
**ROCK
FRACTURE**

Estimation of Specific Cutting Energy and Noise Level in Circular Saw Cutting Process by Leeb, Shore and Schmidt Hardness Values of Rocks

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Abstract—In this study, the rebound hardness values (Shore–Schmidt–Leeb) were calculated for 12 different carbonate rocks using three different devices. The relationships between hardness values and rock cuttability properties (specific cutting energy and noise level) were investigated by simple and multiple regression analyses. It is determined that the Leeb hardness of the rocks can be an alternative to the Shore hardness and Schmidt hardness and that both the specific cutting energy and the noise level can be estimated with the Leeb hardness values.

Keywords: Natural stone, Shore hardness, Schmidt hardness, Leeb hardness, specific cutting energy, noise level.

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INTRODUCTION

Slab/strip production from natural stone blocks has an important place in natural stone processing. The success of this process directly affects the success and performance of the sizing, polishing, surface treatments, etc. Therefore, the cutting processes of natural stone blocks should be carried out most appropriately, taking into account the production flow chart. For this purpose, various cutting methods and machines suitable for these methods are used for the production of slabs/strips from natural stone blocks. Circular saw cutting machines are also very widely used machines for slab/strip production [1].

The cutting process with diamond socket circular saws is a complex mechanism consisting of many parameters. The circumferential speed, feed rate, cutting depth, cutting direction, cooling water flow rate and socket structure of the circular saw directly affect the cutting efficiency [2]. In addition to the machine and cutting conditions, the physical and mechanical properties of the stone to be cut and the hard mineral content also play an important role in the cutting efficiency. In particular, the hardness values that change depending on the mineral content of the rocks directly affect the cutting process.

One of the characteristics of rock-forming minerals is hardness, which is measured as the resistance of a mineral's surface to abrasion or scratching. Since minerals make up rocks, the percentage of those minerals that have a low or high hardness value determines the hardness of the rock [3]. The engineering properties of rocks have been identified and evaluated using a variety of test procedures. Indirect methods among these methods are relatively easy to apply, cheap, and test methods with fast results [4]. Methods for determining the surface hardness of rocks are also included in this group.

The hardness of rocks is not used as a direct input parameter in engineering projects, they are indirectly used to estimate mechanical properties or to compare with other materials [5]. In many studies, the surface hardness values of the rocks have been used as important parameters in the estimation of the strength, drillability and cuttability of rocks due to their inexpensive, easy, and practical properties, as they represent the internal texture of the rock [2].

There are three methods used to determine the rock hardness. These include the indentation hardness tests (Brinell, Rockwell, Vickers, Knoop), the dynamic or rebound hardness tests (Shore, Schmidt), and the scratching hardness test (Mohs) [6, 7]. The rebound of an object hitting the surface of a rock or falling on it is measured in terms of rebound hardness. The amount of impact energy lost due to rock fracture and plastic deformation at the impact point determines how much recoil occurs [8]. Due to their ease of use and affordability, the Shore C-2 Scleroscope (HSC) and the L-type Schmidt hammer (HSL) have long been the most popular rebound hardness measurement techniques used to characterize rocks. The Leeb hardness method (HL), however, stands out for its accuracy and usefulness [7]. The Leeb hardness, also referred to as Equotip Leeb hardness, was proposed in the middle of the 1970s for use in measuring the surface hardness of metallic materials [9]. However, it is also being used more frequently to test materials like rocks and stones [10]. With a wider hardness scale and different test directions, this technique was created to provide a faster, more practical, and practical hardness test [11].

Determination of rock cuttability properties is very difficult due to the need for large-size samples, the difficulty of providing optimum test conditions, and the cost and long time it takes. Numerous studies have been conducted in the literature to optimize the cutting of natural stone and estimate energy and production amounts in light of these costs [12–23].

Within the scope of this study, it is aimed to estimate the specific cutting energy and noise level from rock cuttability parameters with rock hardness values. Twelve different rocks were examined to determine their Shore–Schmidt–Leeb rebound hardness values. The relationships between the three different hardness values determined and the rock cuttability properties, the specific cutting energy, and the noise level were examined by simple and multiple regression analyses and it was seen that the rock hardness values and the cuttability properties could be predicted successfully.

1. CUTTABILITY PROPERTIES

When the studies in the literature are examined, the basic cuttability properties, such as cutting force (normal and tangential), specific wear, specific cutting energy, and noise level are all taken into consideration.

The amount of energy needed to cut a unit volume of rock is known as specific cutting energy. Maximum cutting speed and minimal specific cutting energy are necessary for an effective cutting process. The point where these conditions are met is when the cutting process is the most economical. As a result, cutting efficiency is measured and evaluated using the specific cutting energy [17]. Although importance is given to increasing the amount of production per unit time in industrial applications, the energy consumption for this process is relatively ignored. However, the capability of the cutting process to be economically viable depends on maximizing output while minimizing energy consumption per unit of time [13].

The intensity of the noise generated during the cutting process of natural stone with circular saws varies depending on the physical and mechanical properties of the cut natural stone. If there is no problem with the cutting machine and cutting tool, the high or low noise level measured during cutting can give an idea about the cutting process [19]. Therefore, it is important to determine the cuttability characteristics such as specific cutting energy and noise level during cutting in terms of cutting efficiency.

2. MATERIALS AND METHODS

Within the scope of the study, 12 different natural stones of carbonate origin were obtained from different regions of Turkey, and their geological origins and production sites are given in Table 1. First of all, the physical and mechanical properties of the supplied natural stones and their hardness (Shore–Schmidt–Leeb) were determined by using three different hardness measurement devices. Then, cutting tests were carried out under the same conditions, and the specific cutting energy and the noise level in the environment during cutting were measured and recorded.

3. EXPERIMENTAL STUDIES

3.1. Mineralogical Analysis

Within the scope of the study, firstly, thin sections were prepared to establish the mineralogical analysis of the rocks. The carbonate origin rocks used in the study were grouped as beige, marble, travertine and limestones. It was determined that the beige group rocks with sample codes B-1, B-2, B-3, B-4 and B-5 were composed of fine-medium grained micrite–sparitic cement and intracalcite+calcite minerals. This analysis revealed that carbonate origin rocks used in the study were grouped as beige, marble, travertine and limestone (Fig. 1). It was determined that the beige group rocks (B-1, B-2, B-3, B-4, B-5) were composed of fine-medium grained micrite-sparitic cement and intracalcite+calcite minerals. Fractures and cracks in these rocks were filled by secondary calcite minerals. The marble group rocks (M-1, M-2 and M-3) were composed of medium-coarse crystalline calcites without micro-fractures. Travertines and limestones are composed of fine-medium grained calcite minerals. In addition, melting cavities were observed in rocks T-1, T-2, K-1 and K-2.

Table 1. Rocks used in this study

Sample name	Sample code	Geological origin	Location	Ref.
Ağlasun Beige	B-1	Sedimentary	Burdur	[25]
Tundra Gray	B-2	Sedimentary	Afyon	[25]
Burdur Beige	B-3	Sedimentary	Burdur	[25]
Karia Beige	B-4	Sedimentary	Burdur	[24]
Hacılar Beige	B-5	Sedimentary	Burdur	[24]
Marmara Gray	M-1	Metamorphic	Balıkesir	[25]
Tiger Skin	M-2	Metamorphic	Afyon	[25]
Muğla White	M-3	Metamorphic	Muğla	[25]
Bucak Travertine	T-1	Sedimentary	Burdur	[25]
Denizli Travertine	T-2	Sedimentary	Denizli	[25]
Simena Limra	K-1	Sedimentary	Antalya	[24]
Calcareous tuff	K-2	Sedimentary	Denizli	[24]

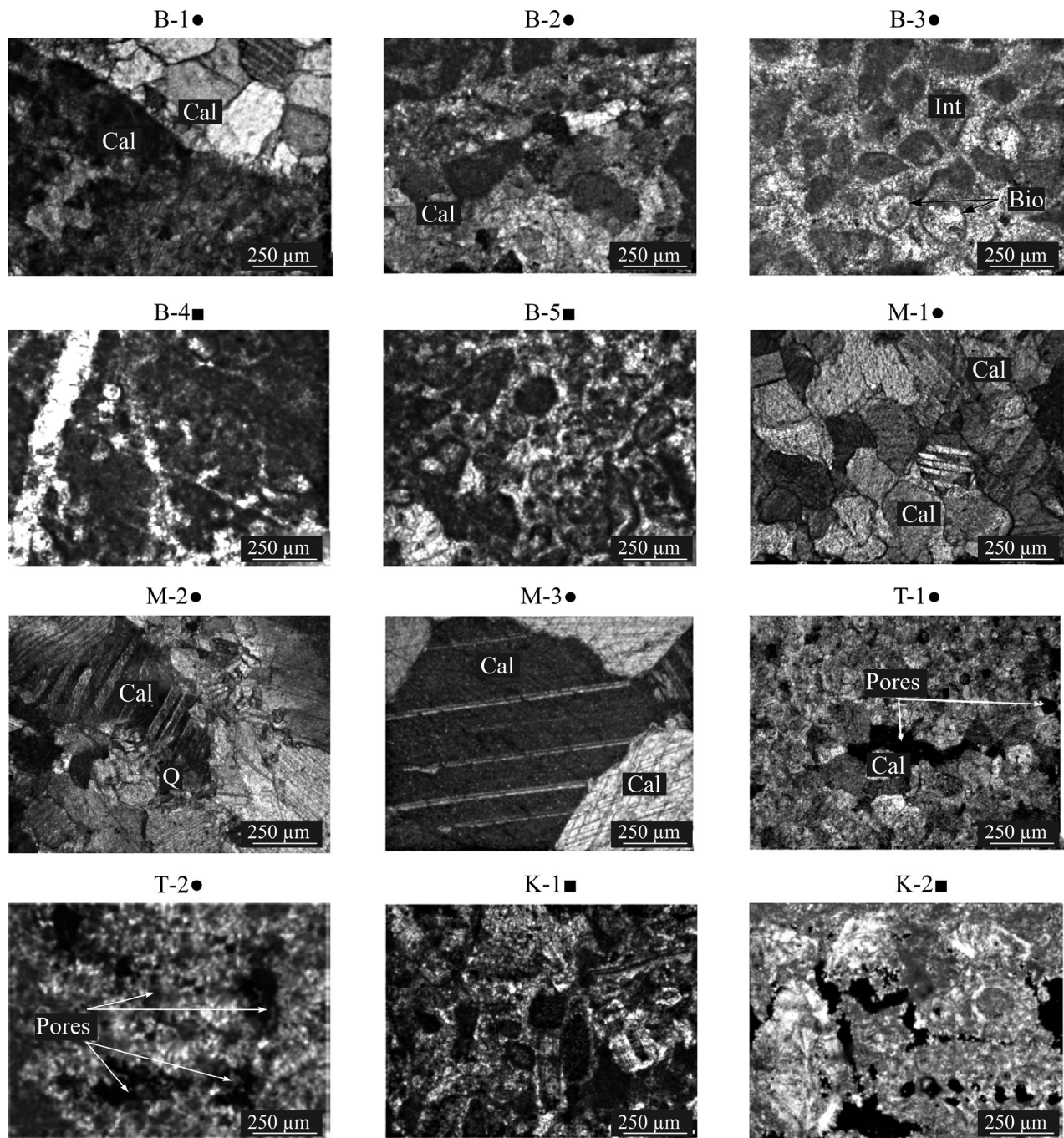


Fig. 1. Thin section images of natural stone: Cal—calcite, Q—quartz, Int—intraclast, Bio—bioclast (■ [24] ● [25]).

3.2. Physical and Mechanical Properties of Rocks

The physical properties of the natural stones used in the study were tested for unit volume weight (UVW) [26], ultrasound seismic velocity V_p [27] and Böhme abrasion resistance (BAR) [28]. From the mechanical properties of the rocks, uniaxial compressive strength (UCS) [29], flexural strength (FS) [30], Brazilian tensile strength (BTS) [31] and point load index ($I_{s(50)}$) [32] tests were carried out (Table 2). The experiments were conducted in Süleyman Demirel University's Natural Stones Technology Laboratory, and the determined physical and mechanical properties of the rocks are given in Table 2.

Table 2. Physical and mechanical properties of rocks

Sample code	UVW, g/cm ³	V_p , m/s	BAR, cm ³ /50 cm ²	UCS, MPa	BTS, MPa	$I_{s(50)}$, MPa	Ref.
B-1	2.682	5521	13.0	109.8	5.6	4.66	[25]
B-2	2.652	5868	14.5	145.5	7.0	5.39	[25]
B-3	2.677	5705	11.6	129.9	8.0	5.33	[25]
B-4	2.688	5849	17.0	130.6	8.1	3.38	[24]
B-5	2.690	5997	15.1	92.3	6.7	6.51	[24]
M-1	2.706	3577	21.3	74.6	6.0	3.26	[25]
M-2	2.710	4720	29.8	70.3	5.4	3.46	[25]
M-3	2.715	4408	24.0	85.7	4.7	3.52	[25]
T-1	2.485	4257	28.0	60.7	4.4	3.99	[25]
T-2	2.384	4425	29.0	62.5	3.4	3.58	[25]
K-1	2.415	4362	40.8	34.9	3.9	3.21	[24]
K-2	2.013	3635	40.9	18.3	2.1	1.51	[24]

3.3. Hardness of Rocks

The C-2 type Shore scleroscope, L-type Schmidt hammer, and Leeb hardness test device were used to measure the surface hardness of natural stones, respectively. Shore hardness and Schmidt hammer hardness measurements of the rocks were carried out in Süleyman Demirel University Natural Stone Technology Laboratory, Leeb hardness measurements were performed in Kırşehir Ahi Evran University Kaman Vocational School Natural Stone Analysis Laboratory.

Shore hardness tests (SH) were carried out in accordance with standard [33] recommended in [34]; Schmidt hardness tests (SCH) were based on standards [31] given in [24, 25]. Since there is no accepted standard for determining the Leeb hardness of rocks, measurements were carried out on the same samples, taking into account the standard suggested by [33] for Shore hardness due to the similarity in the test methodology. For Leeb hardness values, 20 impacts were made on each sample and the arithmetic average of these 20 impacts was calculated. Taken and measured hardness values of natural stone samples are given in Table 3.

3.4. Cuttability Properties of Rocks

Cutting tests were performed on prismatic test specimens with the dimensions of 50×100×200 mm to determine the specific cutting energy and noise level values that occur during cutting, which are the cuttability properties of rocks. During the cutting tests, the cutting depth (20 mm), the circumferential speed of the saw (60 m/s), and the feed rate (0.5 m/min) parameters were kept constant.

Table 3. Hardness of rocks

Sample code	SH	SCH	HL
B-1	56.6 [25]	46.0 [25]	599.7
B-2	53.6 [25]	52.0 [25]	638.4
B-3	62.6 [25]	49.6 [25]	644.8
B-4	61.5 [24]	42.3 [24]	648.0
B-5	63.0 [24]	49.0 [24]	625.2
M-1	41.6 [25]	43.0 [25]	533.5
M-2	43.5 [25]	38.5 [25]	582.6
M-3	47.5 [25]	39.0 [25]	581.0
T-1	36.7 [25]	34.6 [25]	528.3
T-2	43.9 [25]	32.6 [25]	512.3
K-1	31.5 [24]	23.4 [24]	498.3
K-2	14.6 [24]	23.9 [24]	421.5

To calculate the specific cutting energy values, firstly instantaneous power values were obtained, and then the power consumption-time of cutting diagram was drawn (Fig. 3). In Fig. 3, the power drawn during the idle operation of the machine and the power values drawn during the full cutting were determined. The difference between these two values gives the net power consumed for the cutting:

$$P_{\text{net}} = P_k - P_b, \quad (1)$$

where P_{net} is net power consumption for cutting, W; P_k and P_b are the powers consumed in full cutting load and in idle mode, respectively, W.

The net power and specific cutting energy values consumed during cutting were determined according to [25]. Specific cutting energy values were calculated as follows:

$$SCE = \frac{P_{\text{net}}}{0.1666 h W_s V_i}, \quad (2)$$

where SCE is specific cutting energy, J/mm^3 ; h is the cutting depth, mm; W_s is the socket width, mm; V_i is cutting advance speed, cm/min.

Not all the energy consumed is used for rock cutting. Some of this energy is spent for heating noise generation. The noise level in rock cutting process varies depending on machine operating parameters and rock properties. Since the machine parameters are kept constant within the scope of the study, the change in the noise level is due to the properties of the rock [35].

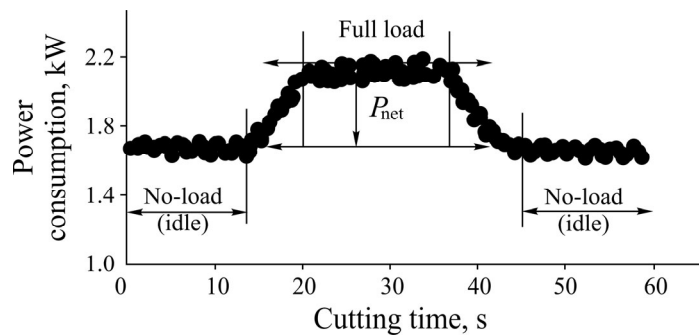


Fig. 3. Power consumption versus cutting time.

Table 4. Cuttability parameters of rocks

Sample code	Specific cutting energy, J/mm^3	Noise level, dB
B-1	0.881*	94.43*
B-2	0.976*	95.03*
B-3	1.108*	94.57*
B-4	0.904	94.22
B-5	0.858	93.88
M-1	0.701*	94.13*
M-2	0.691*	92.75*
M-3	0.735*	95.06*
T-1	0.519*	93.84*
T-2	0.482*	93.20*
K-1	0.375	91.00
K-2	0.152	90.80

*[25].

In this study, CEM DT-8852 sound level measuring device was used during rock cutting operations. During the measurements, the distance between the cutting area and the noise level measuring device was kept constant as 2 m. Noise levels are measured in the dB band, which is sensitive to machine noise. During the cutting process, the noise level measuring device was set to receive 5 data per second and the data was saved to the computer with the software of the device by connecting to the computer [25]. The specific cutting energy and noise level values taken and calculated after the cutting tests are given in Table 4.

4. RESULTS AND DISCUSSION

As a result of the data obtained in this part of the study, first of all, the relations between the hardness values of the rocks measured by different devices and methods were examined. Afterwards, the relationships between the three different hardness values and the cuttability properties of the rocks, the specific cutting energy, and the noise level values were examined by simple and multiple regression analyses. In addition to examining the specified relations, the relations between the other physical and mechanical properties of the rocks and the cuttability properties were examined using the SPSS 2021 program and the general relation matrix created is given in Table 5. Multiple regression analyses were performed using the SPSS 2021 program, and physical and mechanical properties and cuttability properties of the rocks were tried to be estimated.

4.1. Relationships Between Leeb–Shore–Schmidt Hardness Values

The surface hardness of the rocks can be used to predict the physical and mechanical properties as well as the important properties in terms of excavation mechanics such as cuttability and drillability due to the fact that it is cheap and practically applicable.

The surface hardness is important in predicting the physical and mechanical rock properties. Surface hardness of rocks such as Shore and Schmidt hammer has been used in many scientific studies because they represent the internal texture of the rocks. In recent years, the use of Leeb hardness (HL) instrument has become increasingly common in determining the surface hardness of rocks, which is easy to read due to its digital display, it provides data on a large scale, makes more precise measurements than other methods, and is relatively economical. Twelve different rocks' Shore, Schmidt, and Leeb hardness values were predicted in this study and the relationships between Leeb hardness (HL) and Shore (SH) and Schmidt hardness (SCH) values were examined by simple regression analysis.

Simple statistical regression method helped to obtain the relationships between Leeb–Shore–Schmidt hardness values for natural stone (Fig. 4). As a result of high correlation values, it is found that Leeb hardness can be used as an alternative to Shore and Schmidt hardness values for carbonate rocks.

4.2. Relationship Between Specific Cutting Energy and Leeb–Shore–Schmidt Hardness Values

In natural stone processing plants, determining the specific cutting energy from the cuttability characteristics of rocks before cutting operations is important for an economical and efficient cutting. Tests to directly determine the cuttability of rocks require special testing equipment, large numbers of samples, and are complex, expensive, and time-consuming.

In this study, since they are easily applicable, the relations between rock surface hardness values and specific cutting energy values were examined with simple regression analyses, and specific cutting energy values were tried to be estimated (Fig. 5).

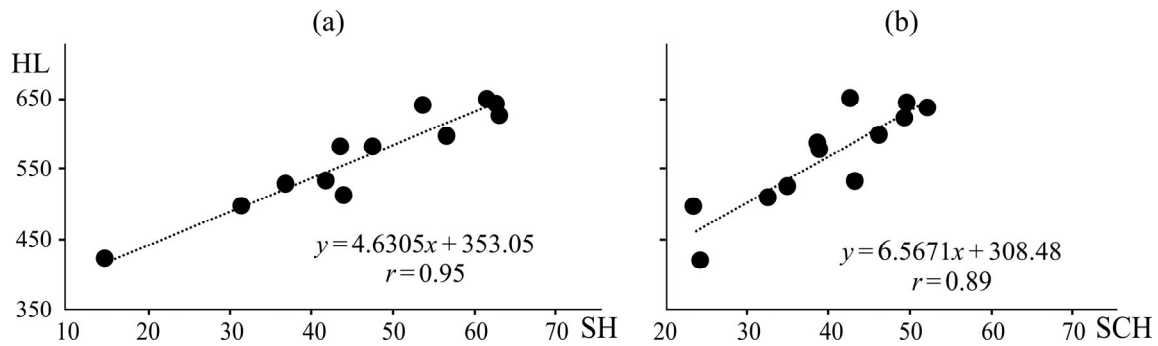


Fig. 4. Relationship between Leeb hardness value (HL) and (a) Shore (SH) and (b) Schmidt (SCH) hardness values.

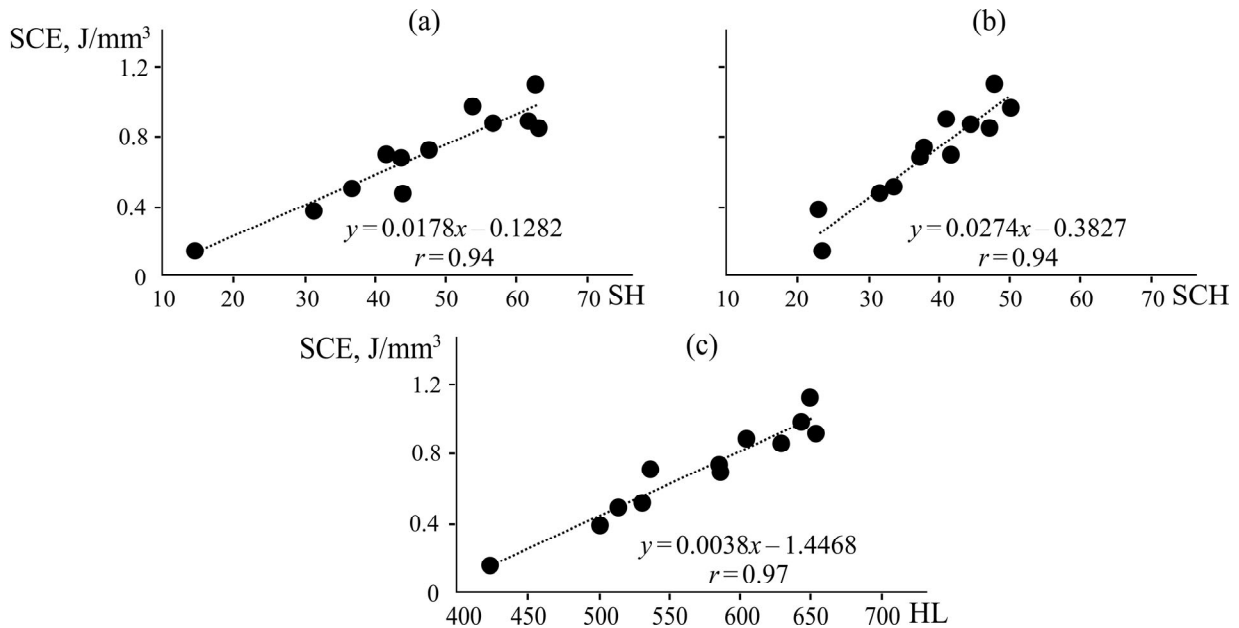


Fig. 5. Relationships between specific cutting energy and (a) Shore (SH), (b) Schmidt (SCH) and (c) Leeb (HL) hardness values.

Highly correlated relationships were obtained between the specific cutting energy values and the hardness values of rocks determined by different test devices and methods. The highest correlation ($r = 0.97$) was obtained between HL and SCE values. This shows that HL hardness value can be used as a rock hardness determination method and also, HL hardness can be used reliably instead of SH and SCH hardness in estimating SCE.

4.3. Relationships Between Noise Level and Leeb–Shore–Schmidt Hardness Values

One of the cutting efficiency measurement parameters in natural stone processing is the noise level occurring in the environment during cutting. However, noise level is a significant physical risk factor in natural stone processing facilities, just like it is in many other industries. For this reason, it is very important in terms of occupational health and safety to determine the rock properties and the noise level that may occur during cutting before the natural stone cutting operations and to take protective measures according to the value to be obtained.

In the study, the relationships between the noise level that occurred during cutting and the surface hardness values of rocks were analysed by simple regression method (Fig. 6). It was determined that noise level values depended linearly on all three hardness values and could be better predicted with SCH hardness values ($r = 0.86$).

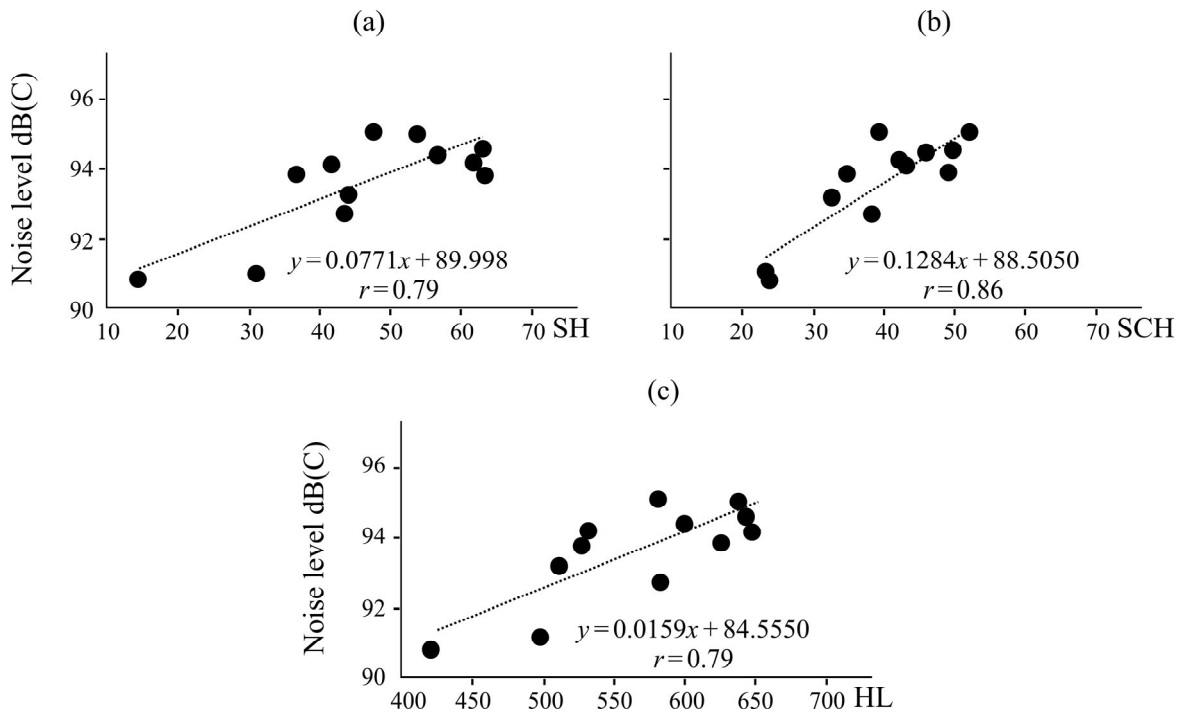


Fig. 6. Relationships between noise level and (a) Shore (SH), (b) Schmidt (SCH) and (c) Leeb (HL) hardness values.

Table 5. Values of correlation coefficients (r)

Cuttability parameters	UVW, g/cm	V_p , m/s	BAR, cm ³ /50 cm ²	UCS, MPa	BTS, MPa	I_{S50} , MPa	SH	SCH	HL
SCE	0.851	0.803	-0.945	0.951	0.932	0.762	0.936	0.944	0.965
NL	0.788	0.528	-0.882	0.837	0.698	0.622	0.785	0.858	0.786

4.4. Relationships Between Cuttability Properties of Rock and Its Physical and Mechanical Properties

To determine the relationship between three different hardness values, other physical and mechanical properties of rocks, specific cutting energy and noise level values, the relationship matrix was created using the SPSS 2021 program (Table 5). Specific cutting energy values were found to have a higher correlation with physical and mechanical properties than noise level values. The reason for this is thought to be the insufficient sensitivity of a noise measuring device. It is believed that the correlation values will increase with the data to be obtained from noise level measurement devices that can measure the sound in the cutting environment more precisely.

4.5. Correlation of Mineralogical Properties with Hardness and Cuttability Values

Beige group rocks are more massive than other rock groups because they are composed of fine-grained minerals (micrite–sparite–calcite) and the cracks are filled by secondary minerals and they do not contain melting spaces. Therefore, the hardness values of the beige group rocks were higher than the other rock groups. Due to the hardening of the rock structure, the fragmentation process during cutting operations becomes difficult. In this case, the specific shear energy values of beige group rocks were higher than other rock groups. The hardness values of the marble group rocks are lower than the beige group rocks due to their coarse-medium grain. Accordingly, the specific cutting energy values consumed during cutting were low. Travertine and limestones have lower hardness values and the lowest specific cutting energy values, because they are formed in coarse-grained calcite minerals and do not contain melting gaps compared to beige group and marble group rocks.

4.6. Multiple Regression Analysis

Multiple regression analysis with two independent variables was used in this study, the models with the highest correlation values are shown below:

Model	<i>r</i>
$SCE = 0.002 \cdot HL - 0.011 \cdot BAR - 0.344$	0.985
$SCE = 0.002 \cdot HL + 0.012 \cdot SCH - 1.107$	0.984
$NL = 0.012 \cdot UCS + 0.082 \cdot SCH + 89.277$	0.870
$NL = 0.001 \cdot HL - 0.119 \cdot BAR + 96.014$	0.882

The Leeb hardness (HL) and Böhme abrasion resistance (BAR) values of rocks have high correlation coefficients in estimating both specific cutting energy and noise level. In other words, hardness and wear resistance of rocks are important parameters that affect the cuttability properties.

CONCLUSIONS

In excavation mechanics, parameters depending on the excavation equipment can be changed, but it is not possible to change the properties of the rock. For this reason, the determination of rock properties before excavation operations is important for obtaining high excavation efficiency. Determining the cuttability of rocks within the rock properties is important in terms of excavation mechanics. However, the tests used to specify the cuttability of rocks are very complex, pricey, and time-consuming methods in terms of the need for special test equipment and large numbers of samples.

For these reasons, the cuttability of rocks is estimated by the rock properties determined by test methods that are easier to determine/measure, as in the prediction of many physical and mechanical properties. One of these rock properties is the hardness value of the rocks. Surface hardness of rocks such as Shore and Schmidt hammer is widely used in estimating the strength, drillability, and cuttability of rocks because of their ability to represent the internal textures of rocks, being inexpensive, easy, and practical. In recent years, while determining the surface hardness of rocks, the use of Leeb hardness (HL) instrument has become increasingly common, which is easy to read due to its digital nature, provides data on a large scale, is more sensitive than other methods, and is relatively economical.

In this study, 12 different rocks' rebound hardness values (Shore–Schmidt–Leeb) were calculated using three different devices. First of all, the relationships between the hardness values of the rocks measured by different methods were examined. Afterwards, the relationships between hardness values and rock cuttability properties (specific cutting energy and noise level) were investigated by simple and multiple regression analyses.

As a result of the analysis, relationships with high correlation coefficients were determined between Leeb hardness and both Shore and Schmidt hardness. As a result of the correlation values obtained, it is thought that Leeb hardness can be used as an alternative to both hardness values on carbonate rocks.

Relationships with high correlation coefficients were determined between Leeb, Shore and Schmidt hardness values. It is found that Leeb hardness can be used as an alternative to Shore and Schmidt hardness values for carbonate rocks.

Highly correlated relationships were obtained between the specific cutting energy values and the hardness values of rocks. It is determined that Leeb hardness values can be used reliably in estimating both the specific cutting energy and the noise level.

It is thought that Leeb hardness can be used to predict the cuttability of carbonate rocks economically and effectively. The results of this study can be helpful for a potential investor to select the engineering equipment and organize the work.

REFERENCES

1. Bayram, F., Estimation of Unit Energy from Cutting and Environment Parameters in Circular Cutting of Natural Stones, *AKU-J, Sci. Eng.*, 2020, vol. 20, pp. 340–347.
2. Ekincioğlu, G., Güney, A., Akbay, D., and Altındağ, R., Estimation of Hourly Slab Productions of Circular Saw Cutting Machines by Artificial Neural Network (YSA) and Regression Analysis (RA) Based on Marble Surface Hardness, *Proc. of the 9th Int. Marble and Natural Stones Congress and Exhibition of Turkey*, Antalya, 2017.
3. Siegesmund, S. and Dürrast, H., Physical and Mechanical Properties of Rocks, in: *Stone in Architecture, Properties, Durability*, Siegesmund S., Snethlage R. (eds.) Berlin, 2014.
4. Shalabi, F.I., Cording, E.J., and Al-Hattamleh, O.H., Estimation of Rock Engineering Properties Using Hardness Tests, *Eng. Geol.*, 2007, vol. 90, pp. 138–147.
5. Çelik, M.Y., Yeşilkaya, L., Ersoy, M., and Turgut, T., Investigation of the Relationship between Grain Size and Knoop Hardness on Carbonate Natural Stones, *Mining*, 2011, vol. 50, pp. 29–40.
6. Bamford, W.E., Van Duyse, H., Nieble, C., Rummel, F., Broch, E., Franklin, J.A., Atkinson, R.H., Tarkoy, P.J., and Deere, D.U., Suggested Methods for Determining Hardness and Abrasiveness of Rocks, *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, 1978, vol. 15, pp. 89–97.
7. Çelik, S.F. and Çobanoğlu, İ., Comparative Investigation of Shore, Schmidt, and Leeb Hardness Tests in the Characterization of Rock Materials, *Environ. Earth Sci.*, 2019, vol. 78, pp. 1–16.
8. Atkinson, R.H., Hardness Test for Rock Characterization, *Comprehensive Rock Engineering: Principles, Practice and Projects*, Hudson, J.A. (Ed.), Oxford, 1993.
9. Leeb, D., *Dynamic Hardness Testing of Metallic Materials*, NDT Int. 12, 1979.
10. Wilhelm, K., Viles, H., and Burke, O., Low Impact Surface Hardness Testing (Equotip) on Porous Surfaces—Advances in Methodology with Implications for Rock Weathering and Stone Deterioration Research, *Earth. Surf. Process. Landf.*, 2016, vol. 41, pp. 1027–1038.
11. Kompatscher, M., Equotip—Rebound Hardness Testing after D. Leeb, *IMEKO TC5 Conference on Hardness Measurements Theory and Application in Laboratories and Industries*, Washington, 2004.
12. Ünver, B., A Statistical Approach for Practical Determination of Sawability of Rocks, *Mining.*, 1992, vol. 31, pp. 17–25.
13. Büyüksağış, İ.S., Analysis of Sawability of Marbles with Diamond Disc Block Cutter Machines, *Ph. D. Thesis*, Osmangazi University, Eskişehir, 1998.
14. Xu, X., Friction Studies on the Process in Circular Sawing of Granites, *Tribol. Lett.*, 1999, vol. 7, pp. 221–227.
15. Yılmaz, Güneş N., Gökten, M., and Onargan, T., Differences Observed in the Sawability Characteristics of Acidic and Basic Commercial Granites, *Proc. of the 5th Int. Min. Machinery Symposium and Exhibition of Turkey*, Eskişehir, 2015.
16. Uçun, I., Aslantaş, K., Taşgetiren, S., and Büyüksağış, İ.S., Fracture Path Prediction of Diamond Segment in a Marble Cutting Disc, *Fatigue Fract. Eng. Mater. Struct.*, 2008, vol. 31, pp. 517–525.
17. Şengün, N., Altındağ, R., and Koççaz, C.E., The Sawability Analysis of Some Magmatic Rocks in Isparta Region, *DEÜFMD*, 2009, vol. 11, pp. 22–31.

18. Yurdakul, M. and Akdaş, H., Prediction of Specific Cutting Energy for Large Diameter Circular Saws during Natural Stone Cutting, *Int. J. Rock Mech. Min. Sci.*, 2012, vol. 53, pp. 38–44.
19. Sengun, N. and Altindag, R., Prediction of Specific Energy of Carbonate Rock in Industrial Stones Cutting Process, *Arab. J. Geosci.*, 2013, vol. 6, pp. 1183–1190.
20. Yurdakul, M., Effect of Cutting Parameters on Consumed Power in Industrial Granite Cutting Process Performed with the Multi-Disc Block Cutter, *Int. J. Rock Mech. Min. Sci.*, 2015, vol. 76, pp. 104–111.
21. Tumaç, D., Predicting the Performance of Large Diameter Circular Saws based on Schmidt Hammer and Other Properties for some Turkish Carbonate Rocks, *Int. J. Rock Mech. Min. Sci.*, 2015, vol. 75, pp. 159–168.
22. Saruşık, G. and Özkan, E., Effects of Natural Rock Properties on Cutting Forces, Specific Energy and Specific Cutting Energy by Four-Axis Machine, *Arab. J. Geosci.*, 2018, vol. 11, pp. 1–19.
23. Ekincioglu, G. and Altındağ, R., Investigation of the Effect of Boron Carbide-Added Diamond Sockets on Cutting Performance in Granite Cutting, *Arab. J. Geosci.*, 2019, vol. 12, p. 170.
24. Ekincioglu, G., Evaluation of the Relationships between Drillability Index Properties and Rock Sawability of Various Limestones, *M. S. Thesis*, Süleyman Demirel University, Isparta, 2008.
25. Şengün, N., The Effects of Fracture Toughness and Brittleness of Rocks on Sawing Efficiency with Circular Discs, *Ph. D. Thesis*, Süleyman Demirel University, Isparta, 2009.
26. *TS EN 1936: Natural Stone Test Methods—Determination of Real Density and Apparent Density, and of Total and Open Porosity*, Turkish Standards Institution, Ankara, 2010.
27. *TS EN 14579: Natural Stone Test Methods—Determination of Sound Speed Propagation*, Turkish Standards Institution, Ankara, 2006.
28. *TS EN 14157: Natural Stone Test Methods—Determination of the Abrasion Resistance*, Turkish Standards Institution, Ankara, 2017.
29. *TS EN 1926: Natural Stone Test Methods—Determination of Uniaxial Compressive Strength*, Turkish Standards Institution, Ankara, 2007.
30. *TS EN 12372: Natural Stone Test Methods—Determination of Flexural Strength under Concentrated Load*, Turkish Standards Institution, Ankara, 2007.
31. *ISRM: Rock Characterization, Testing and Monitoring—ISRM Suggested Methods*, Brown, E.T. (Ed.), Pergamon Pres, Oxford, 1981.
32. ISRM: Suggested Method for Determining Point Load Strength, *Int. J. Rock Mech. Min. Sci. Geomech.*, 1985, vol. 22, pp. 51–60.
33. *ISRM: Rock Characterization, Testing and Monitoring—ISRM Suggested Methods*, Brown, E.T. (Ed.), Pergamon Pres, Oxford, 2007.
34. Altındağ, R. and Güney, A., ISRM Suggested Method for Determining Shore Hardness Value for Rock, *Int. J. Rock Mech. Min. Sci.*, 2006, vol. 43, pp. 996–997.
35. Şengün, N., Altındağ, R., and Demirdağ, S., Investigation into Variations of Saw Rotation and Noise Level in Cutting by Circular Saw, *Pamukkale Univ. Muh. Bilim. Derg.*, 2013, vol. 19, pp. 121–126.