Evaluation of different surface characteristics and mineral grain size in the estimation of rock strength using the Schmidt hammer

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Abstract

This study investigated the effect of surface roughness on Schmidt rebound hardness (R_L). Four different test surfaces of rock samples were studied: natural, ground, cut surfaces, and core samples. There was significant variability of standard deviation based on the R_L on the natural surface, which indicated high roughness of the rock surface, whereas surface polishing caused a significant decrease in standard deviation. ISRM and ASTM methods were compared to estimate unconfined compressive strength (UCS) for different testing surfaces. R_L obtained from the cut surface was found to be more reliable than those obtained from other testing surfaces for the prediction of UCS; however, regression and ANOVA analyses revealed that the ISRM method gave a more accurate UCS estimation of rocks with highly rough surfaces. It was also shown that R_L values obtained from a cut surface were significantly higher than those obtained from core samples. Therefore, a comparison between R_L values obtained from core samples and cut surfaces was made based on previous studies. This study statistically showed that estimated UCS values are not statistically significant if Schmidt rebound tests are not performed on similar surfaces. In addition, the mineral grain sizes of the studied rocks, different testing surfaces compared with those in literature, and standard deviation from R_L are evaluated and discussed. The Schmidt hammer technique is a rapid, inexpensive, and straightforward method for estimating UCS for preliminary assessment; however, roughness of the surface should be eliminated if variations are shown in the surface rebound hardness.

Keywords

Schmidt hammer technique, unconfined compressive strength estimation, surface roughness, mineral grain size

Introduction

The Schmidt hammer technique was initially developed in the late 1940s for testing the hardness of concrete (Schmidt, 1951) and, since the early 1960s, it has been used in rock mechanics practice (Deere and Miller, 1966). It has also been used for an increasing range of purposes, including the study of various weathering phenomena (Gokceoglu and Aksoy, 2000; Karpuz and Pasamehmetoglu, 1977), strength of joint walls (ISRM, 1978), rock discontinuity assessment (Young and Fowell, 1978), control of mine roof (Kidybinski, 1968), rock mass excavatability classification (Karpuz, 1990), performance of tunnel boring machine and roadheader (Bilgin et al., 1990; Poole and Farmer, 1978), penetration rate of drilling machines (Kahraman et al., 2003), determination of stabilization of glacially transported boulders (Wilson and Matthews, 2016), and saturation effect on strength and hardness (Karakul, 2017).

The use of the Schmidt hammer technique has been standardized by both the International Society for Rock Mechanics (ISRM, 2007) and the American Society for Testing and Materials (ASTM, 2013). Schmidt hammer models, such as L and N types, are designed with different impact energy levels. Orientation of the hammer, spacing between the impacts, surface roughness, weathering of the rock, size of the test sample, and the adopted test procedure are among significant parameters that influence the rebound values of rocks (Aydin, 2009; Goudie, 2006; ISRM, 1978; Karaman, 2020; Katz et al., 2000).

Hucka (1965) and Poole and Farmer (1980) indicated that the peak rebound values of repeated impacts at individual points are more reliable than first- or single-impact values; however, Shorey et al. (1984) used lower rebound values because they were more reliable for the estimation of unconfined compressive strength (UCS). Aydin (2009) stated that the density, distribution, and connectivity of its weak microstructural elements strongly affect the UCS values of a material; thus, high and low rebound values are equally necessary to reflect the nature of heterogeneity. Although different test procedures might be suitable for different applications, various researchers and institutions have suggested testing procedures that exhibit a wide variation in rebound values (Goktan and Gunes, 2005).

Some authors mention surface roughness properties for the Schmidt rebound test. Williams and Robinson (1983) stated that rough surfaces yield lower hardness values than smooth surfaces for fresh gritstone blocks. Katz et al. (2000) carried out field measurements on three different surfaces: naturally weathered rock surfaces, surfaces manually polished with a grinding stone, and surfaces polished with an electrical grinder. They only published the standard deviation value changes from 1.93–5.57 (1.93 for surfaces polished with an electrical grinder, 3.80 for manually polished surfaces, and 5.57 for naturally weathered surfaces). They stated that high-quality polishing profoundly improved the quality of field measurements. Dabski (2009) studied limestone boulders that had early stages of weathering of glacially abraded surfaces and generally found higher rebound hardness values on polished surfaces than those obtained from non-polished surfaces. Cerna and Engel (2011) investigated variations of Schmidt hammer rebound value on the surface and sub-surface for a granite outcrop. They compared rebound hardness values obtained from natural and prepared surfaces, revealing that grinding before measurement provided more accurate data. Matthews et al. (2016) indicated that the first impact on surfaces tends to yield a relatively low R_L value due to higher surface roughness, and such roughness effects were only removed after further impacts (usually less than five). Kogure (2019) proposed equations that distinguished two types of weathered surfaces, with higher rebound values at the surface of the indents than those at the surface of cliffs without indents. Karaman (2020) investigated the effect of rock surface roughness on Schmidt hammer rebound number and confirmed that rebound values increased as the surface roughness decreased.

Many studies on the Schmidt hammer technique have been conducted on different surfaces (Table I). Some researchers performed the Schmidt hammer technique on surfaces without any polishing processes, while some used grinding stones before measurements. Surfaces were also prepared by researchers using an electric grinder and saw machine. Natural surfaces were widely used to determine weathering state and stabilization of glacially transported boulders. According to Table I, different researchers used various polishing methods before the Schmidt rebound measurements. Therefore, even if the rock types were the same, different rebound values were obtained because of variations in surface roughness properties.

According to the literature review, no study focused experimentally on the UCS estimation of rocks with different surface roughness properties. The main objective of this study was to investigate the effect of surface roughness on the relationship between UCS and R_L. For this purpose, the UCS results for nine different rock types were correlated with the corresponding R_L results. Many researchers compared their equations with previous studies, regardless of whether the test surface was the same. Therefore, this study aimed to investigate the usability of relevant test surfaces for comparison and how grain size and standard deviation affect R_L measurements.

Table I

Summary of testing surface properties and conditions from the literature

Researchers	Subject	Rock/s	Type	Test surface processes
Kogure (2019)	Mechanical characteristics of weathered pyroclastic rock surfaces	Pyroclastic rocks	N	The test was performed **without any polishing** of the surfaces before the impact.
Wilson et al. (2019)	Age determination of glacially transported boulders	Granite boulders	N	Boulder surfaces were **not prepared** before measurement.
Yilmaz and Goktan (2019)	Comparison of Schmidt hammer technique and Equotip hardness tester for rock strength evaluation	Masonry and building stones	L	**No treatment** was necessary for surface smoothening for the core samples.
Han et al. (2019)	A deep learning-based method for rock strength	Not given	N	Before measuring, **the weathered layers** of the rocks were **removed**.
Goktan and Gunes (2005)	Prediction of rock-cutting machine performance	Mudstone, shale, sandstone	N	The rock surfaces were ground by hand with a **carborundum wheel**.
Ozkan and Bilim (2008)	Application of the Schmidt hammer technique in-situ on a coal face	Coal	L	The surfaces were manually polished with a **grinding stone**.
Cerna and Engel (2011)	Rebound value variation for strongly weathered and weakly weathered granite outcrops	Granitic outcrops	N	The surfaces were prepared using an **electric grinder**.
Buyuksagis and Goktan (2007)	Effect of Schmidt hammer technique and test methods on UCS prediction	Different rock types	L/N	The specimen surfaces were precision cut by diamond-segmented circular **sawblades** in the processing plant.
Vasconcelos et al. (2007)	Prediction of mechanical properties of granites	Granitic rocks	N	The specimens were cut utilizing a **saw machine**.
Katz et al. (2000)	Evaluation of mechanical rock properties	Fine-grained quartz-syenite	N	**Naturally** weathered rock surfaces. The surfaces were manually polished with a **grinding stone**. The surfaces were polished with an **electrical grinder**.

Materials and methods

Sampling and characterization of rocks

Rock samples were taken from the Black Sea region of Turkey (Trabzon and the surrounding area) (Figure 1). Their mineralogical and textural properties were determined using a trinocular polarizing research microscope. For the geological nomenclature of the claystone and quartzite samples, X-ray diffraction (Rietveld) analysis was performed (Karaman and Bakhytzhan, 2020). Petrographic thin-section analyses of the other samples are shown in Figure 2.

Each block sample was inspected for visible defects to provide standard testing samples free from cracks and fractures. Anisotropy is a significant parameter affecting the strength of the rocks. The studied rocks with no anisotropy (schistosity and foliation) showed no bedding planes, prismatic, pillow lava, or flow structure. The vicinity of the sampling locations was also checked to ensure that there were no faults or shear cracks.

Schmidt hammer measurements

Points were selected that avoided edge effects, cracks, and other visible structural weaknesses in the rock surface. Special attention was paid to ensuring that single impacts separated by at least the plunger diameter were made precisely on the rock surface. The hammer was periodically checked using the manufacturer's test anvil. All R_L tests were performed with the hammer held vertically downward. R_L tests were performed using the L-type hammer in the laboratory on NX-size (54.7 mm diameter) core samples of five rock types belonging to different lithology definitions (granodiorite, basalt, diabase-1, diabase-2, and andesite). Hack et al. (1993) stated that no treatment is necessary for surface smoothening when the test specimens are obtained by coring. Test samples were rigidly supported using a core holder with a steel base during the testing. Aydin (2009) recommended sample sizes for the rebound hardness test: NX size (54.7 mm) for core samples and at least 100 mm thickness for block samples.

R_L measurements were also made on block samples with different surface properties, such as natural surface (without any polishing process), ground surface (using an electric grinder), and cut surface (using a saw machine). ISRM and ASTM methods that are widely used for rebound hardness determination (Buyuksagis and Goktan, 2007; Jamshidi et al., 2018; Karaman and Kesimal, 2015a) were used. These methods are described below.

Test Procedure 1 (ISRM, 2007): It is recommended to record twenty rebound values from single impacts separated by at least a plunger diameter and average the upper ten values.

Test Procedure 2 (ASTM, 2001): It is recommended to record ten rebound values from single impacts separated by at least the diameter of the piston, discarding readings that differ from the average of ten readings by more than seven units and determining the average of the remaining readings.

Roughness measurements

Barton and Choubey (1977) proposed ten standard joint roughness coefficient (JRC) profiles ranging from 0 to 20. The JRC value is the most commonly used measure for representing surface roughness (Hsiung et al., 1995). Each profile covers a range of two scales of JRC (i.e., 0–2). In the current study, a unique value (middle value of a range) was practically assigned to each profile, as in the study of Hsiung et al. (1995). The surface roughness was measured using a comb profilometer. The rock-surface roughness was quantified to assess its influence on rebound values and UCS estimation. The effects of weathering, instrument errors, and sample design were minimized to determine the surface roughness. The electric grinding tool was used stepwise to minimize dust formation and heating. Six roughness measurements, including impact points, were performed for each rock surface, and representative surface roughness was determined (Figure 3).

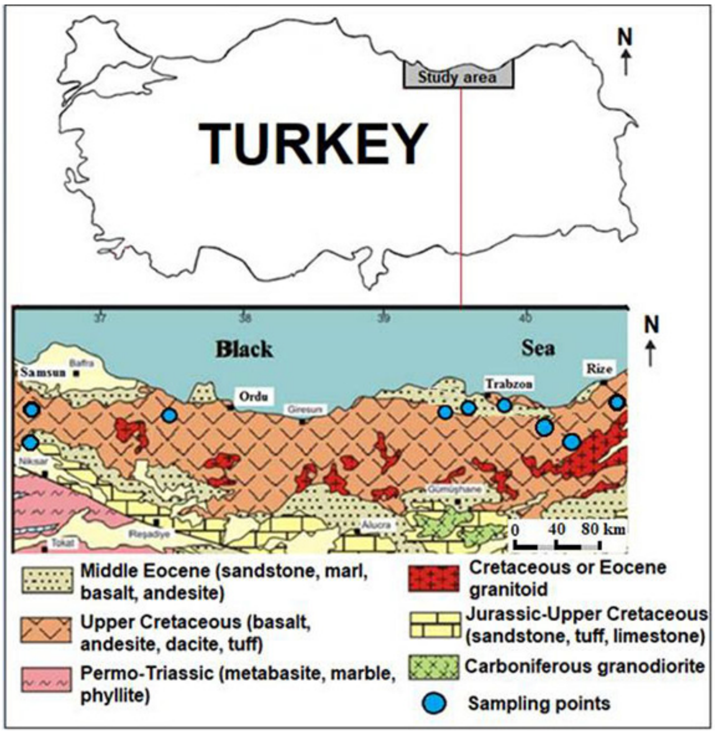

Figure 1—Major geological features of the study area (modified from Okay and Sahinturk, 1997)

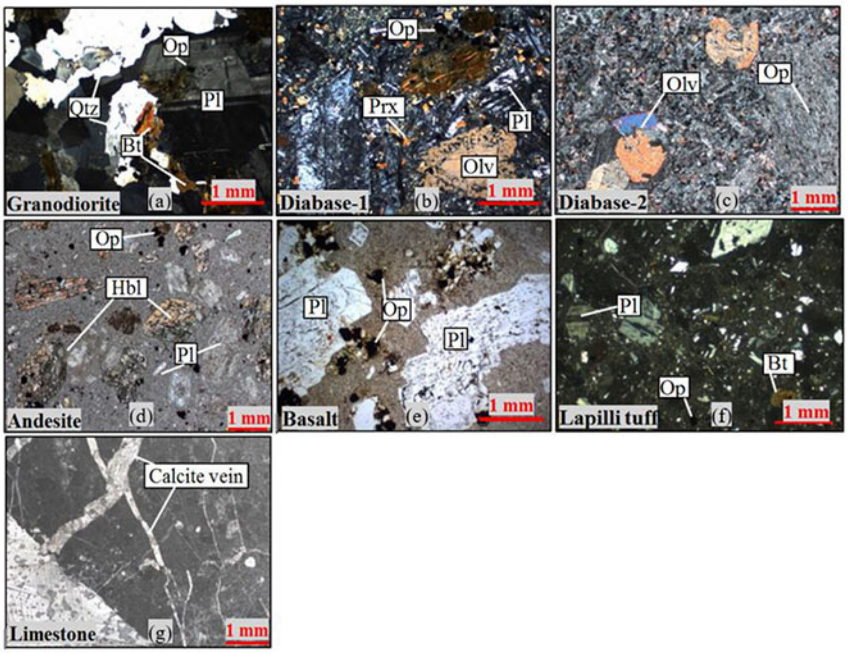

Figure 2—Microscopic images of the rock samples studied: (a) granodiorite, (b) diabase-1, (c) diabase-2, (d) andesite, (e) basalt, (f) lapilli tuff, and (g) limestone. Bt: biotite, Hbl: hornblende, Op: opaque mineral, Olv: olivine, Qtz: quartz, Pl: plagioclase, Prx: pyroxene

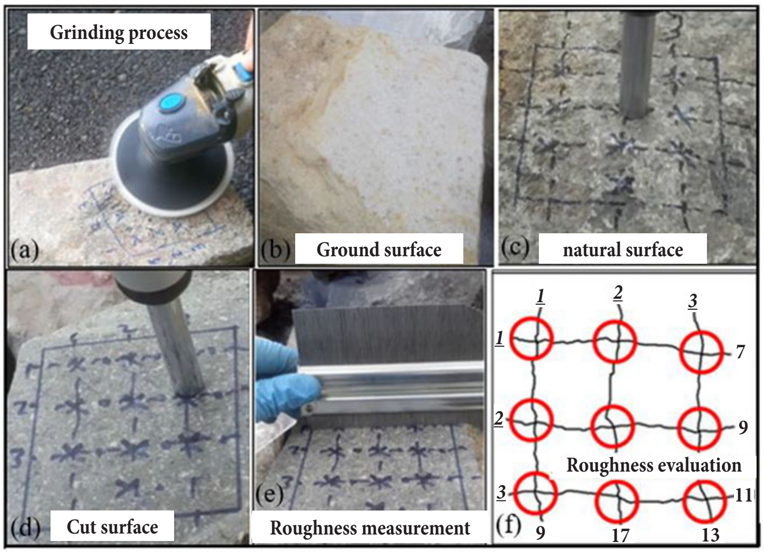

Figure 3—(a) Grinding process, (b) ground surface, test on (c) natural and (d) cut surfaces, (e) roughness measurements, and (f) evaluation

Density, porosity, and unconfined compressive strength tests

Core samples were prepared using a laboratory core drill and saw machines. For coring the rock blocks, a 54.7 mm diameter diamond coring bit was used. Trimmed core samples were used in the determination of density. The values of apparent porosity were obtained using saturation and caliper techniques. The UCS tests for fresh rocks were performed with a length-to-diameter ratio of 2.5, following the recommendations of ISRM (2007). All tests were carried out on intact rock samples. A machine with a 200 t capacity servo-control system was used for the UCS tests. The loading speed was applied within the limits of 0.5–1.0 MPa/s. The test was repeated five times for each rock type, and the average values are recorded as the UCS (Figure 4). The mechanical and physical properties of the samples are given in Tables II and III, respectively.

Results

Evaluation of standard deviation and roughness

The standard deviation of the Schmidt hammer rebound measurements was obtained in the range of 5.1–11.6 for the raw data. The average standard deviation of all rocks was 7.8 ± 2.4 for raw data, 4.3 ± 1.6 for natural surfaces (ASTM), 2.9 ± 0.8 for surfaces polished with an electrical grinder (ASTM), and 1.8 ± 0.5 for cut surfaces (ASTM). The average standard deviation of all rocks was 3.8 ± 1.3 for natural surfaces (ISRM), 2.0 ± 0.6 for surfaces polished with an electrical grinder (ISRM), and 1.1 ± 0.5 for cut surfaces (ISRM) (Table II). It was shown that the roughness of the test surface considerably affected the standard deviation. Figure 5 demonstrates a positive correlation between surface roughness

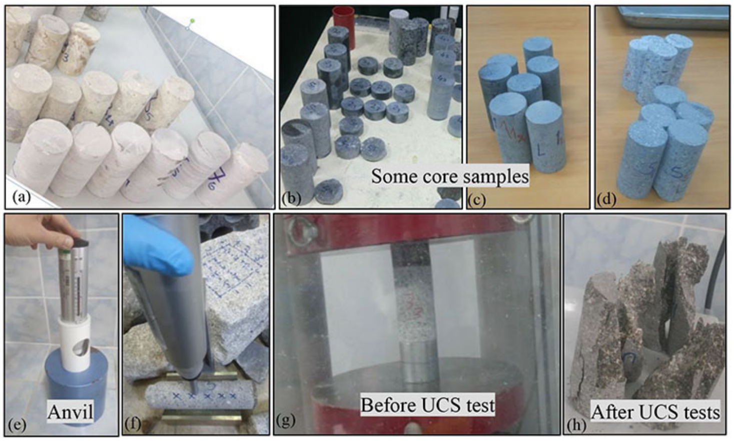

Figure 4—(a–d) Some core samples, (e) Schmidt calibration anvil, (f) Schmidt hammer test, (g) before and (h) after the unconfined compressive strength test

Table II

Results of Schmidt rebound values for different surfaces

Rock type	Natural surface (ISRM)	Natural surface (ASTM)	Ground surface (ISRM)	Ground surface (ASTM)	Cut surface (ISRM)	Cut surface (ASTM)	Core samples (ISRM)	Core sample (ASTM)
Granodiorite	51.2 ± 3.0	46.3 ± 4.0	62.0 ± 1.2	60.4 ± 2.3	66.0 ± 1.0	64.6 ± 1.8	47.8 ± 1.3	46.8 ± 1.4
Diabase-1	44.0 ± 2.7	40.8 ± 2.4	55.2 ± 1.5	53.6 ± 2.0	60.4 ± 0.5	59.3 ± 1.5	42.4 ± 2.2	40.6 ± 2.5
Diabase-2	53.6 ± 2.5	51.1 ± 2.3	59.6 ± 1.4	57.3 ± 1.9	64.5 ± 0.6	63.9 ± 0.8	48.5 ± 1.8	47.3 ± 2.5
Andesite	45.4 ± 5.3	37.0 ± 6.9	50.6 ± 3.0	47.7 ± 3.7	57.0 ± 1.9	55.4 ± 2.2	38.2 ± 1.8	36.5 ± 2.3
Basalt	48.7 ± 4.2	44.1 ± 3.8	55.8 ± 2.3	53.4 ± 3.4	62.4 ± 1.2	60.8 ± 2.2	44.1 ± 2.2	42.3 ± 2.7
Lapilli tuff	18.7 ± 5.4	15.8 ± 5.8	21.4 ± 2.5	19.3 ± 2.8	23.7 ± 0.9	22.5 ± 1.6	-	-
Clay stone	21.8 ± 4.9	16.1 ± 5.6	26.7 ± 1.9	23.0 ± 3.4	30.2 ± 1.3	28.2 ± 2.1	-	-
Limestone	47.8 ± 4.3	41.3 ± 3.5	55.0 ± 2.1	52.9± 2.8	57.2 ± 0.8	56.0 ± 1.5	-	-
Quartzite	43.4 ± 1.7	40.8 ± 4.0	49.4 ± 1.7	47.8 ± 4.1	51.0 ± 1.6	48.0 ± 2.2	-	-

Table III

Average test results and standard deviation values of samples

Rock type	Density (g/cm³)	Apparent porosity (%)	UCS (MPa)
Granodiorite	2.65 ± 0.1	1.3 ± 0.3	170 ± 20
Diabase-1	2.79 ± 0.1	4.6 ± 0.3	116 ± 17
Diabase-2	2.83 ± 0.3	2.3 ± 0.5	183 ± 4
Andesite	2.55 ± 0.1	5.0 ± 0.3	86 ± 23
Basalt	2.56 ± 0.4	4.5 ± 0.9	163 ± 20
Lapilli tuff	1.86 ± 0.6	27.2 ± 1.2	12 ± 2
Clay stone	2.40 ± 0.5	8.0 ± 1.0	25 ± 10
Limestone	2.67 ± 0.1	0.7 ± 0.5	81 ± 12
Quartzite	2.39 ± 0.2	6.9 ± 0.6	60 ± 8

and standard deviation, indicating that as the surface roughness increased, the standard deviation also increased. A decrease in the standard deviation was shown for the natural surfaces compared with the raw data due to the rule of seven units (ASTM) and discarding the lowest 50% values (ISRM). According to the ISRM method, the standard deviation values were lower for all surfaces because the lowest ten of the twenty readings were not included in the calculations.

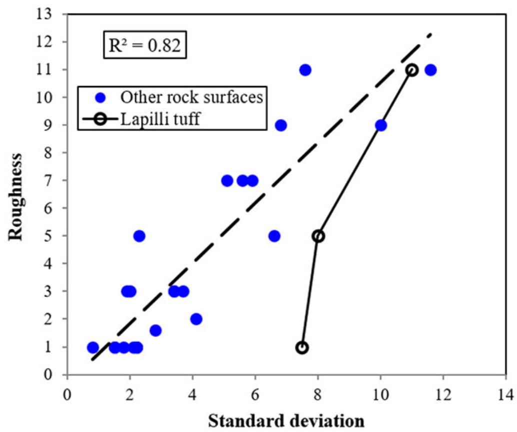

Figure 5—Relationship between roughness and standard deviation

According to Figure 5, a high coefficient of determination (R^2 = 0.82) was obtained between the standard deviation and roughness values of the test surfaces of all rocks except for Lapilli tuff. Large grains of various types and sizes were observed in a macroscopic view of the Lapilli tuff. Scattered data can be obtained from pyroclastic and breccia rocks.

Rock samples with rough surfaces were selected for this study to evaluate roughness effects, so natural roughness values of lapilli tuff, andesite, and granodiorite were found to be similar (Table IV).

Table IV

Average roughness values of the testing surfaces

Rock types	Natural surface (JRC)	Ground surface (JRC)	Cut surface (JRC)
Granodiorite	11	5	1
Diabase-1	9	3	1
Diabase-2	7	3	1
Andesite	11	3	1
Basalt	7	3	1
Lapilli tuff	11	5	1
Clay stone	9	3	1
Limestone	5	1.6	1
Quartzite	7	2	1

However, granodiorite contains quartz, which is harder than other minerals, and lapilli tuff contains rock fragments with different hardness. Therefore, the grinding process is affected by different hardness of particles (rock fragments, minerals, etc.) on the surfaces. Accordingly, the ground surfaces of granodiorite and lapilli tuff were rougher than those obtained from other rocks.

Relationship between rebound value and unconfined compressive strength

Predictive Analytics Software (PASW Statistics 18) confirmed the statistically derived equations. All variables (i.e., UCS and R_L for all surfaces) were found to be normally distributed according to the Kolmogorov–Smirnov Z test and were then subjected to parametric statistical tests. Linear, power, exponential, logarithmic, and quadratic relationships between the variables were examined to obtain the most reliable equations. Analysis of variance (ANOVA) tables were also checked to determine whether regression models were significant. Similarly, the significance of coefficients in equations was examined.

Figure 6 shows the relationship between the UCS and rebound values obtained from different surfaces. Strong relationships ($R^2 \geq 0.90$) were obtained between the data pairs. As expected, the UCS values increased with increasing rebound values for all test surfaces. Statistically significant relations (exponential and power) within a 95% confidence level were obtained between UCS and R_L for all test surfaces (Table IV). However, the natural surface and core samples had slightly lower coefficients of determination than those of the ground and cut surfaces. The study showed that the lapilli tuff and clay stone samples, which are weak rocks, affected the relationship type due to their low values of UCS and R_L. Therefore, the relationship type for core samples is different (linear). A scatter plot of the Schmidt rebound hardness derived from the cut surfaces (JRC = 1) against the UCS values had the highest R^2 value. The highest coefficient of determination could be related to the similar surfaces (cut and smooth) that were used in the UCS tests.

According to Figure 6 and Table V, the ISRM procedure gives a better prediction of UCS, for which the determination coefficients are within the range of 0.91–0.97. In contrast, the determination coefficients vary between 0.90 and 0.97 for the ASTM test procedure. These results agree with those of Buyuksagis and Goktan (2007) and Jamshidi et al. (2018), who obtained slightly higher coefficient of determination values with ISRM than ASTM. This study also revealed that the ISRM method provided a more accurate estimation of UCS for the natural test surfaces (JRC between 5 and 11); however, as the JRC decreased, the standard deviation values of the rebound readings also decreased, so the difference between the ISRM and ASTM methods became smaller (Figure 6).

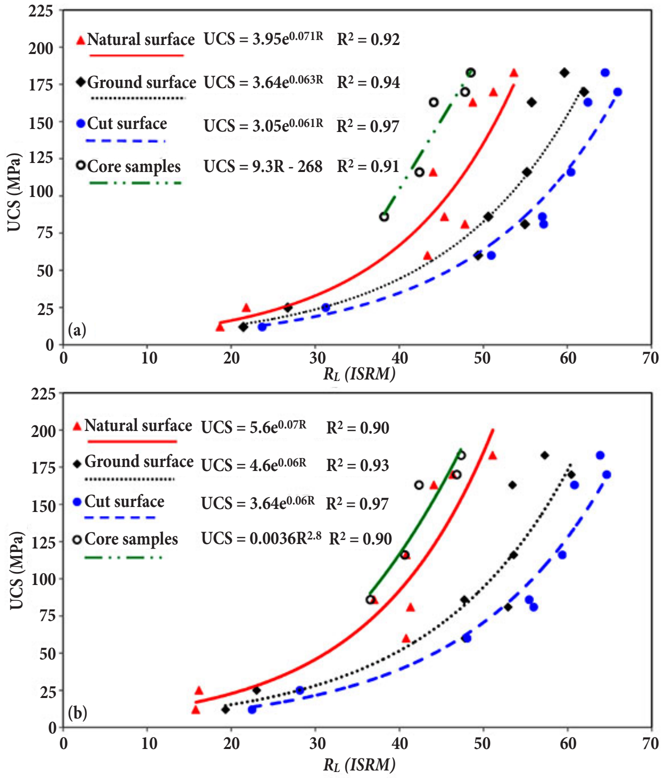

Figure 6—Relationship between UCS and R_L for different testing surfaces: (a) ISRM and (b) ASTM

The rebound values obtained from the cut surface were only close to those measured from the ground surface in the estimation of the UCS. It was observed that quite different UCS values could be predicted for the same rock type due to the effect of JRC (natural and cut surfaces). Increased JRC value leads to deviations not only in the standard deviation, but also in the empirical equations derived. A higher coefficient of determination was obtained as the JRC value decreased.

Comparison of R_L values obtained from different rough surfaces

As seen in Table V, strong coefficients of determination were obtained between the UCS and R_L data pairs of different rough surfaces within a 95% confidence level ($R^2 \geq 0.90$). The variations of R_L values obtained from different rough surfaces were also tested using the one-way ANOVA for both methods (ISRM and ASTM). The Dunnett two-sided T-test was used to compare the R_L values obtained in multiple tests to investigate the relationships between different surfaces: the R_L values obtained from the cut surfaces were considered the control group. A significance level (SL) close to 1.00 indicates perfection of variance homogeneity (SL > 0.05). The variances of R_L values were homogeneous (Levene statistic values = 1.397 and 1.416, and SL = 0.264 and 0.259 for ISRM and ASTM, respectively). When SL > 0.05, there was no difference between the mean values of the groups. According to the ANOVA results, no difference was obtained among the mean values of the groups (F = 1.163 and 1.717 and SL = 0.341 and 0.186 for ISRM and ASTM, respectively). The mean R_L values from the ground surfaces were very close to the R_L values obtained from the cut surfaces, with the lowest variation (Table VI and Figure 7).

Table V

Results of the statistical evaluations

Surfaces	Relation type	R^2 (ISRM)	R^2 (ASTM)	ANOVA (ISRM)		ANOVA (ASTM)		Coefficients SL
				F	SL	*F*	SL	
Natural	Exponential	0.92	0.90	77.03	0.000	61.4	0.000	< 0.05
Ground	Exponential	0.94	0.93	108.5	0.000	87.0	0.000	< 0.05
Cut	Exponential	0.97	0.97	256.7	0.000	225.5	0.000	< 0.05
Core	Linear/Power	0.91	0.90	31.4	0.011	26.9	0.014	< 0.05

S. Le : Significance level

Table VI

Multiple comparisons of the R_L

(I) C	(J) C	ISRM SL	ISRM MD (I-J)	ASTM SL	ASTM MD (I-J)	ISRM 95% CI		ASTM 95% CI	
						Lower Bound	Upper Bound	Lower Bound	Upper Bound
N-S	C-S	0.209	−10.98	0.091	−13.93	−26.3825	4.4270	−29.6306	1.7640
C-S	C-S	0.541	−8.40	0.567	−8.27	−26.6272	9.8272	−26.8400	10.3066
G-S	C-S	0.845	−4.19	0.795	−4.81	−19.5937	11.2159	−20.5084	10.8862

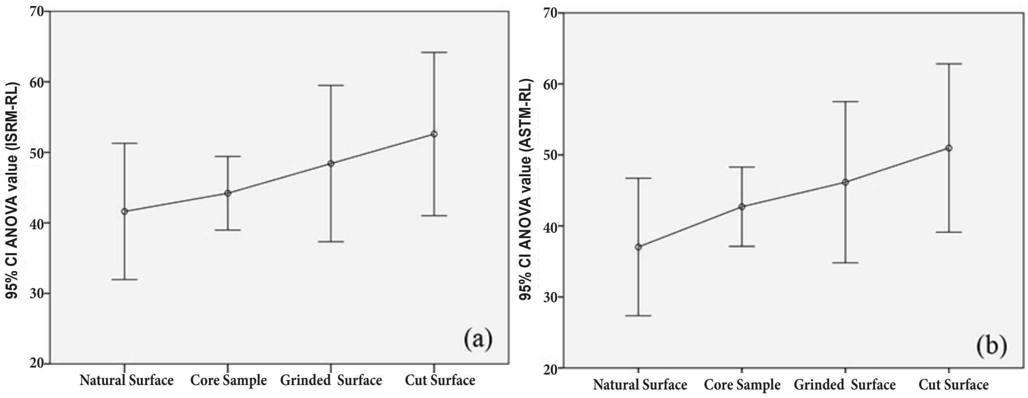

Figure 7—Comparison of mean values of R_L obtained for different surfaces: (a) ISRM and (b) ASTM

The value of significance (SL > 0.05) for all groups revealed that there was no difference between the mean values of the groups (Table VI); however, SL (0.091) between the natural and cut surfaces was very close to the threshold value (0.05) for the ASTM method due to the high JRC values of the natural surface. In contrast, the study showed that R_L values derived from the natural surface using the ISRM gave more similarity than ASTM, according to the SL value. It can be inferred from these findings that the ISRM method gives more accurate R_L values for natural surfaces with high JRC values. Statistically, the ISRM method also provides better UCS prediction, especially on rough surfaces, because it excludes low values caused by surface roughness. Consequently, in terms of surfaces, using a ground or cut surface to find an R_L value gives a more accurate prediction of UCS and lower JRC value than other surfaces.

Comparison of R_L and estimated unconfined compressive strength values obtained from smooth surfaces

The rebound values obtained from core samples were lower than those obtained from cut surfaces, although both were smooth. For this reason, to verify the results obtained in this study, R_L differences were also examined by comparing surfaces (core and block samples) used in previous studies (Table VII) and extracting 125 R_L–UCS values. The highest UCS–R_L values are given in Figure 8. According to literature, the rebound values obtained from a cut surface are significantly higher than those obtained from core samples, although similar rock types were studied. This study confirmed that the differences between the rebound values obtained on smooth surfaces (core and block samples) were in close agreement with those obtained from previous studies. However, different Schmidt rebound values can also be obtained depending on the rock characteristics, test method, and application of the test parallel or perpendicular to the weakness planes (i.e., anisotropy and bedding planes, etc.).

Using the R_L and UCS values from this study, the estimated UCS values were calculated and compared with the values from empirical equations proposed by different researchers (Buyuksagis and Goktan, 2007; Nazir et al., 2013) (Figure 9). The equation proposed by Nazir et al. (2013) for core samples was also used to estimate the UCS from R_L of the block samples to compare the sample types (core and block). Similarly, the equation proposed by Buyuksagis and Goktan (2007) for block samples was also used in

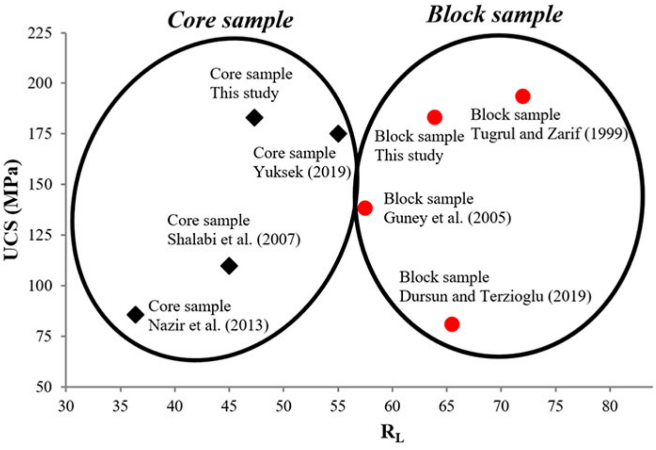

Figure 8—Effect of testing surfaces on peak rebound values

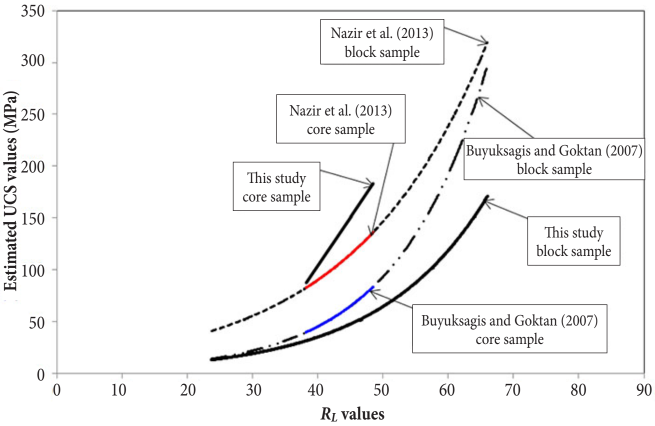

Figure 9—Comparison of estimated unconfined compressive strength values with previous studies

the estimation of UCS from R_L of the core samples. As shown in Figure 9, the relationship between the UCS and R_L derived from this study was very similar to that of Buyuksagis and Goktan (2007) at lower rock strength for the block samples.

According to the ANOVA results, no differences were detected between the mean values of this study and those reported by Buyuksagis and Goktan (2007) (SL = 0.248) for the block samples; however, estimated UCS values derived from the equation of Nazir et al. (2013) were significantly different from those of the current study (SL = 0.039). The disparity could be related to the equation of Nazir et al. (2013) being developed using core samples (Figure 10(a)). Based on the ANOVA results, no difference was found between the mean values of this study and the study of Nazir et al. (2013) (SL = 0.184) for the core samples (Figure 10(b)); however, estimated UCS values derived from the equation of Buyuksagis and Goktan (2007) differed significantly from those of the current study (SL = 0.001) because their original equation was developed for block samples.

Effect of grain size on Schmidt rebound number

A trinocular research microscope was utilized to analyse the grain sizes of the samples. Although a grain exists in three-dimensional form in a sample, the grain size was expressed by area in this study. Three-dimensional grains were minimized by scanning the entire section with the help of a motorized table. Thin-section images related to grain sizes were examined using Clemex Image Analysis System software.

The largest and approximate average grain areas were calculated based on the grain sizes (Figure 11). While the average grain areas of the samples ranged from 0.23 to 4.8 mm², the largest grain areas varied between 1.64 mm² (andesite) and 58.33 mm² (lapilli tuff). Furthermore, the plunger area of the Schmidt hammer (176.7 mm²) was about three times larger than the largest grain areas of lapilli tuff. However, larger grains (550–600 mm²) could be individually observed in macroscopic samples of the lapilli tuff (Figure 12).

This study confirmed that larger grains affected the rebound values, even if the surface of the lapilli tuff was smoothed. Aydin (2009) stated that when a surface contains grains with sizes comparable to the plunger tip diameter, the readings from these grains might significantly deviate from the average, depending on their strength relative to the matrix or dominant grain size. Findings that agreed with this suggestion of Aydin (2009) were obtained for the lapilli tuff samples (Figure 13(a)). In contrast, similar to the other rock samples, diabase-2 yielded consistent results regarding the effect of surface roughness and grain areas on Schmidt rebound values (Figure 13(b)). Scatter of the data increased as the JRC of the test surface of diabase-2 increased.

In such cases, impact points should be selected to obtain separate rebound readings from individual coarse grains and matrices (Aydin, 2009). On smooth surfaces where there were no large rock fragments, the readings were quite close to each other and showed a smooth line for cut surfaces (Figure 13(a)). However, the coarse grains of lapilli tuff had different rock fragments, which reflected different rebound values. Although all surfaces were

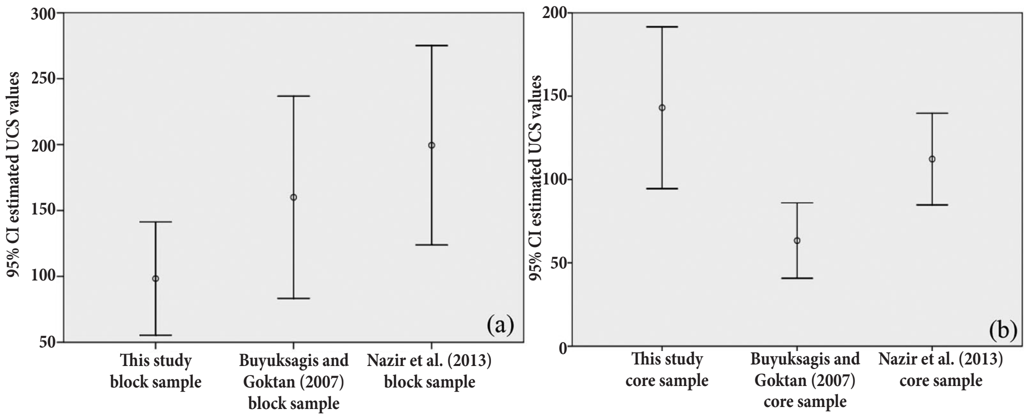

Figure 10—Comparison of estimated unconfined compressive strength values with those of previous studies: (a) core samples and (b) block samples

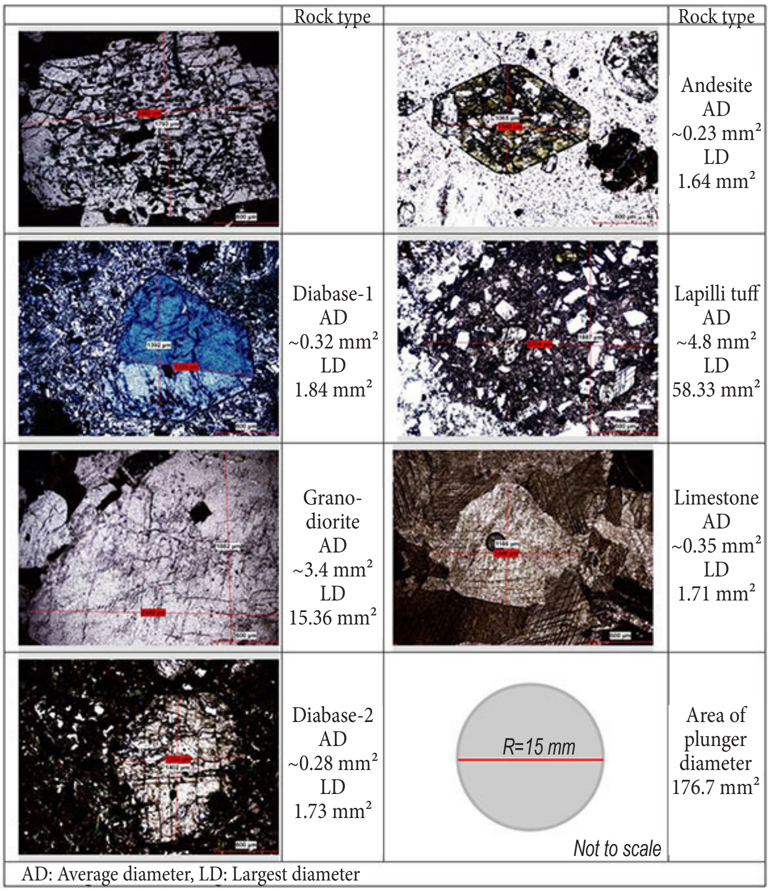

Figure 11—Grain sizes of samples

Figure 12—Views of lapilli tuff samples

evaluated together in this study, the findings derived from this rock were not utilized in some graphs (Figure 5) to avoid affecting the results. In such rocks, the average hardness value is not affected and only the standard deviation values are variable.

According to the literature review, the effect of grain size on Schmidt rebound number has been addressed by a few researchers. Guney et al. (2005) stated that the estimation of engineering properties of rock materials (e.g., UCS via Schmidt rebound hardness) needs to be improved to account for more qualitative values that better represent the rock material, such as its origin, porosity, and grain shape. Atapour and Mortazavi (2018) produced artificial sandstones with different textural characteristics (median grain size: 0.31–1.63 mm and cement content: 15%–25%). They observed that the point load strength index and Schmidt rebound hardness of the samples increased as grain size increased.

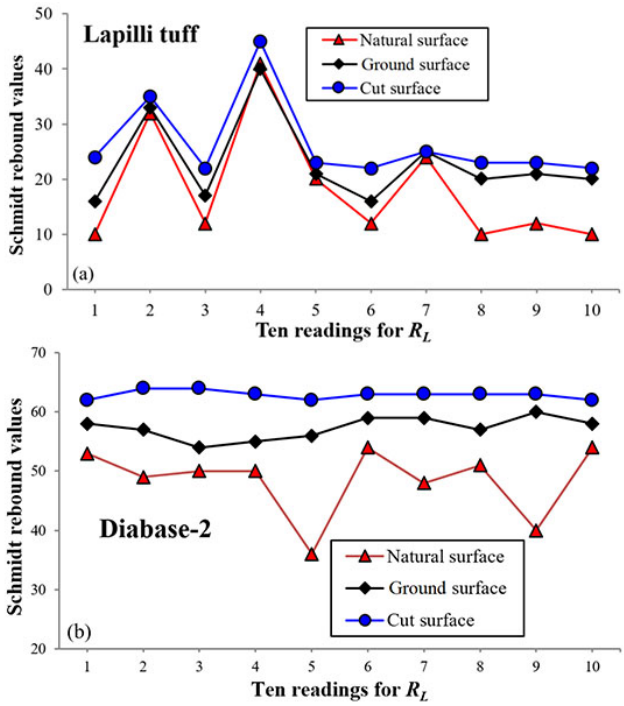

Figure 13—Effect of testing surface on variation of R_L: (a) lapilli tuff and (b) diabase-2

Discussion

Aydin and Basu (2005) and Buyuksagis and Goktan (2007) studied the effect of hammer type on UCS estimation. It was reported that the percentage difference (ISRM method) between L- and N-type hammers was about 15% on core samples in the study of Aydin and Basu (2005) and about 15%–20% on block samples in the study of Buyuksagis and Goktan (2007). Some researchers investigated the effect of the test procedure on Schmidt rebound hardness (Buyuksagis and Goktan, 2007; Jamshidi et al., 2018; Kahraman et al., 2002). Differences between the testing procedures similarly reached approximately 15% in the studies of Buyuksagis and Goktan (2007) and Jamshidi et al. (2018). In the current study, the average differences between the ISRM and ASTM methods were 12.30% for natural surfaces with high JRC values and 3.32% for cut surfaces with minimum JRC values. Some researchers investigated the effect of water content on Schmidt hammer rebound values and stated that water content reduces rebound values (Karakul, 2017; Sumner and Nel, 2002). In this study, the samples were kept in air-dried conditions at room temperature for five days to eliminate moisture in the samples and tests were carried out under the same conditions.

A rebound value of a core sample can be determined as, for example, 40 using one of the many testing procedures and an L-type hammer; however, for the same rock type, the rebound value of a cut-block sample can be calculated as 70 using another testing procedure with an N-type hammer. Researchers agree that the Schmidt hammer is quick, easy to apply, and inexpensive for either a site or laboratory, and technical expertise is not needed to use it; however, experience is required to evaluate and interpret the data primarily for UCS estimation. Moreover, scatter of data for Schmidt rebound values can be decreased through meticulous attention in the tests by following the instructions.

According to the revised version of the Schmidt rebound test (Aydin, 2009), the test may be stopped when any ten subsequent readings differ only by 4 (corresponding to an R_L repeatability range of ± 2), instead of twenty rebound values. Soiltest Inc. (1976) recorded fifteen rebound values from single impacts and averaged the highest ten, provided that the maximum deviation from the mean was less than 2.5. It is understood from literature that a low standard deviation or scatter of readings is desired for the Schmidt rebound test. Cut surfaces and core samples typically exhibit a small standard deviation. Karaman and Kesimal (2015b) investigated more practical Schmidt hammer tests by reducing the rebound readings, especially for estimating UCS. The standard deviation of their study was below 2.5. If the standard deviation is small, the average rebound values will be close to each other, even if different methods are used. According to the current study, standard deviation, which is an indirect parameter, is also a good indicator that reflects the roughness of the surface. Roughness of a surface where the Schmidt hammer is applied should be eliminated, and the test surface should be re-evaluated if the standard deviation is high.

Many researchers have found correlations between UCS and rebound values on different rock types (Aydin and Basu, 2005; Fener et al., 2005; Kahraman, 2001; Karaman and Kesimal, 2015a; Yagiz, 2009). They generally found strong correlations between R_L and the UCS. Some researchers also compared their equations with those of various authors who correlated UCS values with rebound values (Andrade and Saraiva, 2010; Kong and Shang, 2018; Wang and Wan, 2019; Wang et al., 2017; Yagiz, 2009; Yilmaz and Sendir, 2002). However, considerable differences exist between the empirical relationships proposed for estimating UCS using the Schmidt rebound value. Yagiz (2009) mentioned that the differences might be related to variations in the type and characteristics of the rock studied, the range of the dataset used (density, UCS, and rebound value), and the test methods chosen by the different researchers. He also stated that a comparison with previous research indicated that these should be used cautiously and only for the specified rock types. The current study also proposes that test surfaces, hammer types, and sample types (core and block) should be similar if the results are to be compared with previous research.

Conclusions and recommendations

The Schmidt hammer rebound test was conducted on different surfaces (natural, ground, cut surfaces, and core samples) to estimate the UCS of rock materials and to experimentally understand the roughness mechanism. Rebound values increased as the surface roughness decreased, and standard deviation values decreased. The highest rebound values and lowest standard deviations were obtained from cut surfaces, while the lowest rebound values and highest standard deviations were taken from natural surfaces. Furthermore, lapilli tuff, which had different rock fragments, led to variations in the rebound values due to coarse grains, even if the sample surface was smooth.

Statistical test results showed strong relationships ($R^2 \geq 0.90$) between R_L and the UCS of the rocks for all test surfaces; however, according to the coefficient of determination, R_L from the cut surface outperformed the other surfaces in the UCS estimation. This study also revealed that the ISRM method provides a more accurate estimation of UCS for rough test surfaces. The study recommends that R_L measurements be conducted on smooth surfaces; at least, an electric grinder is highly suggested for block samples.

According to this study, the standard deviation from the impact readings is an indirect parameter that presents knowledge about a test surface. Therefore, the test surface should be re-evaluated if the standard deviation is high. This study also suggests that Schmidt hammer rebound values can be compared with those previous studies if similar surfaces (ground or cut) and test conditions (hammer type and test procedure) are evaluated.

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Conflicts of interest

The author confirms that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this study that could have influenced its outcomes.

References

Andrade, P.S. and Saraiva, A.A. 2010. Physical and mechanical characterization of phyllites and metagreywackes in central Portugal. *Bulletin of Engineering Geology and the Environment*, vol. 69, pp. 207–214. https://doi.org/10.1007/s10064-009-0251-9

ASTM. 2013. Standard Test Method for Determination of Rock Hardness by Rebound Hammer. ASTM International. West Conshohocken, PA. pp. 1–6.

Atapour, H. and Mortazavi, A. 2018. The effect of grain size and cement content on index properties of weakly solidified artificial sandstones. *Journal of Geophysics and Engineering*, vol. 15, pp. 613–619. https://doi.org/10.1088/1742-2140/aaa14a

Aydin, A. and Basu, A. 2005. The Schmidt hammer in rock material characterization. *Enginering Geology*, vol. 81, pp. 1–14. https://doi.org/10.1016/j.enggeo.2005.06.006

Aydin, A. 2009. ISRM suggested method for determination of the Schmidt hammer rebound hardness: revised version. *International Journal of Rock Mechanics and Mining Sciences*, vol. 46, pp. 627–634. https://doi.org/10.1007/978-3-319-07713-0_2

Barton, N. and Choubey, V. 1977. The shear strength of rock joints in theory and practice. *Rock Mechanics Felsmechanik Mecanique des Roches*, vol. 10, pp. 1–54.

Bilgin, N., Seyrek, T., Erding, E., and Shahriar, K. 1990. Roadheaders glean valuable tips for Istanbul Metro. *Tunnels and Tunnelling International*, vol. 22, pp. 29–32.

Buyuksagis, I.S. and Goktan, R.M. 2007. The effect of Schmidt hammer type on uniaxial compressive strength prediction of rock. *International Journal of Rock Mechanics and Mining Sciences*, vol. 44, pp. 299–307. https://doi.org/10.1016/j.ijrmms.2006.07.008

Cerna, B. and Engel, Z. 2011. Surface and sub-surface Schmidt hammer rebound value variation for a granite outcrop. *Earth Surface Processes and Landforms*, vol. 36, pp. 170–179. https://doi.org/10.1002/esp.2029

Dąbski, M. 2009. Early stages of weathering of glacially-abraded limestone surfaces as determined by various Schmidt hammer tests: Biferten glacier forefield, Glarner Alps (Switzerland). *Landform Analysis*, vol. 11, pp. 11–15.

Deere, D.U. and Miller, R. 1966. Engineering classification and index properties for intact rock. *Technical Report Air Force Weapons Laboratory*, vol. 1, pp. 65–116.

Dursun, A.E. and Terzioglu, H. 2019. Prediction of specific energy using p-wave velocity and Schmidt hammer hardness values of rocks based on laboratory studies. *Scientific Mining Journal*, vol. 58, pp. 173-187.

Fener, M., Kahraman, S., Bilgil, A., and Gunaydin, O. 2005. A comparative evaluation of indirect methods to estimate the compressive strength of rocks. *Rock Mechanics and Rock Engineering*, vol. 38, pp. 329–343. https://doi.org/10.1007/s00603-005-0061-8

Gokceoglu, C. and Aksoy, H. 2000. New approaches to the characterization of clay-bearing, densely jointed and weak rock masses. *Engineering Geology*, vol. 58, pp. 1–23. https://doi.org/10.1016/S0013-7952(00)00032-6

Goktan, R.M. and Gunes, N. 2005. A comparative study of Schmidt hammer testing procedures with reference to rock cutting machine performance prediction. *International Journal of Rock Mechanics and Mining Sciences*, vol. 42, pp. 466–472. https://doi.org/10.1016/j.ijrmms.2004.12.002

Goudie, A.S. 2006. The Schmidt Hammer in geomorphologial research. *Progress in Physical Geography*, vol. 30, pp. 703–718. https://doi: 10.1177/0309133306071954

Guney, A., Altindag, R., Yavuz, H., and Sarac, S. 2005. Evaluation of the relationships between Schmidt hardness rebound number and other (engineering) properties of rocks. *Proceedings of the 19th International Mining Congress and Fair of Turkey, IMCET2005*. İzmir, Turkey. pp. 83–89.

Hack, H.R.G.K., Hingira, J., and Verwaal, W. 1993. Determination of discontinuity wall strength by Equotip and ball rebound tests. *International Journal of Rock Mechanics and Mining Sciences*, vol. 30, pp. 151–155. https://doi: 10.1016/0148-9062(93)90707-K

Han, S., Li, H., Li, M., and Rose, T. 2019. A deep learning based method for the non-destructive measuring of rock strength through hammering sound. *Applied Sciences*, vol. 9, pp. 1–14. https://doi: 10.3390/app9173484

Hsiung, S.M., Ghosh, A., and Chowdhury, A.H. 1995. On natural rock joint profile characterization using self-affine fractal approach. *Proceedings of 35th US Symposium on Rock Mechanics*. United States Rock Mechanics Society. pp. 681–687.

Hucka, V. 1965. A rapid method of determining the strength of rocks in situ. *International Journal of Rock Mechanics and Mining Sciences*, vol. 2, pp. 127–134. https:// doi: 10.1016/0148-9062(65)90009-4

ISRM. 1978. Suggested methods for determining hardness and abrasiveness of rocks. *International Journal of Rock Mechanics, Mineral Science and Geomechanical Abstracts*, vol. 15, pp. 89–98.

ISRM. 2007. *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974–2006. Suggested Methods Prepared by the Commission on Testing Methods, International Society for Rock Mechanics*. Ulusay, R. and Hudson, J. A. (ed.). Compilation arranged by the ISRM Turkish National Group, Ankara, Turkey.

Jamshidi, A., Yazarloo, R., and Gheiji, S. 2018. Comparative evaluation of Schmidt hammer test procedures for prediction of rocks strength. *International Journal of Mining and Geo-Engineering*, vol. 52, pp. 199–206. https://doi: 10.22059/IJMGE.2018.244154.594702

Kahraman, S. 2001. Evaluation of simple methods for assessing the uniaxial compressive strength of rock. *International Journal of Rock Mechanics and Mining Sciences*, vol. 38, pp. 981–994. https://doi: 10.1016/S1365-1609(01)00039-9

Kahraman, S., Bilgin, N., and Feridunoglu, C. 2003. Dominant rock properties affecting the penetration rate of percussive drills. *International Journal of Rock Mechanics and Mining Sciences*, vol. 40, pp. 711–723. https://doi: 10.1016/S1365-1609(03)00063-7

Kahraman, S., Fener, M., and Gunaydin, O. 2002. Predicting the Schmidt hammer values of in-situ intact rock from core sample values. *International Journal of Rock Mechanics and Mining Sciences*, vol. 39, pp. 395–399. https://doi: 10.1016/S1365-1609(02)00028-X

Karakul, H. 2017. Investigation of saturation effect on the relationship between compressive strength and Schmidt hammer rebound. *Bulletin of Engineering Geology and the Environment*, vol. 76, pp. 1143–1152. https://doi.org/10.1007/s10064-016-0883-5

Karaman, K. 2020. Kaya Yüzey Pürüzlülüğünün Schmid Sertliği Ölçümlerine Etkisi. *Scientific Mining Journal*, vol. 59, pp. 5–24 (in Turkish).

Karaman, K. and Bakhytzhan, A. 2020. Effect of rock mineralogy on mortar expansion. *Geomechanics and Engineering*, vol. 20, pp. 233–241. https://doi.org/10.12989/gae.2020.20.3.233

Karaman, K. and Kesimal, A. 2015a. Correlation of Schmidt rebound hardness with uniaxial compressive strength and p-wave velocity of rock materials. *Arabian Journal for Science and Engineering*, vol. 40, pp. 1897–1906. https://doi: 10.1007/s13369-014-1510-z

Karaman, K. and Kesimal, A 2015B. A comparative study of Schmidt hammer test methods for estimating the uniaxial compressive strength of rocks. *Bulletin of Engineering Geology and the Environment*, vol. 74, pp. 507–520. https://doi: 10.1007/s10064-014-0617-5

Karpuz, C. 1990. A classification system for excavation of surface coal measures. *Mining Science and Technology*, vol. 11, pp. 157–163. https://doi: 10.1016/0167-9031(90)90303-A

Karpuz, C. and Pasamehmetoglu, A.G. 1997. Field characterisation of weathered Ankara andesites. *Engineering Geology*, vol. 46, pp. 1–17. https://doi: 10.1016/s0013-7952(96)00002-6

Katz, O., Reches, Z., and Roegiers, J.C 2000. Evaluation of mechanical rock properties using a Schmidt Hammer. *International Journal of Rock Mechanics and Mining Sciences*, vol. 37, pp. 723–728. https://doi: 10.1016/S1365-1609(00)00004-6

Kidybiński, A. 1968. Rebound number and the quality of mine roof strata. *International Journal of Rock Mechanics and Mining Sciences*, vol. 5, pp. 283–292. https://doi: 10.1016/0148-9062(68)90001-6

Kong, F. and Shang, J. 2018. A validation study for the estimation of uniaxial compressive strength based on index tests. *Rock Mechanics and Rock Engineering*, vol. 51, pp. 2289–2297. https://doi.org/10.1007/s00603-018-1462-9

Kogure, T. 2019. Analysis of Schmidt hammer rebound test results with repetitive impacts for determining the mechanical characteristics of weathered pyroclastic rock surfaces: a case study along the Isotake coast, Japan. *Bulletin of Engineering Geology and the Environment*, vol. 78, pp. 3425–3432. https://doi: 10.1007/s10064-018-1334-2

Matthews, J.A., Owen, G., and Winkler, S. 2016. A rock-surface microweathering index from Schmidt hammer R-values and its preliminary application to some common rock types in southern Norway. *Catena*, vol. 143, pp. 35–44. https://doi: 10.1016/j.catena.2016.03.018

Nazir, R., Momeni, E., Armaghani, D.J., and Amin, M.F.M. 2013. Prediction of unconfined compressive strength of limestone rock samples using L-type Schmidt hammer. *Electronic Journal of Geotechnical Engineering*, vol. 18, pp. 1767–1775.

Okay, A.I. and Sahinturk, O. 1997. Geology of the Eastern Pontides. *Regional and Petroleum geology of the Black Sea and Surrounding Region*. American Association of Petroleum Geologists, Tulsa, Oklahoma, USA, pp. 291–311.

Ozkan, I. and Bilim, N. 2008. A new approach for applying the in-situ Schmidt hammer test on a coal face. *International Journal of Rock Mechanics and Mining Sciences*, vol. 45, pp. 888–898. https://doi: 10.1016/j.ijrmms.2007.09.012

Poole, R.W. and Farmer, I.W. 1978. Geotechnical factors affecting tunnelling machine performance in coal measures rock. *Tunnels and Tunnelling*, vol. 10, pp. 27–30.

Poole, R.W. and Farmer, I.W. 1980. Consistency and repeatability of Schmidt Hammer rebound data during field testing. *International Journal of Rock Mechanics and Mining Sciences*, vol. 17, pp. 167–171. https://doi: 10.1016/0148-9062(80)91363-7

Schmidt, E. 1951. A non-destructive concrete tester. *Concrete*, vol. 59, pp. 34–35.

Shalabi, F.I., Cording, E.J., and Al-Hattamleh, O.H. 2007. Estimation of rock engineering properties using hardness tests. *Engineering Geology*, vol. 90, pp. 138–147. https://doi: 10.1016/j.enggeo.2006.12.006

Sheorey, P.R., Barat, D., and Das, M.N. 1984. Schmidt hammer rebound data for estimation of large scale in situ coal strength. *International Journal of Rock Mechanics and Mining Sciences*, vol. 21, pp. 39–42. https://doi: 10.1016/0148-9062(84)90008-1

Soiltest, INC. 1976. Operating instructions—concrete test hammer. Soiltest Inc, Evanston, IL.

Sumner, P. and Nel, W. 2002. The effect of rock moisture on Schmidt hammer rebound: tests on rock samples from Marion Island and South Africa. *Earth Surface Processes and Landforms*, vol. 27, pp. 1137–1142.

Tugrul, A. and Zarif, I.H. 1999. Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey. *Engineering Geology*, vol. 51, pp. 303–317. https://doi:10.1016/S0013-7952(98)00071-4

Vasconcelos, G., Lourenço, P.B., Alves, C.A., and Pamplona, J. 2007. Prediction of the mechanical properties of granites by ultrasonic pulse velocity and Schmidt hammer hardness. *Proceedings of the 10th North American Mason Conference*, pp. 980–991.

Wang, M. and Wan, W. 2019. A new empirical formula for evaluating uniaxial compressive strength using the Schmidt hammer test. *International Journal of Rock Mechanics and Mining Sciences*, vol. 123, p. 104094. https://doi: 10.1016/j.ijrmms.2019.104094

Wang, H., Lin, H., and Cao, P. 2017. Correlation of UCS rating with Schmidt hammer surface hardness for rock mass classification. *Rock Mechanics and Rock Engineering*, vol. 50, pp. 195–203. https://doi.org/10.1007/s00603-016-1044-7

Williams, R.B.G. and Robinson, D.A. 1983. The effect of surface texture on the determination of the surface hardness of rock using the schmidt hammer. *Earth Surface Processes and Landforms*, vol. 8, pp. 289–292. https://doi: 10.1002/esp.3290080311

Wilson, P., Linge, H., and Matthews, J.A. 2019. Comparative numerical surface exposure-age dating (10Be and Schmidt hammer) of an early-Holocene rock avalanche at Alstadfjellet, Valldalen, southern Norway. *Geografiska Annaler Series A Physical Geography*, vol. 101, pp. 293–309. https://doi: 10.1080/04353676.2019.1644815

Wilson, P. and Matthews, J.A. 2016. Age assessment and implications of late Quaternary periglacial and paraglacial landforms on Muckish Mountain, northwest Ireland, based on Schmidt-hammer exposure-age dating (SHD). *Geomorphology*, vol. 270, pp. 134–144. https://doi: 10.1016/j.geomorph.2016.07.002

Yagiz, S. 2009. Predicting uniaxial compressive strength, modulus of elasticity and index properties of rocks using the Schmidt hammer. *Bulletin of Engineering Geology and the Environment*, vol. 68, pp. 55–63. https://doi: 10.1007/s10064-008-0172-z

Yilmaz, N.G. and Goktan, R.M. 2019. Comparison and combination of two NDT methods with implications for compressive strength evaluation of selected masonry and building stones. *Bulletin of Engineering Geology and the Environment*, vol. 78, pp. 4493–4503. https://doi: 10.1007/s10064-018-1382-7

Yilmaz, I. and Sendir, H. 2002. Correlation of Schmidt hardness with unconfined compressive strength and Young's modulus in gypsum from Sivas (Turkey). *Enginering Geology*, vol. 66, pp. 211–219. https://doi: 10.1016/S0013-7952(02)00041-8

Young, R.P. and Fowell, R.J. 1978. Assessing rock discontinuities. *Tunnels and Tunnelling*, vol. 10, pp. 45–48.

Yuksek, S. 2019. Mechanical properties of some building stones from volcanic deposits of Mount Erciyes (Turkey). *Materiales de Construcción*, vol. 69, no. 334, p. 187. https://doi: 10.3989/mc.2019.04618. ◆