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ESTIMATING THE HARDNESS AND ABRASION PROPERTIES OF IGNEOUS ROCKS FROM CERCHAR INDENTATION DEPTH (CID)

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Highlights

- A new experimental data was obtained by calculating the average depth of the scratch that emerged in the CAI test.
- The CID parameter is directly related to the hardness and abrasiveness of the rocks.
- The strongest statistical relationships with the CID parameter belong to Bohme Abrasion Resistance.
- Carefully prepared core samples are needed to measure the CID parameter.

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ABSTRACT: The most known and applied method for determining the abrasivity of rocks is the Cerchar Abrasivity Index (CAI). Properties of rocks such as abrasive mineral content, density, strength, and degree of cementation are the main factors affecting abrasivity, and these parameters likewise control their hardness properties. In this study, the average scratch depth formed on the rock surface after the CAI test was determined and it was investigated whether this calculated new parameter had the properties to represent the rock. Measurements were taken from four points along the scratch line formed on the surface with the help of a comparator and the average value was defined as the Cerchar Indentation Depth (CID). Measurements have shown that igneous rocks have CID values in the range of 0.01 mm-0.68 mm. Apart from the CID parameter, nine different properties (hardness, abrasivity, and physical) of fifty igneous rocks were tested. Statistically significant results were obtained by establishing relationships between CID and other rock mechanics tests. In CAI tests, it has been shown that CID measurements can be determined very sensitively if well-leveled core samples with parallel lower and upper surfaces are used. It has been determined that the CID value is directly related to the investigated rock properties and can be used as very useful experimental data in estimation studies.

Keywords: *Cerchar indentation depth, Cerchar abrasivity index, Abrasion, Hardness, Regression*

1. INTRODUCTION

In mining works, excavation is carried out either by the drilling-blasting method or by mechanized methods. All tools used in mining are subject to abrasion because they interact with the rock. In the meantime, deformation and fragmentation occur in the rock. Especially in mining operations, increased tunnel advancement rates or increased production rates require more rock abrasion information. By predicting rock abrasivity according to changing geology and rock type, project budgets can be controlled by preventing unexpected tool abrasion. Rock abrasion can be defined as the detachment of particles from the material surface, while tool abrasion can be defined as the loss of tool material interacting with the rock. The CAI is an index determination method for the abrasivity of rock and is frequently used in academic research as well as industry. The CAI test method is highly preferred due to its fast and simple applicability and the use of a small number of rock samples.

Hardness is defined as a rock's resistance to an object impacting or submerging on a rock's surface. Rock hardness is a function of the hard mineral composition and the strength and bonding capacity of the matrix material. Applications, where hardness is important, are engineering studies where rock-metal interaction is intense. Mining operations such as rippering, drilling, crushing, transportation, grinding, and excavation can be shown among these engineering applications. The most widely used rock hardness methods are Schmidt hammer hardness (SHH) and Shore schlerescope hardness (SSH) due to the advantage of being applicable in the field. Hardness methods such as Brinell hardness (HB) and Vickers hardness (HV) are designed for metal. It requires special tools with certain characteristics and their use in rock engineering applications is limited. Among these methods, the Indentation hardness index (IHI) is the newest proposed method for determining rock hardness. Determining the hardness and excavability of rocks can be defined as the main objectives of the CAI test. At the Montreal meeting of the International Society of Rock Mechanics, it was suggested that the CAI test be used as a

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standard rock mechanics test on the cuttability, drillability, and excavability of rocks [1]. The American Society for Testing and Materials has published a standard for CAI testing [2]. Many aspects of the original design and modified CAI have been studied by various researchers.

Using in-situ measurements, Johnson and Fowell [3] showed that the cutter consumption of excavators is directly related to the CAI values of the rocks. Çopur and Eskikaya [4] determined some physical and mechanical properties of marls in the TKİ Eynez region and made a classification in the direction of workability with the mechanized method. Al-Ameen and Waller [5] investigated the relationship between rock strength and CAI. The authors determined that some high-strength rocks with low abrasive mineral content may have a high abrasivity index, while some low-strength rocks with high abrasive mineral content may have a low abrasivity index. Plinninger et al. [6] determined correlations between CAI and Modulus of Elasticity (E), equivalent quartz content.

Yaralı and Akçın [7] determined the hardness of the rocks with the help of a modified experimental setup and drill bits with two different tip angles and revealed the relationships between the drill bit angle and CAI. Tercan and Ozcelik [8] investigated the relationships between the mechanical and hardness properties of andesites and their mechanical and abrasion properties and obtained strong correlations. Mateus et al. [9] developed correlations between IHI values (248 samples) and mechanical properties of Colombian sandstones. Tumac et al. [10] calculated two different SSH values and deformation coefficient (K) for 30 different rocks. Using these values, they determined the relationship between SSH values, K, and Roadheader cutting speed for different rock types. Regression analysis results showed satisfactory correlations.

Kahraman et al. [11] focused on the predictability of E and Uniaxial compressive strength (UCS) values of Misis fault breccia from some indirect methods such as unit volume weight (UW), CAI, and P-wave velocity (Vp) using neural network analysis and regression analysis. In his study, Deliormanli [12] used simple and multiple regression methods to determine the strength values of rocks such as UCS, direct shear strength (DSS), and abrasion properties such as BSA, Wide-Wheel Abrasion (WWA) with the help of CAI. The first chart they created according to the results of the study shows the relationship between CAI-UCS-DSS, while the second chart shows the relationship between CAI-BSA-WWA.

Dipova [13] investigated the relationships between CAI data and strength properties of weak limestones by testing rock samples from the inner city tunnel of Austin (Texas, USA). Considering the abrasion of rock and steel together, wear on the steel and indentation on the rock that occured at the same time were measured and tried to be correlated. As a result of statistical studies, the researcher determined that there is a relationship between CAI and UCS and Brazilian tensile strength (BTS) values, and also between CAI and CID and between CID and UCS and BTS values.

Boutrid et al. [14] showed that there are significant correlations between HB and the strength properties of rocks, according to the results of the Hassi Messaoud field study. Yaralı [15] conducted Point load index (Is), CAI, SSH, UCS, and BTS experiments on 29 coal-surrounding rocks, all of which are sandstones. Then, CAI evaluated the strength and index test results with regression analysis methods. Teymen [16] conducted a statistical study to estimate difficult and time-consuming bedrock mechanics tests with CAI. Apart from the parameters that are frequently researched in the literature, the relationships between parameters such as BSA, rate of penetration (ROP), block punch index (BPI), fracture toughness (K_{IC}), and CAI have been investigated in detail.

In this study, new experimental data was obtained by measuring the depth of the scratch formed on the surface of the rocks in the CAI test. Depth measurements were made at four points along the one-centimeter scratch line using a comparator. The mean value is defined as the CID. Abrasivity and hardness tests were applied to fifty igneous rocks and the relationships between these parameters and CID were investigated. Statistically significant results were obtained with the CID parameter. In addition to simple regression analyses (SRA), nonlinear multiple regression analyses (NMRA) were performed by including the physical properties of rocks such as unit volume weight (UW) and porosity (Pg) into the models. Performance indices were used to measure the estimation capacity of the equations produced by regression analysis and to determine their reliability.

As it is known, the CAI test is a practical abrasivity test method that can be applied in the field and is designed to be measured on rough rock surfaces. This study was carried out to estimate some properties of many igneous rocks under standard conditions. In such prediction studies, it is of great importance to test the rocks under the same conditions. Core samples with regular geometry were used to determine the CAI values of the rocks under the same conditions. It has been determined that accurate measurements can be made on the surfaces of the cores cut with a rough cutting machine, provided that no polishing is done. The fact that the test samples used had a shaped geometry allowed data to be obtained from the scratches formed on the rock surface after the CAI test. By measuring the average scratch depth, it was possible to obtain a new/additional data set in addition to the CAI data. The measurement method presented in this study is experimental and open to improvement/updating. While the data obtained by the CAI test is an indicator of the wear occurring in the excavation tools used in mining, the CID value represents the deformation/wear occurring in the rock in contact with the excavation tools. It is thought that the CID value can be considered as a new rock property in this respect.

2. MATERIAL AND METHODS

19 of the igneous rocks used in the study are of volcanic origin, 15 of them are of plutonic, 9 of them are pyroclastic and 7 of them are of subvolcanic origin. Laboratory experiments were carried out on block and core samples taken from fresh parts of 50 rocks. Rocks types, geological origins, and average test results are given in Table 1. The test devices used in the study are shown in Figure 1.

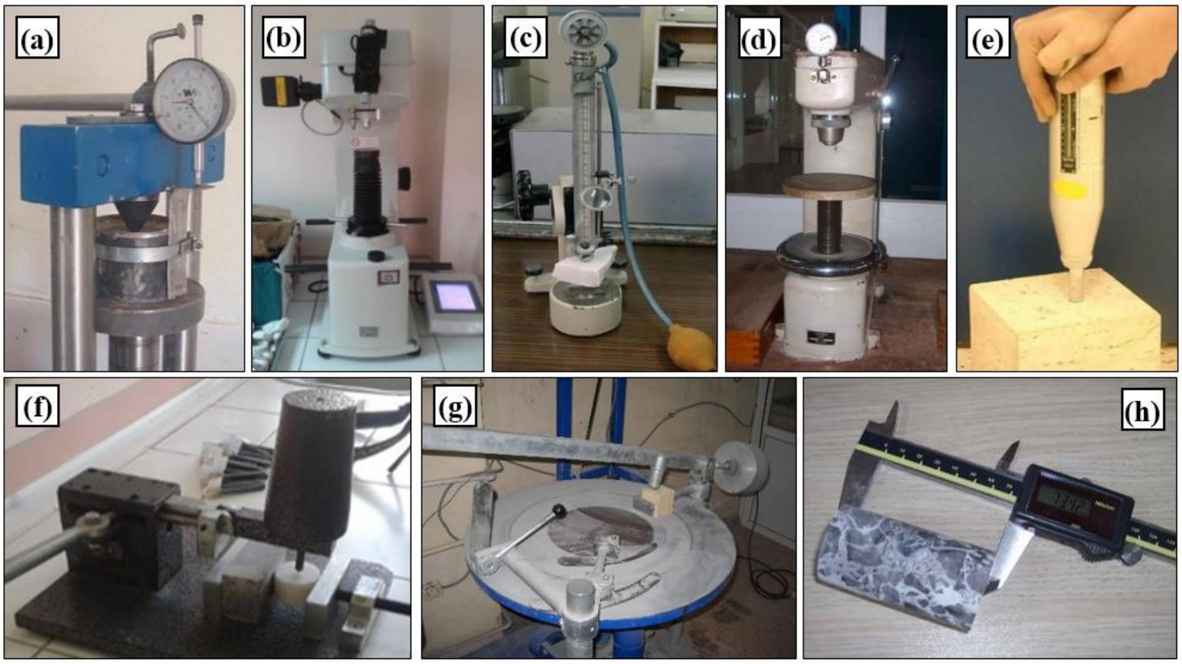

Figure 1. Test devices a) IHI, b) HV, c) SSH, d) HB, e) SHH, f) CAI, g) BSA, and h) UW-Pg

2.1. Cerchar Abrasivity Index (CAI)

The standard Cerchar test [17] instrument was used in the CAI test (Fig. 1f). The steel inserts used in the experiment had a Rockwell HRC 54-56 hardness, 2000 MPa tensile strength, and a 90° apex angle. This conical steel tip was pulled for 10 mm at a speed of 1 mm/s on the rock sample surface with a pressing force of 70 N and the size of the abrasion surface formed on the tip of the tip was measured. Abrasivity measurements were carried out on core samples with a diameter of 42-54 mm and a length of 30-50 mm. The cores were cut on a rough cutting machine and no sanding/polishing process was specifically applied to their surfaces. If the surface to be worn is completely polished, the steel tip does not sink into the rock and slides easily along the surface. If the rock surface on which the process will be applied is completely polished, the steel tip does not sink into the rock and slides easily along the surface. This makes a reliable measurement impossible. Tip wear was detected using a high-resolution camera and a calibrated digital caliper program.

2.2. Schmidt Hammer Hardness (SHH)

An N-type Schmidt hammer was used for the SHH hardness test (Fig. 1e). Measurements were made from smooth surfaces of core rock blocks [18]. 20 hits were applied to the block surfaces and the average of the 10 highest values was calculated. A correction factor was used to correct the measured SHH values.

2.3. Shore Schlerescope Hardness (SSH)

SSH is a method of measuring the surface hardness of any rock in terms of elasticity. The test was carried out with a C-2 model device on rock samples with a surface area of approximately 14 cm^2 and a thickness of 2 cm [18]. The measurements were repeated 20 times with at least 5 mm intervals and the mean of the ten highest measurements was determined as the SSH value (Figure 1c).

2.4. Brinell Hardness (HB)

HB is a commonly used test method for metals but is generally not preferred for rocks due to its brittle nature. A 30 mm thick and 42 mm diameter core and a 10 mm diameter spherical steel ball were used for the experiment. By applying a load of up to 3000 kg on the steel ball, the pressure was applied to the rock surface of the ball for 30 seconds (Figure 1d). The HB value was determined by dividing the load applied to the rock by the calculated indentation surface area [19].

2.5. Vickers Hardness (HV)

The large-scale HV tester shown in Figure 1b was developed as an alternative to the HB method. For the experiment, loads varying between 1-50 kg, depending on the type of rock, were applied to the rock surface for 10-15 seconds. The trace formed on the rock surface was measured under the microscope and the average of the two diagonal values was calculated. Similar to the HB test, the ratio of the applied load to the calculated sinking area gives the HV value [20].

2.6. Indentation Hardness (IHI)

Tests were performed with a 30 kN capacity point load tester (Fig. 1a). Smooth core specimens (42 mm diameter and 30 mm thickness) placed in a steel frame with resin were used in the experiment. Penetration amounts were monitored with a manual comparator. IHI values for rocks loaded up to 20 kN were calculated by dividing the maximum load by the maximum penetration values.

2.7. Bohme Surface Abrasion (BSA)

This test is a test defined in [21] to determine the surface abrasion resistance of the rocks used as building and covering stones. After drying in the oven, the cube samples with a side length of 71 mm prepared for the experiment were measured and recorded with the help of a caliper. A pressure of 0.6 kg/cm^2 was created on the friction strip by applying a load of 30 kg on the sample with a steel lever. 20 abrasion periods (total 440 cycles) were applied for each sample and approximately 20 g of abrasive dust was used for each cycle. After the test, the dimensions were re-measured and the amount of abrasion was determined volumetrically (Figure 1g).

2.8. Unit Weight (UW), Apparent Porosity (Pg)

Laboratory tests described in the ISRM [22] standard have been used to determine the physical properties of the rocks. The core samples were dried at 105ºC for 24 hours, cooled to room temperature in a desiccator, and their dry weights were determined. Samples were kept in water for 24 hours and their saturation weights were determined. UW and Pg values were calculated with the help of the volumes, and saturated-dry weights of the samples whose dimensions were measured with 0.1 mm precision with the help of calipers (Figure 1h).

2.9. Cerchar Indentation Depth (CID)

The CAI test, the details of which are given in Section 2.1, was applied to the disc-shaped specimens prepared by cutting the cores in a rough stone-cutting machine. The samples used in the CAI experiment and with 1 cm long scratches on them were taken to the measurement setup shown in Figure 2 for CID measurements. The setup is formed by mounting a needle thick enough to penetrate the scratches formed on the rock surface to the tip of a comparator with 100 times magnification. The device to which the comparator is connected was measured and fixed in contact with the rock surface at an angle of 90 degrees. The average of the depth measurements taken from four points along the one cm-long scratch line on the rock surface with the help of a comparator is called the CID. The details and constraints to be considered to make these measurements can be summarized as follows.

The test can be applied to core or prismatic specimens. For the measurements to be carried out reliably and precisely, samples with their lower and upper surfaces cut parallel to each other must be prepared. Cores should be cut with a rough cutting machine at a very low speed. Samples with saw marks on the surface after cutting or with roughness at a level that would affect measurements should not be used in the test. The measured surfaces of core samples without polishing reflect the structure and texture of the rock. As it is known, all rocks contain pores, although they vary depending on their formation mechanism. The steel tip used during the CAI test, with the help of the weight, sinks into these pores to a certain extent, allowing the test to be carried out healthily.

A precise measurement will be made by determining the level difference between the point where the measurement is made within the scratch and the flat area at the edge of this point (as close as possible). Average sample thickness should not be used in calculations. Possible errors will be avoided by making the measurements as described. It should be noted that all rocks were cut using the same cutting machine and the experiments were carried out under the same conditions. The CID value, which is the subject of this study, is not an absolute rock property but is proposed as a new parameter that will enable us to compare different rocks relatively. Therefore, negligible measurement errors resulting from possible roughness on the rock surface will be valid for all rocks compared.

Table 1. Tested rocks and average test results.

No	Rock Type	Rock Class	CID mm	CAI *	BSA cm³/50cm²	SSH rebound	SHH rebound	HB kg/mm²	HV kg/mm²	IHI kN/mm	UW g/cm³	Pg %
1	Andesite-1-	Volcanic	0.142	2.75	22.11	77.25	53.40	101.27	127.30	20.01	2.35	6.50
2	Andesite-2-	Volcanic	0.038	3.20	16.98	72.00	52.92	384.68	237.30	21.60	2.64	0.33
3	Andesite-3-	Volcanic	0.045	2.79	16.86	71.50	54.12	203.00	136.20	18.12	2.60	2.60
4	Andesite-4-	Volcanic	0.242	2.32	28.00	53.67	42.30	8.12	59.78	7.89	2.15	10.58
5	Aplite	Subvolcanic	0.017	4.23	7.86	88.80	58.23	450.96	415.40	22.99	2.63	0.30
6	Basalt-1-	Volcanic	0.055	3.09	12.03	65.75	59.28	108.49	131.50	14.08	2.69	4.22
7	Basalt-2-	Volcanic	0.045	4.10	9.28	74.80	57.28	269.86	134.30	26.65	2.56	1.58
8	Basalt-3-	Volcanic	0.024	4.38	13.53	84.60	53.82	304.35	231.20	22.85	2.71	0.60
9	Basalt-4-	Volcanic	0.042	3.75	13.50	72.00	57.45	194.40	128.45	23.24	2.64	2.29
10	Basalt-5-	Volcanic	0.151	3.30	18.02	67.20	50.31	245.36	125.40	19.81	2.62	2.42
11	Basalt-6-	Volcanic	0.051	3.14	11.25	65.30	52.47	115.89	109.45	18.67	2.69	2.48
12	Basalt-7-	Volcanic	0.156	2.45	18.09	64.86	42.15	72.70	70.45	10.84	2.61	1.82
13	Basalt-8-	Volcanic	0.180	2.80	22.75	65.33	46.12	99.29	33.40	14.39	2.51	3.97
14	Dacite-1-	Volcanic	0.226	2.45	26.07	62.20	40.80	40.96	72.23	14.29	2.26	12.74
15	Dacite-2-	Volcanic	0.083	3.24	33.85	68.75	44.00	115.70	106.74	15.81	2.42	6.80
16	Dacite-3-	Volcanic	0.105	3.05	24.09	62.67	44.12	116.76	66.47	15.99	2.27	9.40
17	Diabase-1-	Subvolcanic	0.087	4.12	17.23	71.60	56.80	351.08	161.50	19.15	2.81	0.70
18	Diabase-2-	Subvolcanic	0.030	4.13	8.86	87.33	60.12	446.54	463.00	22.73	2.83	0.71
19	Diabase-3-	Subvolcanic	0.135	2.95	15.60	63.00	45.26	115.89	78.36	12.15	2.54	2.71
20	Diabase-4-	Subvolcanic	0.112	3.25	16.30	68.00	55.12	108.49	132.26	17.12	2.54	3.13
21	Diorite-1-	Plutonic	0.021	3.29	12.96	82.60	53.71	170.34	181.70	18.08	2.62	0.45
22	Diorite-2-	Plutonic	0.039	2.90	21.68	75.75	52.20	152.66	136.70	10.98	2.67	0.60
23	Dunite-1-	Plutonic	0.117	2.57	29.30	59.67	51.20	140.25	69.50	15.12	2.53	1.83
24	Dunite-2-	Plutonic	0.136	2.38	28.60	58.50	46.00	103.32	100.46	13.43	2.57	0.95
25	Gabbro-1-	Plutonic	0.030	3.32	10.84	88.40	52.20	360.18	250.20	17.47	2.84	1.18
26	Gabbro-2-	Plutonic	0.025	4.14	11.43	85.10	54.00	257.99	282.35	19.76	2.88	0.21
27	Gabbro-3-	Plutonic	0.019	4.49	13.13	85.50	60.24	317.30	390.00	22.19	2.96	0.73
28	Gabbro-4-	Plutonic	0.091	2.96	20.28	77.50	51.59	321.14	157.90	23.54	2.69	1.27
29	Granite-1-	Plutonic	0.056	3.88	11.29	72.75	56.00	196.06	135.60	26.94	2.71	0.86
30	Granite-2-	Plutonic	0.017	3.91	12.98	96.00	50.96	243.32	150.50	21.98	2.58	1.21
31	Granite-3-	Plutonic	0.058	3.62	10.29	92.00	54.15	175.03	152.80	16.95	2.59	0.99
32	Granite-4-	Plutonic	0.031	3.77	16.80	88.20	52.00	254.45	122.00	18.40	2.57	0.91
33	Granite-5-	Plutonic	0.030	4.18	12.50	91.00	60.40	255.52	119.60	19.92	2.59	0.49
34	Granodiorite	Plutonic	0.021	3.44	8.50	75.20	61.78	241.15	160.45	15.87	2.61	1.12
35	Ignimbrite-1-	Pyroclastic	0.680	0.75	139.13	9.17	16.85	1.89	7.45	1.08	1.34	37.48
36	Ignimbrite-2-	Pyroclastic	0.634	0.68	130.00	15.89	22.82	2.22	11.12	1.15	1.52	31.65
37	Ignimbrite-3-	Pyroclastic	0.413	0.97	113.13	15.13	17.78	2.69	9.45	1.21	1.50	30.26
38	Microdiorite-1-	Subvolcanic	0.014	4.86	5.00	85.12	57.33	614.25	511.10	21.14	2.85	0.27
39	Microdiorite-2-	Subvolcanic	0.020	4.30	11.12	93.20	55.00	232.70	232.10	22.90	2.61	1.07
40	Rhyolite-1-	Volcanic	0.098	2.89	22.10	75.10	44.14	95.42	72.10	14.57	2.42	2.91
41	Rhyolite-2-	Volcanic	0.023	4.21	12.06	95.10	58.12	220.93	184.20	22.85	2.56	1.86
42	Spilite	Volcanic	0.050	4.14	13.09	79.75	56.30	207.35	248.10	24.46	2.77	2.01
43	Syenite	Plutonic	0.033	3.02	10.93	88.29	59.85	107.67	166.30	13.79	2.54	0.53
44	Trachyte	Volcanic	0.079	2.45	16.75	55.50	45.60	109.11	50.12	8.90	2.48	6.18
45	Tuff-1-	Pyroclastic	0.421	0.92	63.70	31.75	22.60	15.63	19.40	2.74	1.61	26.85
46	Tuff-2-	Pyroclastic	0.484	1.40	65.59	40.00	23.91	12.00	25.00	6.26	1.89	18.18
47	Tuff-3-	Pyroclastic	0.407	1.27	58.61	37.00	36.50	18.05	9.30	3.57	1.83	25.77
48	Tuff-4-	Pyroclastic	0.563	0.46	70.23	29.50	31.50	6.42	14.00	2.08	1.57	28.14
49	Tuff-5-	Pyroclastic	0.460	0.95	67.00	19.20	22.00	7.48	11.00	3.12	1.70	21.46
50	Tuff-6-	Pyroclastic	0.386	1.31	68.25	32.00	26.15	16.65	30.46	4.23	1.77	18.22

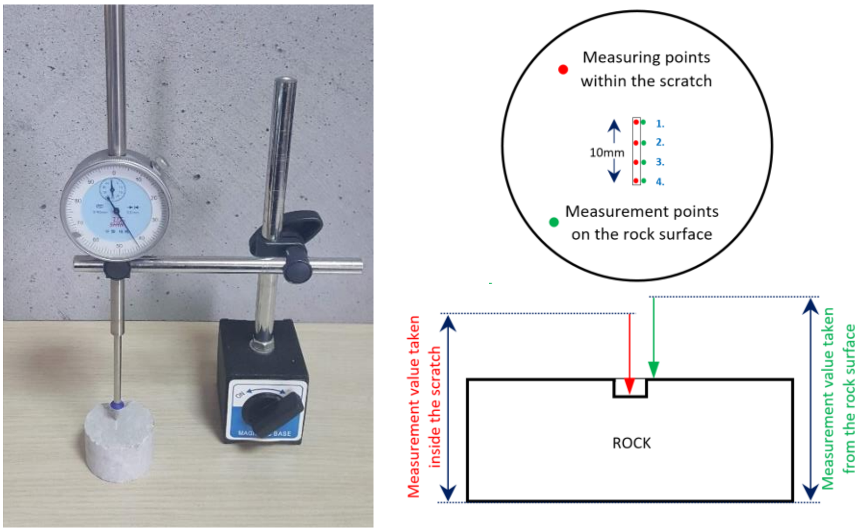

Figure 2. Cerchar indentation depth (CID) measuring device and schematic representation of CID measurement.

3. RESULTS AND DISCUSSION

SRA is frequently used to model the relationships between rock properties. SPSS computer software was used for all statistical analysis. For SRA, all models (Linear, power, logarithmic, cubic, inverse, quadratic, logistic, compound, s-curve, exponential, and growth) in the "Curve Estimation" menu were tried. While choosing the most suitable model for each parameter, attention was paid to ensuring that the models meet all validity/reliability conditions within the 95% confidence interval, as well as having a high coefficient of determination. The equations obtained from SRA using the data set consisting of 50 rocks, the details of which are given in Table 2, are given in Equations 1-7.

SRA

$$SSH = 104.7CID^2 - 178.5CID + 87.7 \quad (1)$$
$$CAI = 4.13 \times 0.05^{CID} \quad (2)$$
$$SHH = 60.5CID^2 - 99.5CID + 59.1 \quad (3)$$
$$HB = 0.0004 \times 303.9^{CID} \quad (4)$$
$$IHI = 0.011 \times 23.87^{CID} \quad (5)$$
$$HV = 10.46CID^{-0.086} \quad (6)$$
$$BSA = 173.2CID^2 - 61.0CID + 10.6 \quad (7)$$

CID values showed significant correlations with the hardness and abrasion values of the rocks, and the coefficients of determination obtained from the equations ranged from 0.81 to 0.91. Detailed graphs of SRA are given in Figures 3-9. Correlation graphs (Figures 3a-9a) were drawn to include the maximum and minimum confidence intervals calculated according to the 95% confidence interval and the maximum and minimum estimation limits. In Figures 3b-9b, it is possible to see the differences (residuals) between the test values of the parameters and the predicted values in detail.

The validity of the equations was determined with the help of F and t-tests at the 95% confidence interval. All of the calculated t-values according to the t-test used to determine the significance level of the R-values of the equations are greater than the table t-values (Table 2). Likewise, the significance coefficients (sig.) of all t-values are less than 0.05, so the established models are valid. Analysis of variance was performed to determine the significance of the regressions. Accordingly, the calculated F values are considerably higher than the tabulated F values. Since the importance of the equations is confirmed by the tests mentioned above, they can be used safely in predictive studies. Since the equations with SRA are estimated with a single independent variable, they are more practical than equations with more than one independent variable.

Table 2. Validity of derived simple regression models (F-test and t-test).

Equation number	Independent variable	B (Coeff.)	Std. Error	R^2	|t| value	*p* value	t table	F value	*p* value	F table
1 (SSH)	CID	-178.5	24.3	0.875	7.34	0.000	2.01	165.1	0.000	3.19
Quadratic	CID^2	104.7	40.5		2.59	0.013				
	(Constant)	87.7	2.0		43.55	0.000				
2 (CAI)	CID	0.05	0.007	0.906	7.25	0.000	2.01	464.1	0.000	3.19
Compound	(Constant)	4.13	0.131		31.51	0.000				
3 (SHH)	CID	-99.46	13.3	0.875	7.47	0.000	2.01	164.7	0.000	3.19
Quadratic	CID^2	60.48	22.2		2.73	0.009				
	(Constant)	59.14	1.1		53.65	0.000				
4 (HB)	CID	0.0004	0.000	0.906	2.42	0.019	2.01	355.0	0.000	3.19
Compound	(Constant)	303.9	28.8		10.54	0.000				
5 (IHI)	CID	0.011	0.003	0.868	3.97	0.000	2.01	315.8	0.000	3.19
Compound	(Constant)	23.87	1.38		17.27	0.000				
6 (HV)	ln (CID)	-0.86	0.06	0.812	14.41	0.000	2.01	207.6	0.000	3.19
Power	(Constant)	10.46	1.73		6.05	0.000				
7 (BSA)	CID	61.0	29.9	0.897	2.04	0.047	2.01	204.8	0.000	3.19
Quadratic	CID^2	173.2	49.8		3.48	0.001				
	(Constant)	10.6	2.5		4.27	0.000				

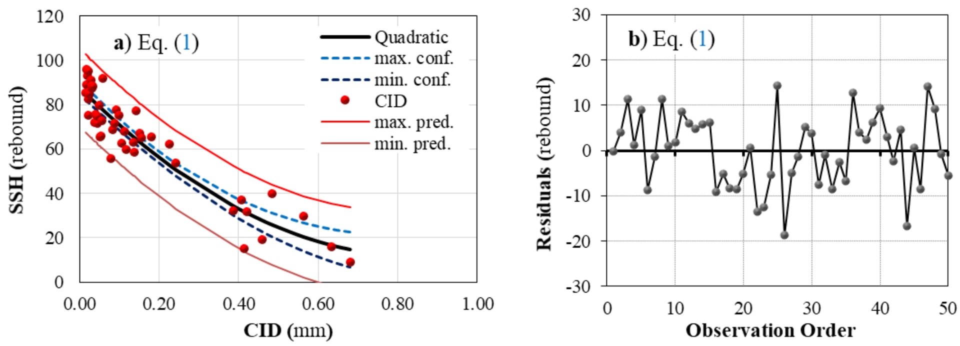

Figure 3. a) SSH-CID correlation graph b) residual graph

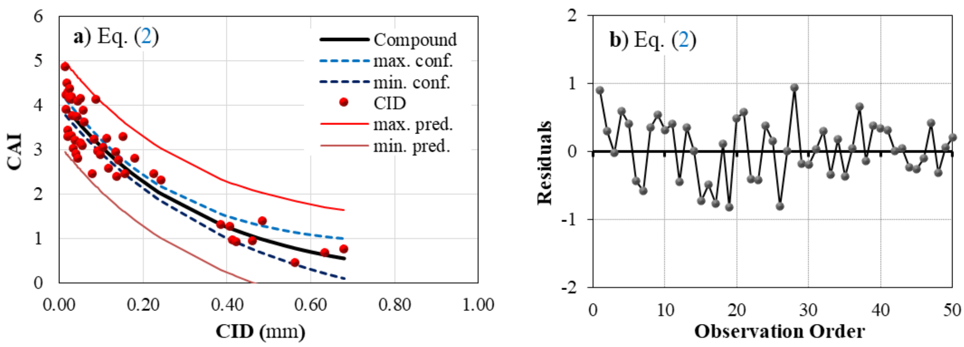

Figure 4. a) CAI-CID correlation graph b) residual graph

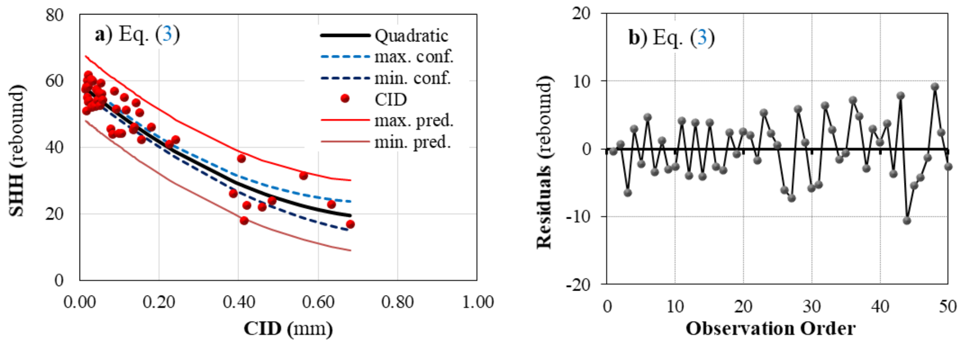

Figure 5. a) SHH-CID correlation graph b) residual graph

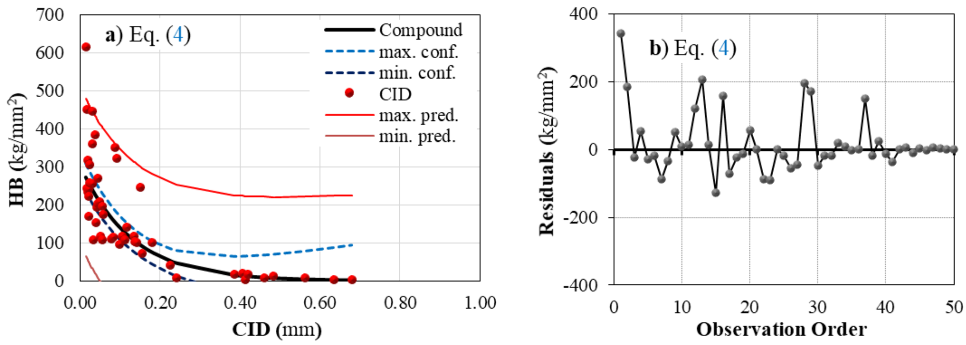

Figure 6. a) HB-CID correlation graph b) residual graph

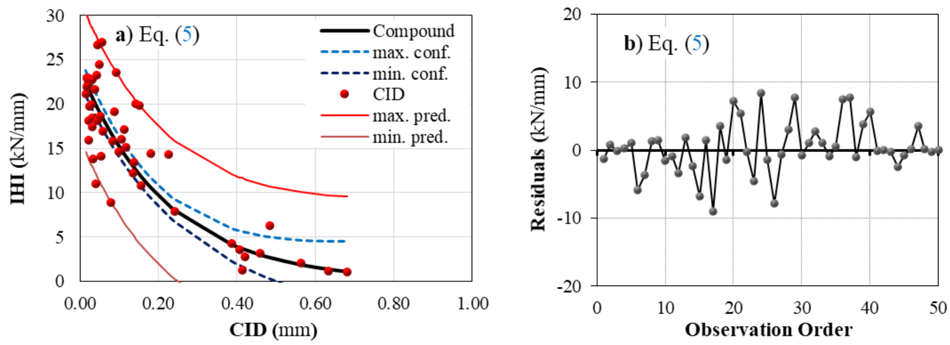

Figure 7. a) IHI-CID correlation graph b) residual graph

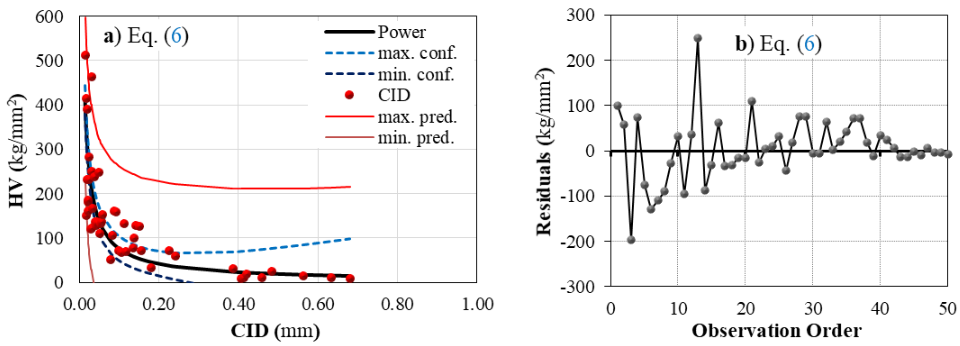

Figure 8. a) HV-CID correlation graph b) residual graph

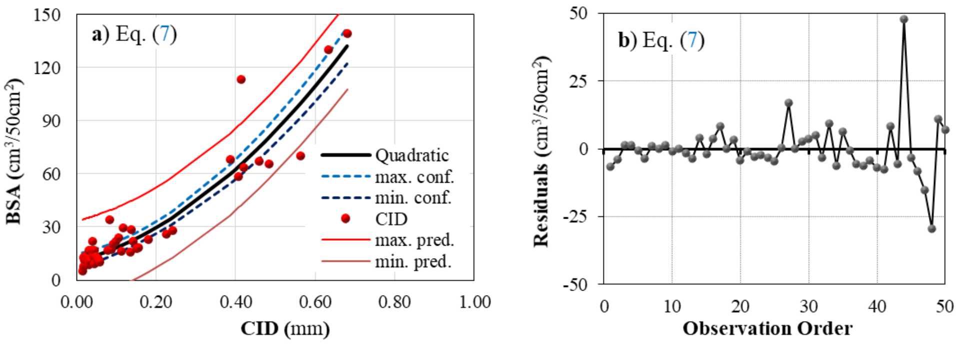

Figure 9. a) BSA-CID correlation graph b) residual graph

Equations with a high coefficient of determination were obtained from SRA. All of these equations are equations whose validity has been proven by F and t-tests, as presented in Table 2. However, as can be seen from the residual graphs given in Figures 3-9, there are points outside the estimation range in some of these equations. To eliminate this handicap, an NMRA study was carried out, in which physical properties of rocks such as UW and Pg were used as independent variables, as well as CID. In this context, two models were constructed. In the first model (NMRA-1), CID and UW were used as independent variables (Eqs. 8-14). In the second model (NMRA-2), the abrasion and hardness properties of the rocks were tried to be estimated with the help of CID, UW, and Pg independent variables (Eqs. 15-21).

Nonlinear regression is a method used to find a nonlinear model of the relationship between a feature determined as the dependent variable and a set of independent variables. Unlike traditional regression, which is limited to the estimation of only linear models, a model with arbitrary relationships between dependent and independent variables can be obtained with the help of nonlinear regression [23]. Multiple nonlinear regression is one of the methods in which Y-dependent values are estimated based on given independent values [24]. In this study, the twin logarithmic method was used in multivariate nonlinear regression analysis for BSA estimation [25]. The parameters used in simple regressions were analyzed in various combinations using the equation described below, and the process was performed using an iterative estimation algorithm. $Y=aX_1^{b1}X_2^{b2}........X_n^{bn}$. Where Y is the dependent variable, a is the intercept, X_1, X_2, and X_n are independent variables and b1, b2, and bn are the regression equation constants. Again, the 95% confidence interval was used to check the validity of the equations obtained from the NMRA studies. The procedure for SRA is also considered here. All of the equations presented are equations with the highest coefficient of determination satisfying the F and t-test conditions.

NMRA-1

$$SSH = 15.97 \times CID^{-0.013} \times UW^{1.2} \quad (8)$$
$$CAI = 0.47 \times CID^{-0.014} \times UW^{1.61} \quad (9)$$
$$SHH = 14.18 \times CID^{-0.06} \times UW^{1.18} \quad (10)$$
$$HB = 1.43 \times CID^{-0.36} \times UW^{4.0} \quad (11)$$
$$IHI = 1.54 \times CID^{-0.1} \times UW^{2.26} \quad (12)$$
$$HB = 0.22 \times CID^{-0.49} \times UW^{5.25} \quad (13)$$
$$BSA = 324.2 \times CID^{0.25} \times UW^{-2.45} \quad (14)$$

NMRA-2

$$SSH = 15 \times CID^{-0.14} \times UW^{1.24} \times P_g^{\ 0.01} \quad (15)$$
$$CAI = 0.43 \times CID^{-0.15} \times UW^{1.68} \times P_g^{\ 0.02} \quad (16)$$
$$SHH = 12.45 \times CID^{-0.07} \times UW^{1.27} \times P_g^{\ 0.02} \quad (17)$$
$$HB = 4.22 \times CID^{-0.25} \times UW^{3.28} \times P_g^{\ -0.17} \quad (18)$$

$$IHI = 1.21 \times CID^{-0.12} \times UW^{2.41} \times P_g{}^{0.04} \quad (19)$$
$$HV = 0.45 \times CID^{-0.42} \times UW^{4.75} \times P_g{}^{-0.11} \quad (20)$$
$$BSA = 419.6 \times CID^{0.3} \times UW^{-2.53} \times P_g{}^{-0.06} \quad (21)$$

Comparison graphs of the estimated and measured values of the three equations produced for each rock feature are given in Figures 10-16. It is very clear that the CID parameter alone is a strong variable in the estimation of the SSH parameter (Figure 10a). The SSH parameter can be strongly estimated by the CID parameter without the need for any physical testing. This situation can be interpreted similarly for the SHH parameter, which is another rock hardness test (Figure 12). Although the CID parameter alone has very high predictive power in the estimation of CAI and IHI parameters, with the inclusion of physical tests in the model, partially stronger estimation equations were obtained (Figures 11 and 14). The positive effect of physical tests in the prediction equations is clearly prominent in the prediction of metal hardness tests such as HB and HV. The low estimation capacities of the regression equations obtained only with CID in the estimation of both parameters can be seen in Figure 13a and Figure 15a. It can be said that the prediction capacities of the models increased in the NMRA equations created with CID and UW in the estimation of these two parameters, but a real significant increase was obtained with the NMRA equations created with CID, UW, and Pg (Figure 13c and Figure 15c). It can be easily said that the rock mechanics property most closely related to the CID parameter is BSA. In the estimation of this parameter, equations with very high predictive power were obtained with both SRA and NMRA models.

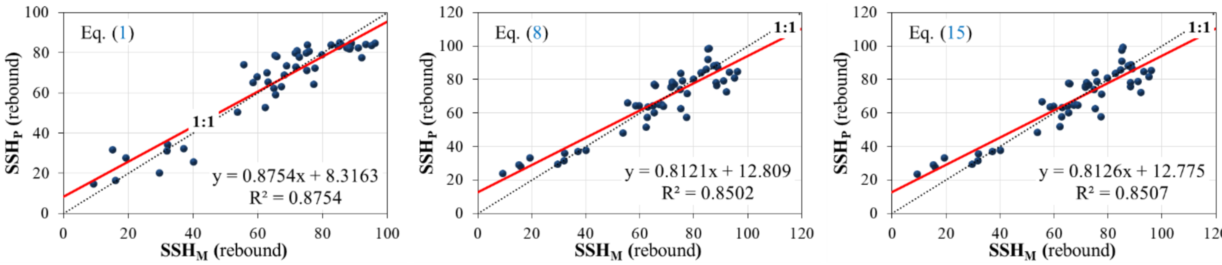

Figure 10. Comparison graphs of measured SSH-predicted SSH.

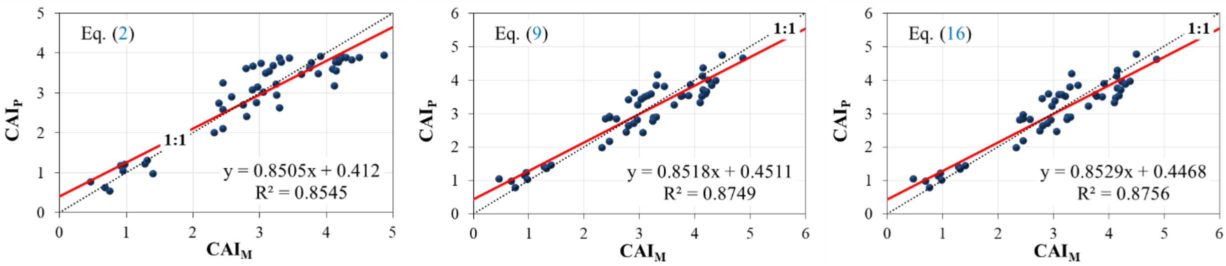

Figure 11. Comparison graphs of measured CAI-predicted CAI.

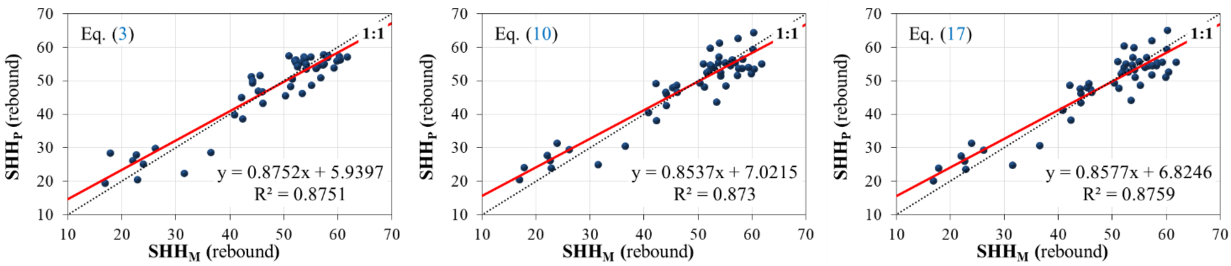

Figure 12. Comparison graphs of measured SHH-predicted SHH.

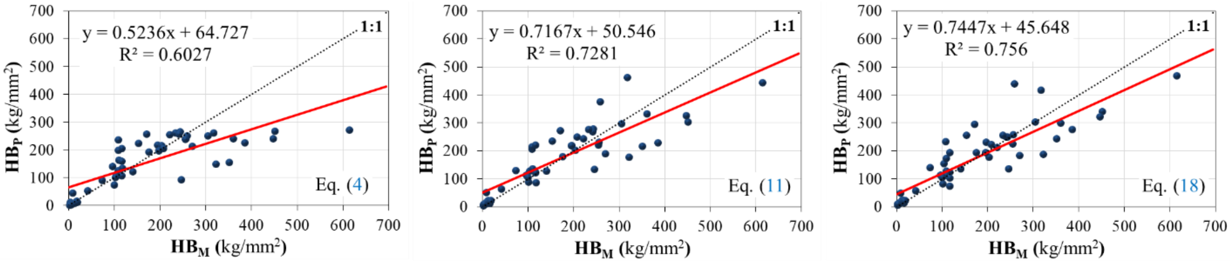

Figure 13. Comparison graphs of measured HB-predicted HB.

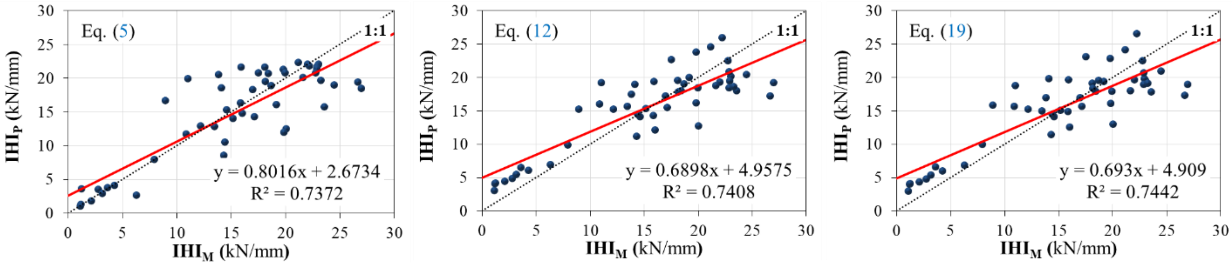

Figure 14. Comparison graphs of measured IHI-predicted IHI.

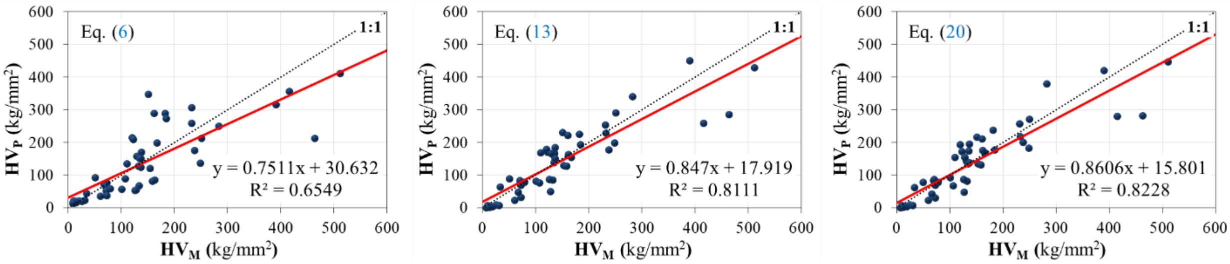

Figure 15. Comparison graphs of measured HV-predicted HV.

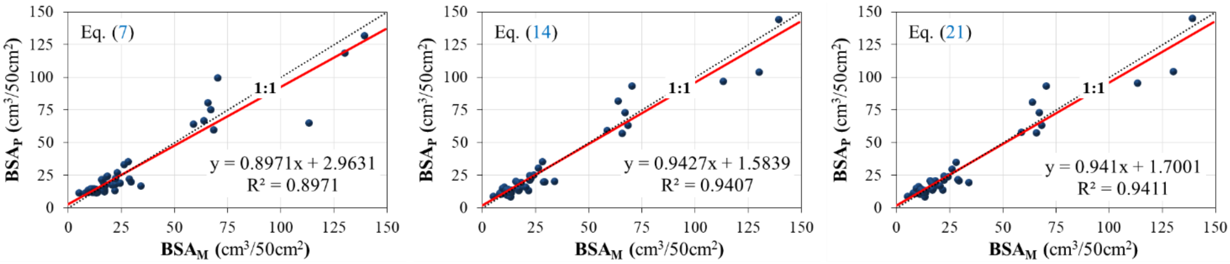

Figure 16. Comparison graphs of measured BSA-predicted BSA.

4. PERFORMANCE ANALYSES OF DERIVED MODELS

To compare the capacity performances of all forecasting models, some statistical performance indices such as RSR, VAF, E, and Adj.R^2 were calculated separately for each model. E is the efficiency coefficient, VAF is the variance calculation factor, and Adj.R^2 is the corrected coefficient of determination. RSR is the root square error rate of the prediction values relative to the standard deviation ratio. PI_{at} is the performance index value developed by the author [26] within the scope of this study. This new performance index given in Equation 22 was created by using four of the above-mentioned performance indexes in the same formula.

$$PI_{at} = \left[Adj.R^2 + \left(\frac{VAF}{100}\right) + E - RSR\right] \tag{22}$$

The theoretical perfection of the performance index given in Eq. 22 depends on the condition that the RSR value is “0”, the E and Adj.R^2 value is “1” and the VAF value is “100”. As it can be understood from here, the perfect PI_{at} value should theoretically be equal to 3, and the equations with the highest predictive power are those with the highest PI_{at} value (Table 3).

Within the scope of this study, estimation equations were developed for a total of seven parameters, with CID being the main independent variable. For each parameter; three equations were generated, one SRA (Eqs. 1-7), one NMRA-1 (Eqs. 8-14), and one NMRA-2 (Eqs. 15-21). According to the calculated average PI_{at} values, the rock properties estimated with the CID parameter in the most reliable way and with the highest estimation capacity are as follows; BSA (2.51), SHH (2.26), CAI (2.23), SSH (2.19), HV (1.78), IHI (1.69), and HB (1.51). The equations with the highest estimation capacity for each rock feature are as follows; Eq. 21 (BSA); Eq. 3 (SHH); Eq. 16 (CAI); Eq. 1 (SSH); Eq. 20 (HV); Eq. 19 (IHI); Eq. 18 (HB).

Table 3. Calculated statistical performance indices for derived simple regression models.

Equation number	Adj.R^2	VAF	E	RSR	PI_{at}
Eq. (1)	0.873	87.54	0.875	0.353	2.27
Eq. (2)	0.851	85.45	0.854	0.383	2.18
Eq. (3)	0.873	87.51	0.875	0.353	2.27
Eq. (4)	0.594	59.23	0.574	0.653	1.11
Eq. (5)	0.732	73.16	0.729	0.521	1.67
Eq. (6)	0.648	64.07	0.639	0.601	1.33
Eq. (7)	0.895	89.71	0.897	0.321	2.37
Eq. (8)	0.844	84.85	0.848	0.389	2.15
Eq. (9)	0.869	87.42	0.874	0.355	2.26
Eq. (10)	0.868	87.25	0.872	0.357	2.26
Eq. (11)	0.717	72.79	0.728	0.522	1.65
Eq. (12)	0.730	73.73	0.737	0.513	1.69
Eq. (13)	0.803	80.95	0.809	0.438	1.98
Eq. (14)	0.938	94.07	0.941	0.244	2.58
Eq. (15)	0.841	84.90	0.849	0.389	2.15
Eq. (16)	0.867	87.49	0.875	0.354	2.26
Eq. (17)	0.868	87.55	0.875	0.353	2.27
Eq. (18)	0.740	75.59	0.756	0.494	1.76
Eq. (19)	0.727	74.06	0.740	0.510	1.70
Eq. (20)	0.811	82.11	0.820	0.424	2.03
Eq. (21)	0.937	94.11	0.941	0.243	2.58

5. CONCLUSIONS

In this study, it is planned to make depth measurements along the scratch line formed on the rock surface with the CAI experiment and thus create a new experimental data set. Detection of this parameter, called CID, requires the use of a specially prepared sample. The determination of CID values is dependent on the condition that the CAI test is applied on well-sized core or prismatic rocks. The fact that mostly irregularly shaped samples are used for CAI experiments is the main reason why the CID parameter is not commonly found in the literature. In this study, which was carried out with test data of a large number of rocks, hardness, abrasion, and physical properties, which are thought to be directly related to the CID parameter, were tried to be correlated. The results obtained from SRA and NMRA have been tried to be summarized in the following items.

- When a general evaluation is made, it is seen that the determination coefficients of the equations obtained with igneous rocks are quite high. The general uniformity of mineral distribution in igneous rocks is the main reason for obtaining these stable results.

- According to the average performance index (PI_{at}) analysis, it is clear that the BSA, SHH, CAI, and SSH tests have a high level of reliability, respectively. The common feature of these parameters is that they are common methods that are frequently applied to rocks. The estimation equations of methods developed to measure metal hardness, such as HB and HV, did not give reliable results as in classical methods.
- The equations with the highest coefficient of determination and performance index value for all data sets in the estimation of the CID parameter were obtained by the BSA test.
- It should be underlined that all of the 30 equations presented in the study meet the reliability test conditions. Equations that fail to meet the F and t-test conditions, although giving a higher coefficient of determination, are not included. The results revealed that the CID parameter has a very significant relationship with the properties of the rocks, especially the surface properties such as abrasion and hardness.
- Within the scope of the study, tests such as BSA, CAI, SHH, SSH, HB, HV, and IHI were carried out. Elements such as abrasive mineral content, porosity, density, degree of cementation, cement (matrix) material, and structure texture affect the abrasion/hardness properties listed above more than mechanical properties. Similarly, CID is controlled by the same parameters. Based on this determination, it is recommended to researchers that the CID values should be determined in case the CAI tests are to be carried out with well-sized core or prismatic samples.
- It is thought that the CID parameter will provide an important data set to the researchers thanks to the sensitive measurements to be made by paying attention to the conditions detailed in the text. This study revealed that a significant data set can be obtained from the scratches on the rock surface as well as the wear on the steel tips used in the CAI test. New studies can be carried out in the future by making the experimental set created in this study more professional/standard. A digital comparator and a more rigid-thin steel tip can be used. In addition to depth, the width of the scratch along the measurement line can also be measured. It is thought that if high-resolution photographs are processed with the help of computer programs, the average scratch width will reveal meaningful relationships with other rock properties.

Declaration of Ethical Standards

The study was conducted in accordance with ethical standards.

Credit Authorship Contribution Statement

Ahmet TEYMEN Conceptualization, Methodology, Designed the Experiments, Writing original draft, Supervision, and Writing review and Editing.

Declaration of Competing Interest

The author declares no conflict of interest.

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Data Availability

Data will be made available on request.

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