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A Correlation for Estimating LCPC Abrasivity Coefficient using Rock Properties

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Abstract

Rock abrasivity, as one of the most important parameters affecting the rock drillability, significantly influences the drilling rate in mines. Therefore, rock abrasivity should be carefully evaluated prior to selecting and employing drilling machines. Since the tests for a rock abrasivity assessment require sophisticated laboratory equipment, empirical models can be used to predict rock abrasivity. Several indices based on five known methods have been introduced for assessing rock abrasivity including rock abrasivity index (RAI), Cerchar abrasivity index (CAI), Schimazek's abrasivity factor (F-abrasivity), bit wear index (BWI), and LCPC abrasivity coefficient (LAC). In this work, 12 rock types with different origins were investigated using the uniaxial compressive strength (UCS), Brazilian test for tensile strength, and longitudinal wave velocity and LCPC tests, and microscopic observations were made to obtain a correlation for estimating the LCPC abrasivity coefficient by conducting the conventional rock mechanics tests. Using the equivalent quartz content, velocity of longitudinal waves, and rock brittleness index, a linear correlation was obtained with a coefficient of determination (R2) of 93.3% using SPSS in order to estimate LAC.

1. Introduction

Rock abrasivity refers to a rock property in drilling operations that causes destruction of steel, tungsten carbide or diamond drill bits [1]. Rock abrasivity plays a key role in underground drilling operations, and is is usually dependent on the quartz content, size and shape of grains, and tensile strength of rocks [2]. It is also a key and determining factor in selecting the type of drilling system and drill bit type and geometry. Therefore, a correct and true understanding of this property greatly helps the designers and planners of underground spaces in selecting the drilling machinery and in evaluating drillability. So far, various methods have been proposed for determining the rock abrasivity indices including RAI, F-abrasivity, CAI, BWI, and RAI (Laboratoire Central des Ponts et Chaussees: LCPC).

Numerous researchers have studied the factors affecting the LCPC abrasivity coefficient. Buchi *et al.* have proposed a correlation between the LCPC abrasivity coefficient and CAI. They also investigated the effect of water content on the LCPC abrasivity coefficient and noticed that CAI was improved with increase in the water content [3]. Plinninger *et al.* have introduced a correlation for calculating CAI for the rock specimens with rough surfaces [4]. Deliormanh has estimated CAI using uniaxial compressive strength and direct shear test, and has presented a correlation in this relation [5]. Thuro *et al.* have investigated the effect of th specimen preparation procedure on the LCPC abrasivity coefficient, observing lower CAI values for natural specimens caused by destruction of sharp edges of grains compared with those prepared by a crusher [6]. Tripathy *et al.* have studied the effects of the geomechanical

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properties on CAI, proposing a correlation using multivariate regression [7]. Moradizadeh *et al.* have investigated the effects of sandstone properties on CAI, and have provided a correlation between CAI, point load strength index, and the second cycle of slake-durability test [8]. Abu Bakar *et al.* have examined the effect of water content on CAI and have noticed that the value of the index increases at higher water contents [9]. Young *et al.* have investigated the effects of geomechanical properties on CAI of rocks with igneous, sedimentary, and metamorphic origins, and have proposed correlations for estimating CAI [10]. Kahraman *et al.* have proposed a correlation between the LCPC abrasivity coefficient, abrasive mineral content (AMC), and grain texture parameters [11]. Capik and Yilmaz have investigated the effect of rock properties on CAI, noticing that the highest correlation coefficient was that between CAI and the uniaxial compressive strength of rocks [12]. According to the literature, CAI is dependent on the uniaxial compressive strength, tensile strength, Young's modulus, equivalent quartz content, and physical properties of rocks. The correlation coefficient between rock abrasivity and the aforementioned parameters, however, varied with the origin of the rocks.
Since most previous studies focused on the Cerchar abrasivity index, this research work estimated the LCPC abrasivity coefficient (LAC) using the physical, mechanical, and geological properties of rock specimens.

2. Studied rocks

Twelve rocks with igneous, pyroclastic, and sedimentary origins were collected from different regions in Iran. Thin cross-sections of each rock specimen were studied under a polarizing microscope at a 50x magnification to determine the types and frequency percentage of the minerals. The equivalent quartz contents of the rock specimens were calculated using Equation 1 [13]. Table 1 lists the equivalent quartz contents of the rocks and the regions where they were collected.

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

Here, *A* represents the percentage of the minerals, *R* is the Rosiwal abrasivity index, and *n* is the number of minerals. The Rosiwal abrasivity index (x) can be calculated from the Mohs scale (Y) of mineral hardness according to Equation 2. Figure 1 shows the correlation for determining the rock abrasivity using Mohs hardness.

$$Y = 2.12 + 1.05\ \ln(x) \quad (2)$$

Figure 2 shows the thin cross-sections of some of the rocks with their mineral compositions. Table 2 summarizes the mineral consituents and their frequency percentage in the rocks.

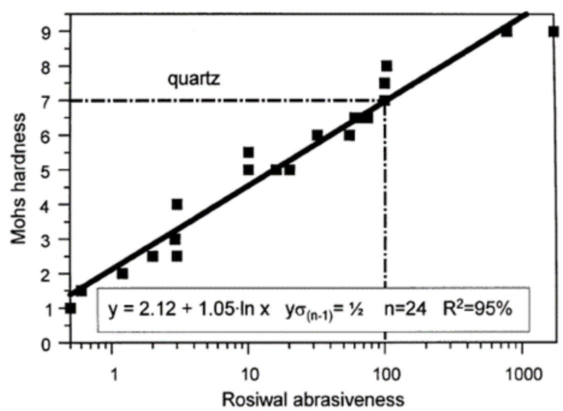

Figure 1: Correlation for determining rock abrasivity using Mohs hardness [14].

Table 1. Equivalent quartz contents of rocks collected from different regions.

Rock type	Region	Equivalent quartz (%)	Rock type	Region	Equivalent Quartz (%)
Shale	Maroon oil field	4.80	Calcareous sandstone	Loshan	23.76
Carbonate sandstone	Abgarm-Qazvin	41.39	Andesite	Buin Zahra	53.11
Sandstone (I)	Abgarm-Qazvin	86.65	Calcareous dolomite	Abgarm-Qazvin	11.16
Sandstone (II)	Abgarm-Qazvin	89.86	Vitric tuff (1)	Abyek-Qazvin	21.4
Sandstone (top quartzite)	Abgarm-Qazvin	96.28	Vitric tuff (2)	North Qazvin	15.8
Monzogranite	Alvand-Hamadan	59.65	Rock salt	Abgarm-Qazvin	0.92

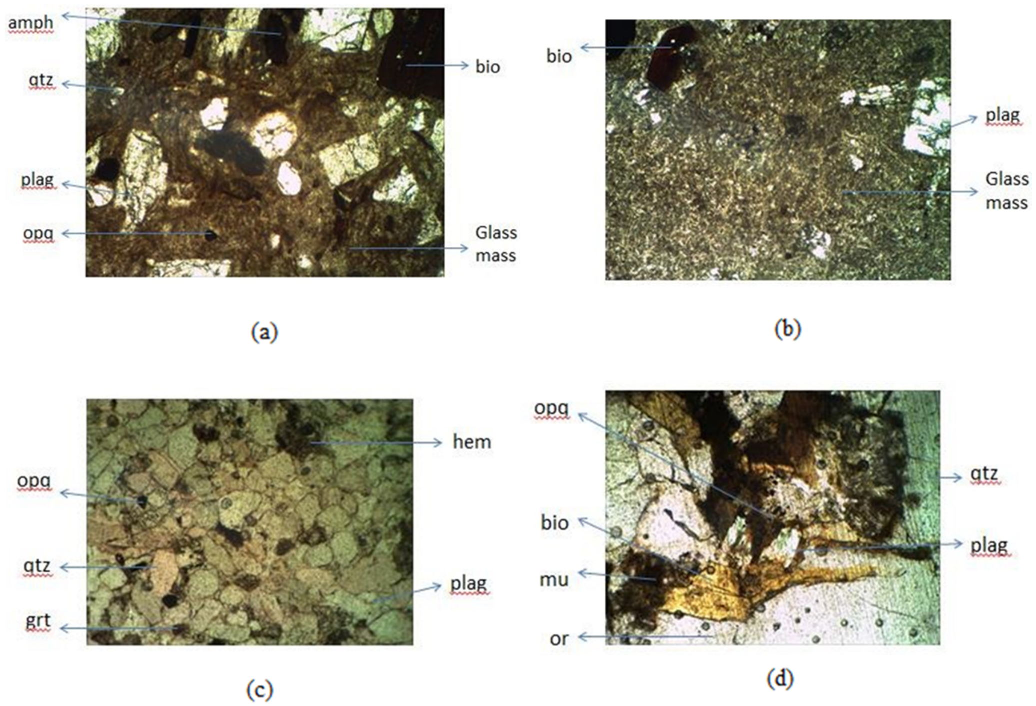

Figure 2. Thin cross-sections of (a) andesite, (b) vitric tuff, (c) sandstone (I), and (d) monzogranite. (Abbreviations: amph: amphibolite, qtz: quartz, plag: plagioclase, opq: opaque, bio: biotite, Glass mass: glass matrix, grt: garnet, hem: hematite, mu: muscovite, and or: orthoclase).

Table 2. Frequency percentage of the mineral consituents of rock specimens.

Rock type	Mineral constituents (frequency percentage)
Calcareous sandstone	Quartz (10%), feldspar (10%), calcite (20%), chert (5%), opaque (5%), a matrix consisting of feldspar clay and quartz (50%)
Andesite	Plagioclase (30%), quartz (10%), amphibolite (10%), biotite (5%), opaque (5%), glass matrix (40%)
Calcareous dolomite	Dolomite (70%), calcite (20%), and opaque (10%)
Vitric tuff (1)	Plagioclase (10%), basaltic rock fragments (10%), and glass matrix (80%)
Vitric tuff (2)	Plagioclase (5%), biotite (10%), and glass matrix (85%)
Rock salt	Halite (96%) and calcite (4%)
Shale	Opaque (5%), iron oxide (5%), and a matrix composed of clay minerals and other minerals and silt grains, in particular, quartz and calcite (90%)
Carbonate sandstone	Quartz (35%), calcite (60%), and chert (5%)
Sandstone (I)	Quartz (60%), chert (5%), plagioclase (5%), opaque (8%), garnet (4%), silica cement (10%), and iron oxide (8%)
Sandstone (II)	Quarz (75%), sedimentary rock fragments composed of chert (5%), iron oxide (12%), calcite (5%) and silica cement (3%)
Sandstone (top quartzite)	Quartz (90%), chert (3%), opaque (5%), and muscovite (2%)
Monzogranite	Quartz (25%), plagioclase (25%), orthoclase (25%), biotite (20%), muscovite (3%), and garnet (2%)

3. Specimen preparation

In order to prepare the specimens for the LCPC tests, the rock blocks were grinded in a jaw crusher to obtain the samples with a maximum dimension of 35 mm. The jaw crusher output was then further grinded in a gyratory crusher. After the crushing operation, the grains with the size of 4-6.3 mm were separated using a sieve to be used in the experiments. According to the Standard P18-579, the grain size of the specimen tested by LCPC machine should be in the range of 4-6.3 mm and weight of 500 ± 2 g. The experiments showed that a 4-5 kg rock block was required to obtain a 500 g specimen. A shaker was used for separating and sieving following the grinding operation. The ground rock obtained from the gyratory crusher was placed on a shaker for 5 min to complete the separation and sieving operations (Figure 3). The specimens for the uniaxial compressive strength (UCS) test were prepared according to the International Society for Rock Mechanics ISRM standards (the complete ISRM suggested methods for rock characterization, testing and monitoring, compilation arranged by the ISRM Turkish National Group, Ankara, Turkey) [15]. A core with an approximate diameter of 54 mm was first prepared from each rock sample using a core drilling machine. The specimens were then cut to the desired length and polished at both ends to obtain the specimens suitable for the UCS test. The UCS specimens could also be used for determining the velocity of longitudinal waves.

Figure 3. Gyratory crusher output after separation. The left-hand side sample: the product passed through a 0.25" sieve remaining on a 5 mesh sieve, and the right-hand side sample: the product remaining on a 0.25" sieve.

The specimens prepared to be used in the Brazilian test for tensile strength were discs with a diameter of 54 mm and a thickness of 27 mm.

4. Experiments

The uniaxial compressive strength, Brazilian test for tensile test, longitudinal wave velocity, and LCPC tests were carried out on the rock specimens in order to estimate the LCPC abrasivity coefficient (LAC). All the experiments were carried out according to the ISRM standards (the complete ISRM suggested methods for rock characterization, testing and monitoring, compilation arranged by the ISRM Turkish National Group, Ankara, Turkey) [15]. The average results obtained are given in the tables.

4.1. Uniaxial Compressive Strength (UCS) test

The UCS tests were performed to determine the UCS and modulus of elasticity of the rock specimens. The uniaxial compressive test is the most commonly used test in the rock mechanics research works (Figure 4). Table 3 shows the results obtained from the UCS tests performed on the rock specimens.

4.2. Brazilian tensile strength (BTS) test

In this test, a diagonal compression force is applied to the cylindrical specimens to induce a tensile stress in a direction perpendicular to the loading axis. The rock is fractured when this stress exceeds its tensile strength. Figure 5 shows the curved loading jaws in the apparatus used in the Brazilian test for the tensile strength and the fractured rock specimens. The results obtained from this test are presented in Table 3.

Figure 4. Rock specimens fractured after the uniaxial compressive test.

Figure 5. Curved loading jaws of the Brazilian test (right) and rock specimens fractured after the Brazilian test (left).

4.3. Test to determine longitudinal wave velocity

An ultrasonic testing instrument was used to determine the speed of longitudinal waves in the rock specimens. The specimens prepared for the UCS tests can be used in this experiment. Table 3 shows the results obtained from this test.

4.4. LCPC test

This is one of the methods used for calculating the abrasivity coefficients of the rocks. A 500 g rock sample with dimensions of 4-6.3 mm is put in the chamber of the machine and the impeller is rotated at 4500 rpm for 5 min and is abraded (Figure 6). The impeller is weighed before and after the experiment. The LCPC abrasivity coefficient is obtained by dividing the difference between the impeller weight before (m_0) and after (m) the experiment by the weight of the rock sample M (500 g) (Equation 3). Figure 7 displays the salt rock sample before and after the LCPC test. The results of this experiment are listed in Table 3.

$$LAC = (m_0 - m)/M \qquad (3)$$

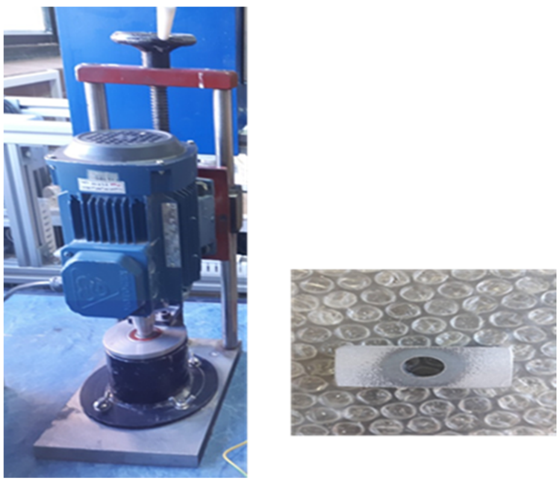

Figure 6. LCPC test machine (*left*), impeller after the LCPC test on andesite (*right*).

Figure 7. The salt rock sample before and after the LCPC test.

Table 3. Results of the tests.

Rock type	Longitudinal wave velocity (m/s)	Tensile strength(MPa)	Uniaxial compressive strength (MPa)	Modulus of elasticity (GPa)	Abrasivity coefficient (g/ton)
Shale	4717	4.00	52.4	8.17	80
Carbonate sandstone	1482	9.58	90	45.86	500
Sandstone (I)	4520	18.65	116.14	43.26	1420
Sandstone (II)	3970	8.89	103.08	32.03	910
Sandstone (top quartzite)	3412	15.14	101.25	26.55	1210
Monzogranite	3329	6.6	103.5	21.05	700
Calcareous sandstone	3397	5.27	61.63	20.25	300
Andesite	5062	11.9	120.44	43.87	1300
Calcareous dolomite	1931	8.87	57.85	60.84	20
Vitric tuff (1)	3929	8.86	118.39	28.68	350
Vitric tuff (2)	5632	2.11	26.16	6.96	150
Rock salt	4176	2.73	24.77	4.87	20

4.5. Brittleness index

This index is one of the most important rock properties for which no single and standard definition has been introduced yet. Ku *et al.* have found that the brittleness index influence the abrasivity coefficients of the rocks [16]. Therefore, the brittleness indices B_1 and B_2 in this research work were calculated using the relations proposed by Hucka and Das [17], while the B_3 index valuated by the relation presented by Plinninger [4]. The results of the calculations of the brittleness indices are presented in Table 4.

$$B_1 = \frac{\sigma_c}{\sigma_t} \qquad (4)$$

$$B_2 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \qquad (5)$$

$$B_3 = \sqrt{\frac{\sigma_t \sigma_c}{2}} \qquad (6)$$

Here, σ_c and σ_t represent the uniaxial compressive strength and tensile strength, respectively.

5. Statistical analysis

The multivariate linear regression in the SPSS software was used to study the correlation between the LCPC abrasivity coefficient and the rock properties.

5.1. LCPC abrasivity coefficient variations with each parameter

Figure 8 shows the correlations between the modulus of elasticity (E), Brazilian tensile strength (BTS), uniaxial compressive strength (UCS), equivalent quartz content (EQC), and longitudinal wave velocity (V_p) with the LCPC abrasivity coefficient.

Table 4. Brittleness indices of the rock specimens.

Rock type	B_1	B_2	B_3
Calcareous sandstone	11.69	0.84	12.74
Andesite	10.12	0.82	26.77
Calcareous dolomite	6.52	0.73	16.01
Vitric tuff (1)	13.36	0.86	22.90
Vitric tuff (2)	12.39	0.85	5.25
Rock salt	9.07	0.80	5.78
Shale	13.1	0.86	10.24
Carbonate sandstone	9.39	0.81	20.76
Sandstone (I)	6.23	0.72	32.91
Sandstone (II)	11.59	0.84	21.04
Sandstone (top quartzite)	6.68	0.74	27.68
Monzogranite	15.68	0.88	18.48

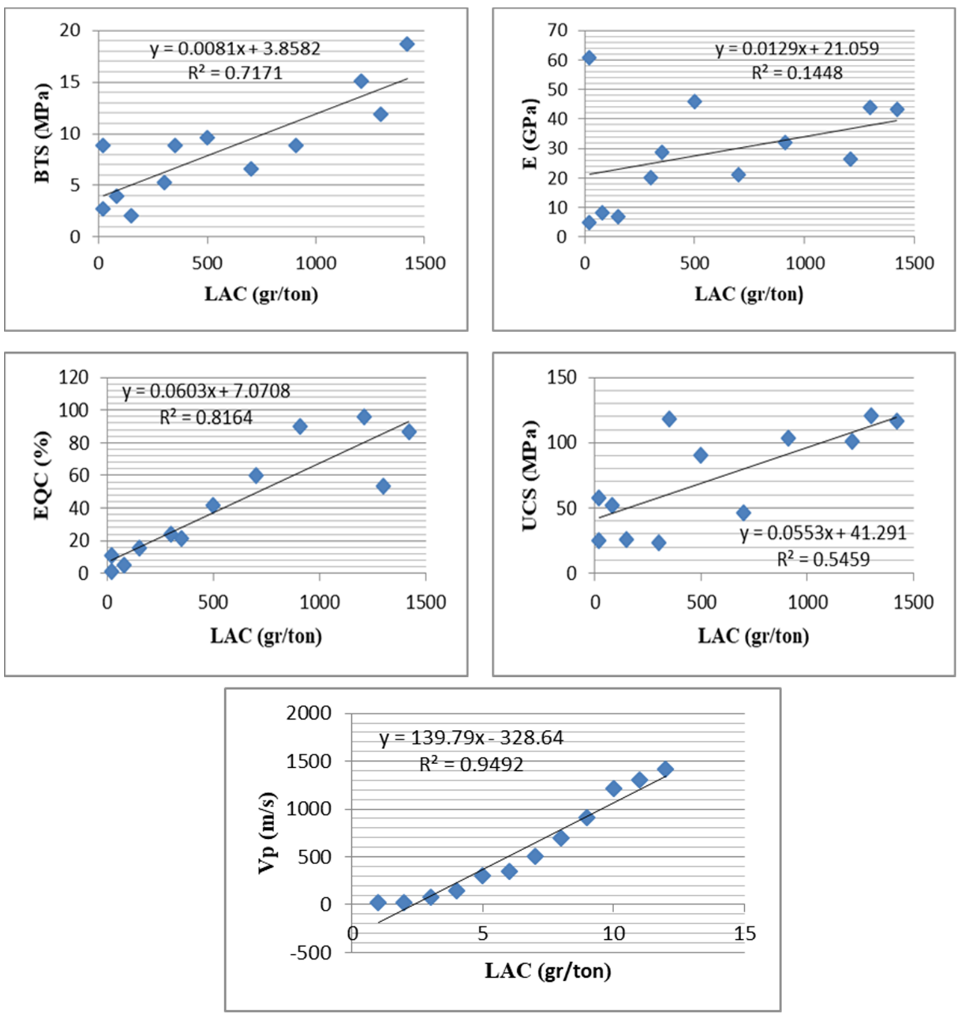

Figure 8. Relationship between the LCPC abrasivity coefficient and the rock properties. (Since the results obtained from the diagrams in Figure 8 showed that the Young's modulus had a weak correlation with the LCPC abrasivity coefficient, it was not used in the final equation).

5.2. Correlations between independent parameters

Study of the correlations between the independent parameters allows us to make a correct decision regarding the presence or absence of a statistically significant correlation between two independent variables. The correlation coefficients always vary from -1 to 1. It is noteworthy that if there is a linear correlation between two variables, i.e. if the correlation coefficient is close to -1 or to 1, only one of the two parameters must be used in the statistical analysis or in the regression equation [18]. The values for the correlation coefficients between the independent variables are presented in Table 5.

Table 5. Values of the correlation coefficients between the independent variables.

		EQC	UCS	BTS	E	B_1	B_2	B_3	V_p
EQC	Pearson correlation	1	0.637	0.771	0.329	-0.449	-0.444	0.744	-0.019
	Sig. (2-tailed)		0.026	0.003	0.296	0.143	0.148	0.006	0.952
UCS	Pearson correlation	0.637	1	0.815	0.594	-0.064	-0.086	0.941	-0.054
	Sig. (2-tailed)	0.026		0.001	0.420	0.844	0.79	0	0.868
BTS	Pearson correlation	0.771	0.815	1	0.659	-0.573	-0.607	-0.963	-0.151
	Sig. (2-tailed)	0.003	0.001		0.020	0.051	0.036	0	0.64
E	Pearson correlation	0.329	0.594	0.659	1	-0.48	-0.486	0.644	-0.559
	Sig. (2-tailed)	0.296	0.042	0.020		0.115	0.11	0.018	0.059
B_1	Pearson correlation	-0.449	-0.064	-0.573	-0.48	1	0.984	-0.367	0.422
	Sig. (2-tailed)	0.143	0.844	0.051	0.115		0	0.24	0.172
B_2	Pearson correlation	-0.444	-0.086	-0.607	-0.486	0.984	1	-0.395	0.382
	Sig. (2-tailed)	0.148	0.790	0.036	0.11	0		0.204	0.22
B_3	Pearson correlation	0.744	0.941	0.963	0.664	-0.367	-0.395	1	-0.117
	Sig. (2-tailed)	0.006	0.000	0.000	0.018	0.24	0.204		0.717
V_p	Pearson correlation	-0.019	-0.054	-0.151	-0.559	0.422	0.382	-0.117	1
	Sig. (2-tailed)	0.952	0.868	0.640	0.059	0.172	0.22	0.717	

UCS, BTS, B_1, B_2, and B_3 are the dependent parameters. As shown in the table above, among B_1, B_2, and B_3, B_3 has the highest correlation coefficient with UCS and BTS. Therefore, B_3 can be used instead of UCS and BTS.

5.3. Development of a model for estimating LCPC abrasivity coefficient

The data was entered into SPSS and the statistical processes were carried out. The results obtained are presented in the following tables (the outputs of the software).

Tables 6 to 8, respectively, show a summary of the statistical model, the variance table, and the coefficient table for regression analysis, respectively, for estimating the LCPC abrasivity coefficient. As shown in Table 6, the value of the correlation coefficient indicates the correlation of the equation. The closer this coefficient is to 1, the stronger the relationship will be. The Durbin-Watson statistic also ranges from 1 to 4. The closer this statistic is to 2, the stronger is the likelihood that there will be no correlation between the residuals. The Durbin-Watson statistic in this model is in the acceptable range.

The analysis of variance (ANOVA) table (Table 7) indicates the significance of the regression and of the linear equation between the variables. The significance level obtained confirms the confidence level. The Fisher statistic (F-value) and the significance level of the regression are shown in this Table. A significance level of less than 0.05 indicates that the independent variables are able to explain well the changes in the dependent variable. In contrast, a significant level of greater than 0.05 means that the independent variables are not able to explain the changes in the dependent variable. The significance level in this model was less than 0.05. Therefore, the F-test is confirmed and the linear regression model can be used.

Table 6. A summary of the statistical model for estimating the LCPC abrasivity coefficient.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.972	0.945	0.924	142.42014	1.725

Table 7. ANOVA table for estimating the LCPC abrasivity coefficient.

	Model	Sum of Squares	df	Mean Square	F	Sig.
	Regression	2781732.022	3	927244.007	45.714	0.000
1	Residual	162267.978	8	20283.497		
	Total	2944000.000	11			

Table 8 presents the main output of the regression analysis. Each column shows the value of the constant, β regression coefficients, standard error, β partial correlation coefficient, t-test, and significance level for each independent variable. A variable with a significance level of less than 0.05 can be used in the equation for estimating the LCPC abrasivity coefficient. As it can be clearly seen in Table 8, all the influential independent variables have a significance level of less than 0.05, and thus can be used in the regression equation.

Table 8. Coefficient table for regression analysis for estimation the LCPC abrasivity coefficient (LAC).

	Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-708.145	189.181		-3.743	.006
	EQC	7.446	2.068	.497	3.600	.007
	B_3	30.775	8.278	.519	3.718	.006
	V_P	.108	.037	.250	2.941	.019

The equation obtained from this model is expressed in relation 7.

$$LAC = -708.145 + 7.446\,(EQC) + 30.775\,(B_3) + 0.108\,(V_p) \quad (7)$$

Here, LAC, EQC, V_p, and B_3 are expressed in g/ton, percentage, m/s, and MPa, respectively.

5.4. Verification of proposed correlation

The data on the tuffs extracted from the Alulak and Haj-Fathali mines located in the north of the Qazvin County were used to verify Equation 7 (Table 9) [19]. The LCPC abrasivity coefficients for the samples were calculated using Equation 7 and compared with the laboratory results. Table 10 presents these results.

Table 9. Mineralogical and mechanical characteristics of the tuffs extracted from the Alulak (row 1) and Haj-Fathali (row 2) mines [19].

Number	B_3 (MPa)	V_P (m/s)	EQC (%)	LAC (g/ton)
1	16.02	3634	64.87	780
2	20.06	3212	29.85	420

Table 10. Comparison of the predicted results (Equation 7) and laboratory results.

LAC (g/ton) (laboratory results)	LAC (g/ton) (predicted results from Equation 7)	Difference of results (%)
780	660.4	15.3
420	478.4	13.9

6. Conclusions

The LCPC abrasivity coefficient was estimated using the physical and mechanical properties of the rocks with the help of SPSS. The speed of longitudinal waves, brittleness index B_3, and equivalent quartz content were used to obtain the best equation for estimating the LCPC abrasivity coefficient. The statistical analyses revealed that the strongest correlation coefficient was that between the LCPC abrasivity coefficient and the speed of longitudinal wave, and the weakest between the LCPC abrasivity coefficient and the modulus of elasticity.

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ارائه رابطه‌ای برای تخمین ضریب سایش LCPC با استفاده از خواص سنگ

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چکیده:

سایندگی به عنوان یکی از مهم‌ترین پارامترهای مؤثر در قابلیت حفاری سنگ‌ها، سرعت حفاری در معادن را به شدت تحت تأثیر خود قرار می‌دهد. بنابراین لازم است که قبل از انتخاب و به کارگیری ماشین حفاری، میزان سایندگی سنگ بررسی شود. با توجه به اینکه آزمایش‌های تعیین سایندگی سنگ نیازمند به امکانات پیچیده آزمایشگاهی است، می‌توان از مدل‌های تجربی برای پیش بینی آنها استفاده نمود. تا کنون شاخص‌هایی بر اساس پنج روش شناخته شده برای ارزیابی سایندگی سنگ‌ها ارائه شده است، که از جمله این شاخص‌ها می‌توان به شاخص سایندگی سنگ (RAI)، اندیس سایش سرشار (CAI)، فاکتور سایش شیمازک (F-abrasivity)، اندیس سایش سرمته (BWI) و ضریب سایش LCPC اشاره کرد. در این تحقیق روی 12 نوع سنگ که منشأ متفاوت دارند، آزمون مقاومت تراکم تک محوری، آزمون برزیلی، آزمون تعیین سرعت امواج طولی و آزمون LCPC به همراه مطالعات میکروسکوپی انجام شده است تا یک رابطه برای تخمین ضریب سایش LCPC با استفاده از آزمایشات مرسوم در مکانیک سنگ بدست آید. در نهایت با نرم افزار آماری SPSS و با استفاده از پارامترهای میزان کوارتز معادل، سرعت امواج طولی و شاخص شکنندگی سنگ‌ها رابطه‌ای خطی برای تخمین ضریب سایش LCPC با ضریب تعیین 93/3 درصد ارائه شده است.

کلمات کلیدی: شاخص سایندگی، خواص سنگ، آزمایش LCPC، نرم افزار SPSS، تحلیل آماری.