for SE_{Elec}

Regression models	Unstandardized coefficients	Standardized coefficients	t	Significance of t	95% Confidence interval for B		
	B	Std. error	Beta			Lower bound	Upper bound
4 (Constant)	-10.678	3.476	-	-3.072	0.000	-17.887	3.469
V_p	9.866	0.770	0.939	12.811	0.000	8.269	11.463
5 (Constant)	-18.171	3.724	-	-4.880	0.000	-25.894	-10.449
R_L	0.990	0.071	0.947	13.883	0.000	0.842	1.137
6 (Constant)	-17.255	2.936	-	-5.876	0.000	-23.362	-11.148
V_p	4.816	1.260	0.458	3.823	0.000	2.196	7.436
R_L	0.561	0.125	0.537	4.482	0.000	0.301	0.822



a

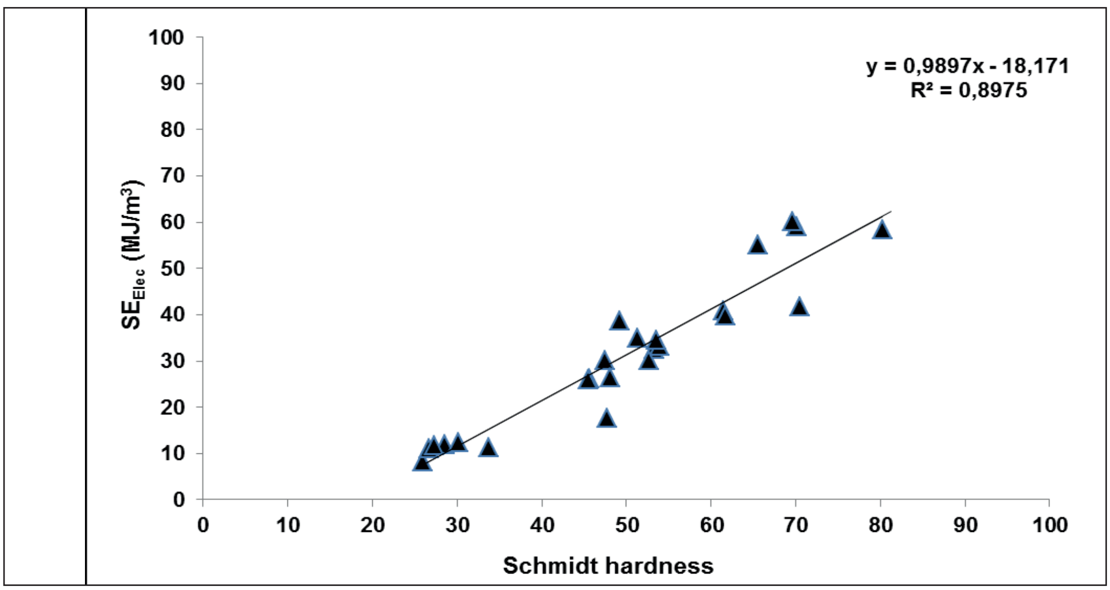


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Figure 6. Prediction of SE_{Elec} using P-wave velocity (a) and Schmidt hardness (b) values of rocks

2.3. Model Results and Performances

In this study, linear regression analyses were constructed to predict the SE_{Mec} and SE_{Elec} values from R_L and V_p values of rocks. In this section, some performance indices such as root mean square error (RMSE) and variance account for VAF were calculated and compared. Every specific energy values were evaluated separately with R_L and V_p values by using linear regression method. Approximately, 6 different predictive models were carried out. To justify the accuracy of the developed equations, F-test was also applied with 99% confidence level to three of relations and they revealed statistically significant correlations.

In order to check and compare the prediction performances of linear regression based models, the variance account for VAF (Equation 10) and the root mean square error RMSE (Equation 11) performance indexes were used:

Table 10. Results of the statistical performance analysis for generated models

Model	Specific energy values (MJ/m^3)	Predictors	VAF (%)	RMSE	Correlation coefficient (r)	Standard error of estimation
1	SE_{Mec}	R_L	97.24	5.46	0.953	5.702
2	SE_{Mec}	V_p	96.91	5.79	0.947	6.044
3	SE_{Mec}	R_L, V_p	98.58	3.89	0.977	4.158
4	SE_{Elec}	R_L	97.46	5.06	0.947	5.282
5	SE_{Elec}	V_p	97.08	5.43	0.939	5.673
6	SE_{Elec}	R_L, V_p	98.49	3.88	0.969	4.151

$$\mathrm{VAF}=\left(1-\frac{\left(\mathrm{var}\left(o_i-t_i\right)\right)}{\mathrm{var}\left(o_i\right)}\right)*100 \quad (10)$$

$$\mathrm{RMSE}=\sqrt{\frac{1}{\mathrm{N}}\sum_{i=1}^{N}\left(o_i-t_i\right)^2} \quad (11)$$

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

The interpretation of the above performance indexes are as follows: the higher the VAF, the better the model performs. For example, a VAF of 100% means that the measured output has been predicted exactly. VAF = 0 means that the model performs as poorly as a predictor using simply the mean value of the data. The lower the RMSE, the better the model performs (Gokceoglu, 2002; Gokceoglu and Zorlu, 2004). Contrary to VAF, RMSE also accounts for a bias in the model, i.e. an offset between the measured and predicted data. Theoretically, the excellent prediction capacities are 100% for VAF, 0 for RMSE and 1 for r.

When the VAF and RMSE performance indexes are considered for each predictive model (Table 10), it's clear that the developed linear regression models employing R_L and V_p values are found to be reliable and accurate models. As utilizing the results given in Table 10, it is too difficult to select the best model within these 6 models for the specific energy prediction. These models have a lower standard error of estimate and a higher correlation coefficient (r). Therefore, it can be said that linear regression methods are the best prediction models for the estimation of SE_{Mec} and SE_{Elec} values from R_L and V_p values for this study.

CONCLUSIONS AND SUGGESTIONS

In this study, rock mechanics and rock cutting tests were carried out on twenty four different rock samples. According to these test results, marble samples were found to be tougher and stronger than travertine and tuff samples. By using the rock properties such as V_P and R_L obtained from these tests, simple and multiple regressions method was used to predict the SE_{Mec} and SE_{Elec} values of the rocks.

Firstly, the correlation between SE_{Mec} and SE_{Elec} values of rocks was determined. According to this, the correlation between SE_{Mec} and SE_{Elec} was evaluated and R^2 value was found as 0.977.

In this study, the experimental results and the prediction model analyses show that the specific energy obtained by using small-scale rock cutting machine can be measured reliably from electrical and mechanical methods.

And then, V_p and R_L values have been used as predictors for SE_{Mec} and SE_{Elec} values based on simple and multiple regressions methods. According to simple regression method, R^2 values were found 0.898, 0.909 between V_p, SE_{Mec} and SE_{Elec} values respectively. In the same regression method, R^2 values were found 0.909, 0.898 between R_L, SE_{Mec} and SE_{Elec} values respectively.

According to multiple regression method using together V_p and R_L values, R2 values were found 0.954 for SEMec and 0.940 for SEElec values respectively.

In the regression analysis these rock properties were also found statistically significant in estimating specific energy both individually and together, depending on the results of linear regression analysis, ANOVA and Student's t-tests, and R^2 values. R_L and V_p values were in positive correlations statistically significant with specific energies at 99% confidence level. The proposed simple and multiple regression-based models performed best when VAF changed between 96.91-98.58, RMSE changed between 3.88-5.79, correlation coefficient changed between 0.939-0.977 and standard error of estimation changed between 4.151-6.044 are considered. The statistical tests showed that both simple and multiple regression models were valid. These models can be reliably used for prediction of specific energy especially for the preliminary studies.

It was recommended that the predicting specific energy values by using these rock properties will be also easier and more practical because the two rock mechanics tests mentioned above can be performed practically both in laboratory and on field.

Rock cutting tests are expensive and time-consuming and also they require complex laboratory facilities using high quality samples in the tests. Therefore, it is important to predict the specific energy using some easy and practical rock mechanics tests without the need to use a rock cutting test equipment.

For the practitioner, each experiment means high cost and time consumption. Therefore, in practice, it is quite important to develop a model that best predicts with the fewest parameters.

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