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Correlation of equivalent quartz content, Slake durability index and Is_{50} with Cerchar abrasiveness index for different types of rock

M. Moradizadeh [a], A. Cheshomi [a,*], M. Ghafoori [b], S. TrighAzali [b]

[a] Department of Structural and Engineering Geology, School of Geology, College of Science, University of Tehran, Iran
[b] Department of Geology, Faculty of Science, Ferdowsi University of Mashhad, Iran

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1. Introduction

Rock abrasiveness is defined as the abrasive effect of a rock on a metal surface. Abrasiveness influences the capacity of various types of soil to wear down excavation tools. The most important properties to consider for abrasiveness is the type of rock or soil, its mineral constituents, the grain size of the abrasive minerals, the strength and density of the soil, and the strength of bonds between rock particles.[1] For sedimentary rocks, grain size, hardness, texture, cement content, compressive and tensile strength, alteration and roundness affect abrasion of excavation tools.[1,2]

Bruland[3] investigated the effect of mineral constituents on rock abrasiveness by calculating their Vickers numbers. The equivalent quartz content is another method used to determine the hardness of rock; it is calculated as

$$EQC = \sum_{i=1}^{n} A_i R_i (\%) \tag{1}$$

The quartz content and other mineral contents are obtained by microscopic examination of the rock, and A_i is the abrasiveness index from the total sample and is multiplied by the Rosiwal (R_i) abrasivity index for the mineral where n is the total number of minerals.[4]

West showed that the abrasiveness of rocks is a function of the quartz and other abrasive mineral contents, average grain size, and grade and type of cement, with quartz content having the dominant effect.[5]

The Cerchar abrasiveness index (CAI) is a common method of predicting abrasiveness in excavation tools. This test was introduced by The Mining Research Institute of the French Coal Association[6] and is defined in French Standard AFNOR (NF904-430-1).[7] ASTM (D7625-10) also describes the testing method and production of the pin to calculate CAI.[8] The test uses a steel pin with a defined quality and geometry to scratch 10 mm of rough rock surface using a static load of 70 N and a speed of 1 mm/s.[9]

Many studies have investigated the factors affecting CAI. Some have focused on issues such as length of scratch, stress dependency, surface conditions of the sample rock, and speed of testing. Others have investigated the equipment used, particularly the metal pin, and on the effect of petrographic and geomechanical properties of the rock.[10–17,1] Deliormanli[18] studied the correlation between CAI and strength in marble rock using different methods and was able to propose correlations. Kohler et al.[19] assessed the performance of a tunnel boring machine, and Deliormanli[18] examined the effect of rock strength using multivariate regression analysis.

The present study investigated possible correlations between CAI and EQC (from thin-section petrographic analysis), point load index (I_{s50}), Slake durability index (I_{d2}) and percentage of water absorption (%S). Testing was carried out on 36 samples of igneous, sedimentary and metamorphic rock. The relationships between them were evaluated using univariate and multivariate regression.

2. Methodology

2.1. Sampling

Samples were taken from different geological formations in Iran and include metamorphic (eight samples), igneous (10 samples) and sedimentary (18 samples) rock.

* Corresponding author.
E-mail address: a.cheshomi@ut.ac.ir (A. Cheshomi).

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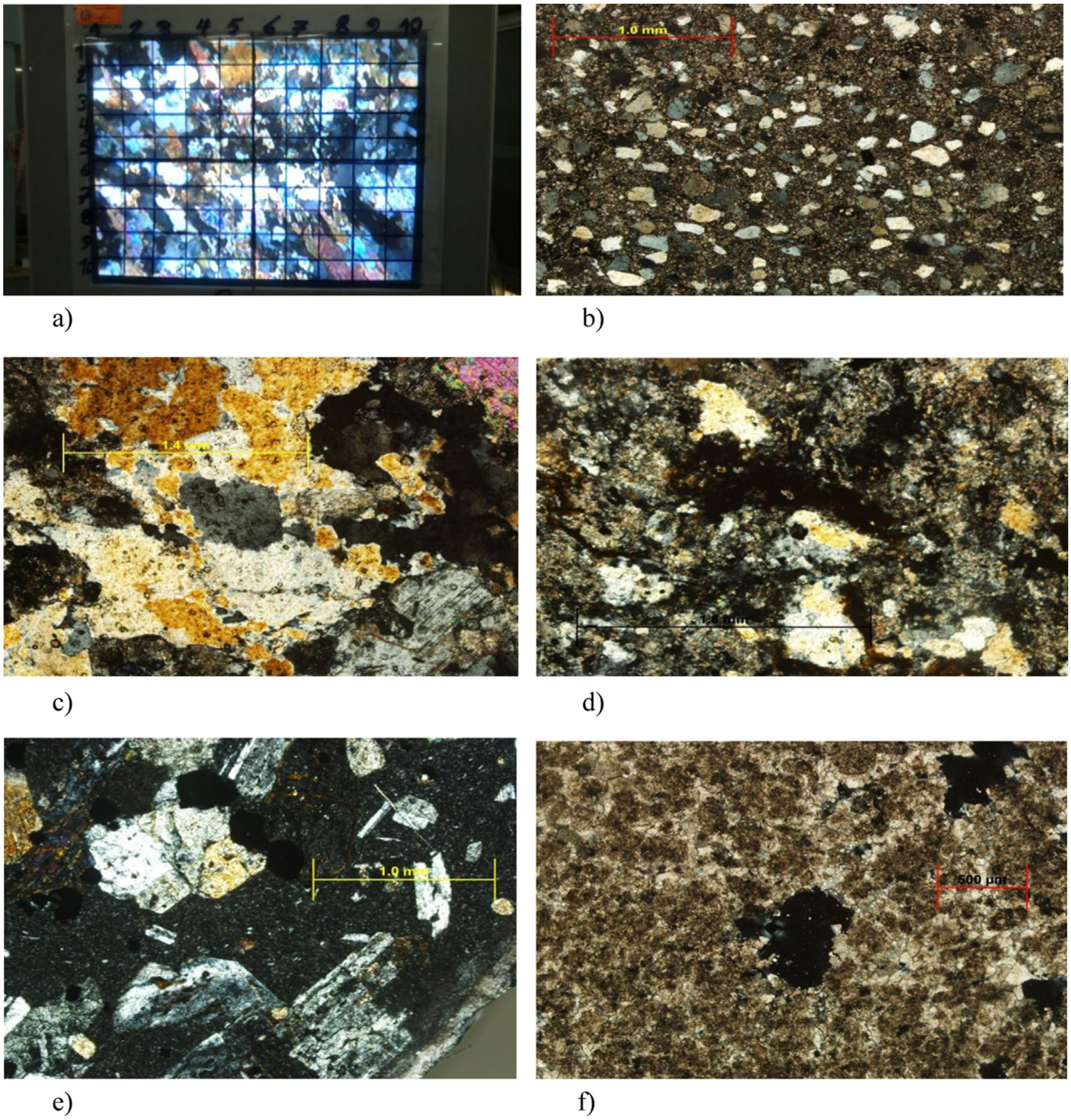

Fig. 1. (a) Gridding the picture of the thin section into 100 identical squares, (b) petrographic analyses: Quartz arenite, (c) Sericite schist, (d) Sericite schist, (e) Andesite, (f) Crystalline limestone.

2.2. Laboratory testing

2.2.1. Petrographic analysis

Petrographic analysis was conducted using the Rosiwal and modal methods using an optical microscope and a mechanical stage as explained in Refs. 20 and 21. Fig. 1 shows that the stages of petrographic analysis differ from the modal methods in that they produce error that decreases the accuracy of measurement. These included errors in measurement of the area of each thin section, overlap of minerals at the sides of an area, and overlap of an image with an adjacent image under the microscope.

Since determining the percentage of error in the modal methods is a lengthy process, a method of analysis was adopted by which the field of view of the microscope is transmitted to a monitor using a camera to allow consideration of similar areas for each thin section. To prevent overlap of the first field of view with the next one, the pictures on the monitor were marked and scaled so as to distinguish between them. A regular grid dividing the total field of view into 100 equal portions was placed on the monitor and the results of the two methods were collected and their averages calculated.

Based on microscopic studies calculated EQC for each samples. The results are shown in Table 1.

2.2.2. CAI

Cerchar tests are done with steel pins of Rockwell hardness HRC-55 and tension strength 2000 MPa. Cerchar tests are done on smooth surface. The CAI was calculated according to ASTM (D7625-10)[8] and the results are shown in Table 1 for different types of rock. ASTM (D-7625-10) categorizes the rock abrasiveness of samples of igneous rocks as very abrasive or extremely abrasive, according to the quartz and glass content of the sample. An increase in granular or porphyrique the grain texture and whether or not the quartz texture contains phenocryst will determine the abrasivity of the rock. Metamorphic rocks fell into the medium to extremely abrasive categories because of differences in temperature and stress. All the limestone samples were categorized as abrasive because of their similar petrography. Siliclastic rock

Table 1
Results of all tests on igneous, metamorphic, sedimentary and limestones rocks.

Sample no.		Rock type	Q%	EQC%	Is_{50} (MPa)	Id_2%	S%	CAI
1	**Igneous Rocks**	Syeniogarnit	50	60.5	9.96	99.71	0.09	4.47
2		Granodiorite	47	61.86	6.12	99.63	0.14	4.48
3		Monzogranite	52	65.61	10.92	99.75	0.18	4.60
4		Syeniogarnit	45	58.87	5.81	99.82	0.42	4.22
5		Quartz diorite	14	41.84	9.16	99.80	0.6	3.81
6		Granodiorite	42	50.28	5.30	99.77	0.47	4
7		Andesite	0	55.89	9.88	99.77	0.09	4
8		Tuff andesite	1.5	51.94	9.89	99.72	1.42	3.23
9		Tuff	8.5	51.95	9.84	99.77	1.55	3.56
10		Quartz tholeit	9	61.76	10.32	99.1	1.98	4.4
11	**Metamorphic Rocls**	Marble	0	3	2.63	99.49	0.11	1.1
12		Sericite schist	44	54.87	10.72	99.79	0.07	4.35
13		Sericite schist	52	53.82	5.53	99.75	0.43	3.71
14		Sericite schist	7	16.36	0.8	97.28	1.7	0.78
15		Muscovite schist	48	50.08	7.1	99.69	0.29	3.39
16		Sericite schist	25	33.33	5.99	99.86	0.51	2.84
17		Serpentinite	0	4.18	5.26	99.53	0.47	1.22
18		Gneiss	65	70.96	6.27	99.74	0.21	4.4
19	**Sedimentary Rocks**	Calcic conglomerate	32	33.58	7.98	99.46	2.12	2.23
20		Quartzarenite	87	87.17	11.78	99.72	0.75	4.1
21		Quartzarenite	72	72.01	10.95	99.76	0.88	3.75
22		Calcic sandstone	28	30.68	2.3	92.74	4.39	1.93
23		Quartzarenite	87.2	87.2	10.67	99.90	1.20	4.18
24		Quartzarenite	73.6	73.6	10.8	99.76	1.63	3.78
25		Sublitharenite	85	85.06	12.42	99.88	0.51	4.31
26		Litharenite	50	50	4.97	99.21	2.94	2.05
27		Litharenite	57	57	4.76	99.05	4.23	2.19
28		Calcic sandstone	63.4	63.4	9.36	99.69	0.14	2.93
29	**Limestones**	Crystalline limestone	0	3.38	7.23	99.81	1.17	1.9
30		Crystalline limestone	0.2	4.05	8.75	99.71	0.6	1.97
31		Microspar limestone	0.6	3.47	2.81	99.21	2.53	1.07
32		Crystalline limestone	0	2.96	5.31	99.66	1.13	1.33
33		Crystalline limestone	0	2.88	4.59	99.14	3.55	1.22
34		Crystalline limestone	2.8	5.87	5.99	99.87	0.12	1.48
35		Fossiliferous limestone	0	2.25	4.19	99.61	0.14	1.41
36		Fossiliferous limestone	1.8	3.79	4.85	99.77	0.21	1.43

samples fell into the abrasive to excessively abrasive categories; the more sublitharenitic and quartz arenitic they were, the more abrasive they were. This was subject to the grain type and cement content. The highest degree of abrasiveness was recorded for igneous and siliclastic sedimentary rock containing quartz arenite and sublitharenite. Of the metamorphic rock, gneiss and sericite schist, which contain a low degree of alteration, were extremely abrasive.

2.2.3. Physical and mechanical tests

The values for S, I_{s50} and I_{d2} were determined based on ASTM D2216-11, Standard ASTM D5731-95 10 and ASTM D4644–04, respectively.[22–24] The results are presented in Table 1. Bieniawski and Deere[25] categorized intact igneous rock as having very high or high strength and metamorphic rock as having very low to very high strength. Igneous rocks have a high level of strength, especially when they are rich in quartz or glass. Limestone is categorized as medium to high strength and siliclastic sedimentary rock is low to very high strength.

Testing on metamorphic rock was carried out for vertical and horizontal schistosity and their averages were calculated. Since these types of rock are formed at varying temperatures and stresses, their strength also varies. The greater the number of strong particles (such as quartz) and the smaller the cement content in siliclastic sedimentary rock, especially if the cement is of the iron oxide type, the stronger the rock will be. The greater the alteration in metamorphic rocks, particularly for sericitic schist, the lower the strength will be. According to the categorization method recommended by Franklin and Chandra[26] all samples were extremely strong in terms of durability, except for sandstone sample 22, which was categorized as very strong.

3. Data analysis

3.1. Statistical analysis

Bivariate and multiple regression analysis were run using SPSS software and the Fischer test. The output of regression analysis included the Fischer index (F), regression coefficient (R^2), adjusted R^2, and level of significance (Sig). Statistically speaking, a model is considered a better fit when the Fischer index (F) is higher and $Sig < 0.05$. If $Sig > 0.05$, a model is not considered to be statistically significant. It should also be noted that the Fischer index is preferred over R^2.[27]

3.2. Simple and bivariate regression analysis

CAI was assumed to be the dependent variable and quartz content (Q), EQC, I_{s50}, I_{d2} and S as the independent variables.

Tab le 2
Correlations obtained from bivariate analysis, classified based on rock type.

Variable	Equation		Rock type	Model type	Adjusted R^2
Q%	$CAI = 1.229e^{0.014\,Q\%}$	(2)	Sandstone	Exponential	0.84
EQC%	$CAI = 1.178e^{0.015\,EQC\%}$	(3)	Sandstone	Exponential	0.85
Is_{50}	$CAI = 1.393\,e^{0.089\,Is50}$	(4)	Sandstone	Exponential	0.87
Is_{50}	$CAI = 0.610 + 0.159\,Is_{50}$	(5)	Limestone	Linear	0.86
Q%	$CAI = 1.060 + 0.055\,Q\%$	(6)	Metamorphic	Linear	0.88
EQC%	$CAI = 0.728 + 0.056\,EQC\%$	(7)	Metamorphic	Linear	0.90
EQC%	$CAI = 2.679\,e^{0.008\,EQC\%}$	(8)	Plutonic	Exponential	0.94
EQC%	$CAI = 1.241 + 0.039\,EQC\%$	(9)	All type	Linear	0.77

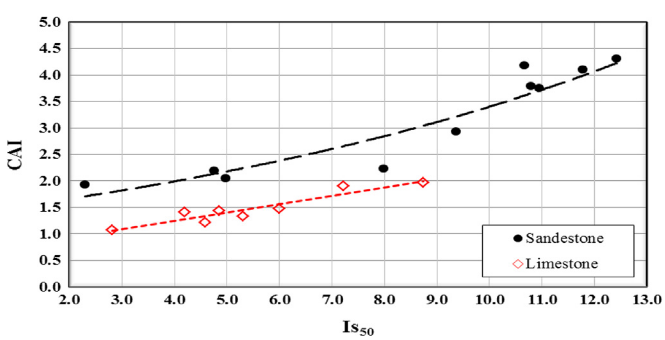

Fig. 2. Cerchar abrasiveness index (CAI) plotted against point load index (Is_{50}) for sandstones and limestones.

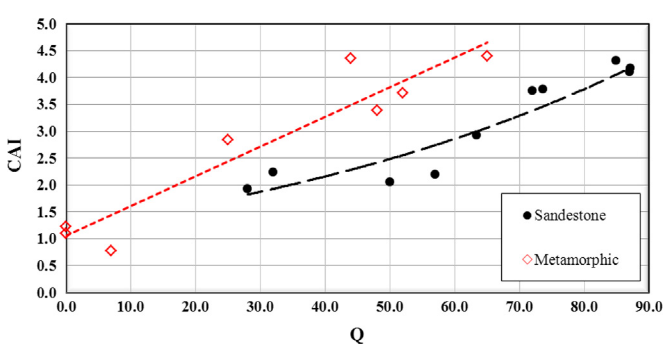

Fig. 3. Cerchar abrasiveness index (CAI) plotted against quartz percent (Q) for sandstones and metamorphic rocks.

Simple and bivariate regression analysis was performed based on rock type for linear, logarithmic, reverse, quadratic, cube, and exponential functions on all data. Samples 5, 9, 12, 14, 31, 34 and 21 were used to validate the correlation. These samples were not subjected to bivariate regression analysis.

In intrusive igneous rocks, *EQC* correlated with *CAI* and the exponential and linear functions showed the best statistical coefficients. *F* was greater in the exponential model than in the linear model. *Q*, *EQC*, and I_{s50} in sandstone samples showed high correlation. For *Q* and *EQC*, the exponential function represented the best model. For I_{s50}, the exponential and linear functions revealed

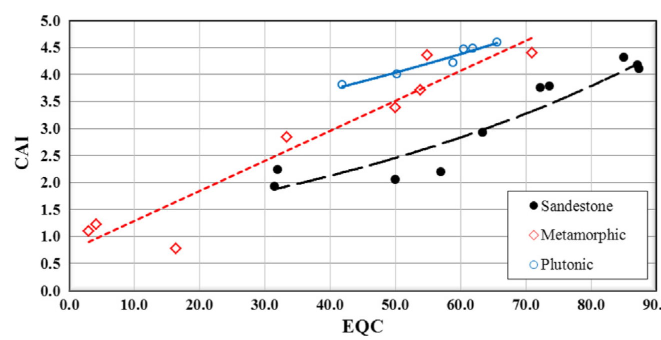

Fig. 4. Cerchar abrasiveness index (CAI) plotted against equivalent quartz content (EQC) for sandstones, metamorphic and plutonic rocks.

the best correlations. Although the exponential function model was better than the linear model for I_{s50}, the linear model also provided good correlation with *CAI*. Furthermore, *F* in the exponential model was greater than for the linear model.

Only I_{s50} showed a good correlation with *CAI* for limestone. The linear model was the best, since *F* was greater in the linear model than in the other models. Simple regression analysis indicated that there is a relationship between the strength of sedimentary rock and abrasiveness, particularly for limestone, which shows a linear relationship.

Both *Q* and *EQC* in metamorphic rock correlated with *CAI* and the linear model represented the best statistical coefficients for both. There was no meaningful relationship for the extrusive igneous rock samples.

In all samples, only *EQC* correlated with *CAI* in the linear model. This indicates that *EQC* is the best possible factor for predicting *CAI*. Coefficients of bivariate regression analysis and *CAI* were obtained for all rocks using available information. The results showed that I_{d2} and *S* had no correlation with *CAI* for any type of rock. This could mean that abrasiveness does not depend on the durability or the percentage of water absorption in rock. It could also mean that the way the variables were distributed did not represent a significant correlation because the samples had low levels of clay and high durability. Table 2 (Eqs. (2)–(9)) and Figs. 2–4 show the correlations between independent variables and *CAI* for the data.

Table 3
Multivariate regression coefficients for the selected models.

Coefficients[a]						
Model		Unstandardized coefficients		Standardized coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1.241	.208		5.969	.000
	EQC	.039	.004	.878	9.707	.000
2	(Constant)	1.153	.198		5.832	.000
	EQC	.054	.007	1.207	7.213	.000
	Q	−.016	.007	−.381	−2.277	.031
3	(Constant)	−13.225	7.836		−1.688	.103
	EQC	.053	.007	1.173	7.262	.000
	Q	−.016	.007	−.371	−2.309	.029
	Id2	.145	.079	.151	1.836	.078
4	(Constant)	−11.396	8.893		−1.281	.212
	EQC	.050	.009	1.122	5.660	.000
	Q	−.015	.007	−.351	−2.087	.047
	Id2	.126	.091	.130	1.386	.178
	Is50	.025	.053	.058	.461	.649
5	(Constant)	4.105	9.602		.428	.673
	EQC	.050	.008	1.109	6.323	.000
	Q	−.014	.006	−.327	−2.189	.039
	Id2	−.027	.097	−.028	−.279	.782
	Is50	.022	.047	.052	.462	.648
	Absorption	−.273	.097	−.261	−2.817	.010

[a] Dependent variable: CAI.

Table 4
Various Rs for the selected models.

Model summary[a]				
Model	R	R square	Adjusted R square	Std. error of the estimate
1	.878[b]	.771	.763	.62701
2	.899[c]	.808	.794	.58481
3	.911[d]	.830	.810	.56073
4	.912[e]	.831	.804	.56942
5	.934[f]	.873	.847	.50383

[a] Dependent variable: CAI.
[b] Predictors: (Constant), EQC.
[c] Predictors: (Constant), EQC, Q.
[d] Predictors: (Constant), EQC, Q, Id2.
[e] Predictors: (Constant), EQC, Q, Id2, Is50.
[f] Predictors: (Constant), EQC, Q, Id2, Is50, Absorption.

3.3. Multivariate regression analysis

Multivariate regression analysis was calculated based on the Enter method using SPSS software. Table 3 shows the five models selected to determine *CAI*. Multiple regression analysis was conducted to specify whether *CAI* can best be estimated by one specific factor or by a combination of engineering properties of rock. Table 4 shows the R^2 values for the models. Table 5 shows the ANOVA coefficients and reveals that the first model has the largest *F*, but only *EQC* correlated with *CAI*. Based on Table 3, the following correlation was obtained:

$$EQC = 1.241 + 0.039CAI \tag{10}$$

Table 5
ANOVA coefficients for the selected models.

ANOVA[a]						
Model		Sum of squares	df	Mean square	F	Sig.
1	Regression	37.041	1	37.041	94. 220	.000[b]
	Residual	11.008	28	.393		
	Total	48.049	29			
2	Regression	38.815	2	19.408	56.747	.000[c]
	Residual	9.234	27	.342		
	Total	48.049	29			
3	Regression	39.874	3	13.291	42.274	.000[d]
	Residual	8.175	26	.314		
	Total	48.049	29			
4	Regression	39.943	4	9.986	30.798	.000[e]
	Residual	8.106	25	.324		
	Total	48.049	29			
5	Regression	41.957	5	8.391	33.057	.000[f]
	Residual	6.092	24	.254		
	Total	48.049	29			

[a] Dependent variable: CAI.
[b] Predictors: (Constant), EQC.
[c] Predictors: (Constant), EQC, Q.
[d] Predictors: (Constant), EQC, Q, Id2.
[e] Predictors: (Constant), EQC, Q, Id2, Is50.
[f] Predictors: (Constant), EQC, Q, Id2, Is50, Absorption.

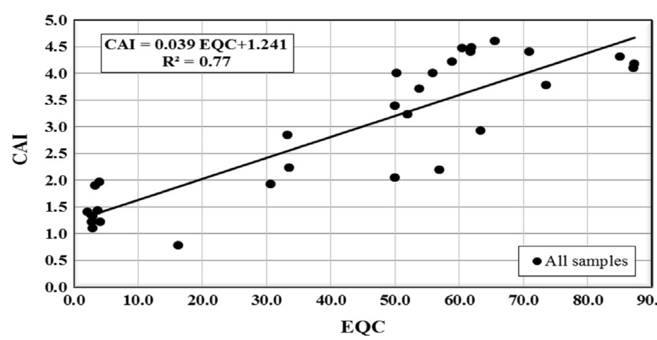

Fig. 5. Cerchar abrasiveness index (CAI) plotted against equivalent quartz content (EQC) for all samples.

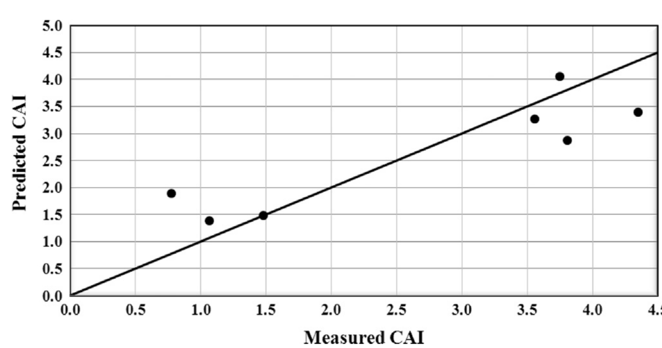

Fig. 6. Comparison between measured and predicted CAI to validation the equation 10.

Multivariate regression analysis of all rocks, similar to bivariate regression analysis, indicates that *EQC* is the best factor for evaluating and predicting *CAI* in all types of rock. Fig. 5 shows *CAI* plotted against *EQC* for all samples.

3.4. Validating the equation

Fig. 6 shows the results of validation of the process. After obtaining a new correlation between *CAI* and *EQC*, it was validated to identify the model's ability compared to the actual testing results. *CAI* from the formula was juxtaposed to obtain with the actual *CAI* from testing. The closer to the fraction (predicted *CAI*/ measured *CAI*), the better and stronger the correlation would be.

4. Conclusion

Abrasiveness is an important characteristic in excavation and tunneling projects many factors affect abrasiveness. One method for determining the abrasiveness of rocks is the Cerchar test. In this study, the effects of the equivalent quartz content (*EQC*), point load index (I_{s50}), Slake durability index (I_{d2}), and percentage of water absorption (*S*) on the Cerchar abrasivity index (*CAI*) of 36 rock samples was evaluated using bivariate and multivariate regression analysis.

The limestone samples showed mineralogical similarities and only I_{s50} was a contributing factor to *CAI*, with a linear correlation. In sandstone, *Q*, *EQC*, and I_{s50} affected *CAI*. This indicates that mineralogical factors in addition to strength affect the level of abrasion in sandstone. The correlation between *Q*, *EQC*, and Is_{50} with the *CAI* is exponential, implying that there are other contributing factors, such as cement type and the degree of cementation, that influence *CAI*. In metamorphic rock, *Q* and *EQC* showed a linear correlation with *CAI*, suggesting that only mineralogical factors influenced *CAI.* In intrusive igneous rocks, only *EQC* affected *CAI* and the correlation between *CAI* and *EQC* was exponential. This indicates that other mineralogical factors, such as interlocking texture, may affect the level of abrasion in these rocks. In igneous and metamorphic rocks, there was no relationship between the strength and *CAI*, only their mineralogy influenced abrasiveness.

Relationships were identified using simple regression analysis between groups of rock. I_{d2} and *S* showed no correlation with *CAI* in any type of rock. Only *EQC* correlated linearly with the *CAI* in all types of rock. This indicates that the only appropriate mineralogical factor for comparison of rock in terms of abrasiveness is *EQC*. A formula was proposed for calculation of *CAI* in terms of *EQC*.

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