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A Modified Schimazek's F-abrasiveness Factor for Evaluating Abrasiveness of Andesite Rocks in Rock Sawing Process

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Abstract

One of the most crucial factors involved in the optimum design and cost estimation of rock sawing process is the rock abrasivity that could result in a significant cost increase. Various methods including direct and indirect tests have been introduced in order to measure rock abrasivity. The Schimazek's F-abrasiveness factor (SF_a) is one of the most common indices to assess rock abrasivity. SF_a is the function of three rock parameters including the Brazilian tensile strength (BTS), median grain size (ϕ), and equivalent quartz content ($EqQtz$). By considering its formulation, it has been revealed that the coefficient of each parameter is equal, which is not correct because each parameter plays a different role in the rock abrasion process. This work aims to modify the original form of SF_a by introducing three correction factors. To calculate these correction factors, an integrated method based on a combination of the statistical analysis and probabilistic simulation is applied to a dataset of 15 different andesite rocks. Based on the results obtained, the values of -0.36, 0.3, and -0.89 are suggested as the correction factors of BTS, $EqQtz$ and ϕ, respectively. The performance of the modified Schimazek's F-abrasiveness factor (MSF_a) is checked not only by the wear rate of diamond wire but also by the cutting rate of the wire sawing process of Andesite rocks. The results obtained indicate that the wear rate and cutting rate of andesite rocks can be reliably predicted using MSF_a. However, it should be noted that this work is a preliminary one on the limited rock types and further studies are required by incorporating different rock types.

1. Introduction

One of the most conventional materials used in the whole human civilization history is building stones. The successful extraction of building stones from mines and cutting them in processing plants requires consideration of both the technical and economical parameters [1]. One of the most crucial properties of rocks that can result not only in a significant cost increase as the economical parameter but also in the operational time reduction as the technical parameter is rock abrasivity [2]. In this paper, the term "abrasivity" is used to describe the potential of a rock to cause wear on a tool, and the term "wear rate" is considered as a parameter to describe the effect of the wear process. In fact, the wear rate describes the velocity of material removal from the cutting tool. The wear rate is a basic factor for calculation of tool consumption and wear costs [3].

Over the last couple of decades, various researchers have tried to describe rock abrasivity and to investigate the effects of rock abrasivity on the wear rate in different geo-engineering problems [4]. One of the most commonly used methods used for an indirect measurement of rock abrasivity has been developed by Schimazek and Knatz. They proposed the Schimazek's F-abrasiveness factor (SF_a) as a function of three parameters including,

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ϕ and BTS. By considering the original form of SF_a, it can be seen that the coefficient of each parameter is equal to the others, which is not correct because each parameter plays a different role in the rock abrasion process. Thus the importance degree of these parameters should be determined according to their abrasive degrees. For this reason, this work was aimed to modify SF_a by adding the correction factors in the original form of SF_a.

The reason for the importance of SF_a and the efforts to improve this factor is that it is one of the influential criteria in civic and mining activities as well as in rock mechanics experiments. For example, SF_a is one of the most effective parameters in the performance evaluation of stone sawing machines and diamond wire saw machines that must be carefully evaluated. For this reason, it is necessary in a study to identify and improve the effects of each one of the parameters affecting SF_a. Thus in this work, with regard to the theory of Schimazek's index, the authors have introduced this factor, evaluated the previous studies, and improved SF_a based on the statistical studies.

The structure of this article is as what follows. A general description of the abrasivity of rocks is presented in Section (2), which includes methods of measurement and an overview of the Schimazek's F-abrasiveness factor. In Section (3), a literature review and in Section (4), the concepts and methods of research used are presented. In Section (5), the researchers seek to find a significant relationship between the parameters affecting SF_a. The results of this work are compared with the previous studies in Section (6). Finally, Section (7) presents the research results.

2. Rock abrasivity

Although wear can be defined as the continuous and unwanted loss of a material from a solid surface in a mechanical process (such as the rock sawing process) [5], the concept of abrasion is not completely clear.

Although the physical and mechanical properties of rocks are intrinsic, rock abrasivity is a behavioral property [6], and it can be defined as the abrasive capacity of rocks [7]. In this section, firstly, a summary of the existing measurement methods of rock abrasivity is presented. In what follows, the Schimazek's F-abrasiveness factor is discussed, and finally, a comprehensive review of the applications of the Schimazek's F-abrasiveness factor in mining engineering problems is presented.

2.1. Measurement methods

Up to the present time, numerous methods have been developed by different researchers in order to assess rock abrasivity. These methods can be classified into two different groups including the indirect and direct measuring methods.

In the first group, rock abrasivity is estimated as the function of abrasivity of containing minerals. In fact, it is assumed that the mineral abrasivity has the greatest impact on rock abrasivity. Mohs hardness is one of the most well-known methods available to estimate rock abrasivity, which is developed based on the mineralogical properties of the rock [8]. In addition, in this group, rock abrasivity is considered not only as the function of the mineralogical properties such as the abrasivity of containing minerals and mineral grain size but also as the function of the strength parameters of rocks such as the uniaxial compressive and Brazilian tensile strength.

In the second group, rock abrasivity is directly obtained by performing a specific test. In fact, the main aim of performing the direct methods is to quantify the actual value of rock abrasivity [9]. Up to now, a wide range of direct methods have been developed to determine rock abrasivity. The CERCHAR and Schimazek's pin-on-disc tests are the most well-known rock abrasivity tests in this group.

2.2. Schimazek method

A literature review revealed that Schimazek's pin-on-disc is one of the widely utilized methods for measuring rock abrasivity in mining engineering problems [2, 10]. This test has been developed by Schimazek and Kantz [11]. In the following, the general process of performing Schimazek's pin-on-disc is reviewed.

The rock sample should be prepared in a disc-shaped form by a water-cooled diamond saw blade. The testing surface of rock sample should be polished with the 240 SiC powder. Afterwards, the rock sample is placed on the rotating plate in the test apparatus. In this test, a 10 mm diameter stylus made of St50 steel is used to evaluate rock abrasivity. The tip of the stylus should have a conical angle of 90 degrees. The stylus should be positioned so it is vertical and perpendicular to the rock surface and loaded on the sample with a load of 44.13 N (4.5 Kg). During the test, the sample holder circulates at a constant speed (about 25 rpm) and the stylus holder moves outward from the center to the periphery of the rock sample, which makes a spiral scratch path on the rock sample. Under these conditions, the stylus is moved by a total distance of 16.0 m across the rock. After testing, the rock abrasivity is evaluated as a function of the stylus weight loss. A minimum of ten test replications must be made on the rock surface, and the result must be averaged [11].

Measuring rock abrasivity by direct methods such as Schimazek's pin-on-disc and CERCHAR requires a special equipment that is expensive and generally unavailable in most rock mechanic laboratories. In order to solve this problem, a number of indirect indices based on different concepts have been developed for an indirect measuring of rock abrasivity.

One of the most common rock abrasivity indices is the Schimazek's F-abrasiveness factor (SF_a). The results obtained from Schimazek's pin-on-disc on different rocks have shown that the amount of stylus weight loss has a linear relationship with the multiplication of $EqQtz$, ϕ, and BTS. SF_a is calculated as:

$$SF\_a = \frac{EqQtz \times \phi \times BTS}{100} \quad (1)$$

where $EqQtz$ is the equivalent quartz volume of rock (%), ϕ is the median grain size (mm), and BTS is the Brazilian tensile strength (MPa). The tensile strength is taken as a measure of the bond strength between grains [12], and we know that ‘‘bond strength between grains’’ is an important factor in rock abrasivity and other methods do not use it for evaluation of rock abrasivity. The Brazilian tensile strength can be performed according to ISRM [13] and the grain size of rock sample can be determined using the thin section analysis.

It is obvious that the tool wear is a function of the mineral content harder than steel (Mohs hardness ca. 5.5), especially quartz (Mohs hardness of 7). To include all minerals of a rock sample, the equivalent quartz content has been determined in thin sections by a modal analysis (Equation 2). Therefore, each mineral amount is multiplied by its relative Rosiwal abrasiveness to quartz (with quartz being 100). The general relation for determining $EqQtz$ is:

$$EqQtz = \sum_{i=1}^{n} A_i . R_i \quad (2)$$

where A is the mineral proportion of the i-th mineral, R is the Rosiwal abrasiveness, and n is the number of minerals in rock.

3. Literature review

The Schimazek's F-abrasiveness factor has been widely utilized by different researchers for a wide range of mining engineering applications. In what follows, the most important and well-known studies of the last couple of decades are reviewed. SF_a has been used to assess abrasivity of sedimentary rocks, especially in the tunneling and coal mining projects. The results obtained have shown that there is a linear relationship between SF_a and wear rate of cutting tools [12, 14, 15]. Hoseinie et al. [16] have developed a classification system to evaluate rock penetrability using five parameters of the rock material including the uniaxial compressive strength (UCS), Schimazek's F-abrasiveness factor (SF_a), Mohs' hardness (MH), median grain size (ϕ), and Young's modulus (E). The results obtained have shown that the rock penetration index has a strong relationship with the actual penetration rate in the rock drilling process. Mikaeil et al. [17] have developed a decision support system for ranking the sawability of ornamental rocks. They concluded that the sawability of rocks was mainly affected by UCS, SF_a, MH and E. In a similar study, Mikaeil et al. [18] have utilized the PROMETHEE method in order to predict the sawability of ornamental rocks. They proposed a decision support system using four rock properties including UCS, SF_a, MH, and E. The results obtained demonstrated that there was a meaningful correlation between the production rate and the proposed method.

Majeed and Abu-Bakar [19] have performed an extensive study for examining the abrasiveness of different rocks. To do this, forty-six rock units including igneous, sedimentary, and metamorphic rocks were subjected to a comprehensive laboratory testing program. They studied the relationship between SF_a and the results of the CERCHAR abrasivity test. The results obtained showed that the CERCHAR abrasivity was related to SF_a through a power relation with $R^2 = 0.7$. Akhyani et al. [20] tried to predict the performance of circular diamond saw of hard rocks through an artificial intelligence method. For this purpose, the information pertaining to fourteen types of hard rocks including UCS, SF_a, MH, and E were used. The results obtained demonstrated that the given artificial intelligence approach was properly capable of evaluating the cutting performance. Almasi et al. [21] have carried out an experimental study to investigate the relationship between the cutting performance of diamond wire saws with the production rate and some important characteristics of hard rocks. A linear relationship with $R^2 = 0.48$ was found between the wear rate and SF_a. In addition to the simple regression analyses, the multiple curvilinear regression analysis was performed in order to obtain more significant and practical models. The results obtained showed that the wear rate of diamond bead could be reliably predicted using the model including SF_a and production rate with a correlation coefficient over 80%.

Dormishi et al. [22] have experimentally studied the performance of gang saw machines in cutting twelve different carbonate rocks. The results of the simple regression analysis showed that the energy consumption of gang saw machine with good coefficient of correlation depended on the rock properties including UCS, SF_a, MH, and E. They also developed several linear and non-linear regression models in order to predict the energy consumption of gang saw. The results of the non-linear regression analyses indicated that UCS, MH, and SF_a were included in the best models.

More recently, Haghshenas et al. [23] have utilized a robust non-linear algorithm of gene expression programming in order to predict the maximum electrical current of gang saws. MH, UCS, SF_a, YM, and production rate were selected as the input parameters. The results obtained showed that a maximum electrical current could be reliability predicted using the proposed method.

Aryafar et al. [24] have proposed the application of metaheuristic algorithms in vibration optimization of sawing machines. The researchers indirectly evaluated the shear efficiency by examining the effectiveness of various criteria such as UCS, MH, YM, and SF_a using genetic algorithm (GA) and differential evolution (DE). The results obtained showed that these factors were very effective and the effect of SF_a was undeniable. Also Dormishi et al. [25] used the ANFIS-DE and ANFIS-PSO hybrid algorithms to evaluate the efficiency of diamond cutting wire. One of the most important criteria they considered in their research work was SF_a, which had significant effects on the efficiency of diamond cutting wire.

4. Concepts and methods used

As mentioned in the previous section, SF_a was developed as a function of three parameters including $EqQtz$, ϕ, and BTS of the rock sample. With respect to Equation (1), it can be seen that the coefficient of each parameter is equal to the others, which is not correct because each parameter plays a different role in the rock abrasion process. In fact, it can be stated that in some cases this index does not have a suitable ability to distinguish and classify the rock abrasivity. In order to solve this problem, this paper tries to modify SF_a by introducing the correction factors in the original form. The equation proposed in this research work is given as follows:

$$SF\_a = BTS^{\alpha} \times \phi^{\beta} \times EqQtz^{\gamma} \quad (3)$$

where α, β, and γ are the correction factors for BTS, ϕ, and $EqQtz$, respectively.

The main aim of this work was to find the optimum correction factors of the proposed equation for evaluating the abrasiveness of andesite rocks in the rock sawing process. In order to approach this goal, an integrated method based on the statistical analysis and probabilistic simulation was applied. In what follows, the main procedure for the utilized approach is discussed.

First of all, a multiple linear regression analysis was performed in order to develop a linear relationship between the measured wear rate (Wr) and the independent parameters including $EqQtz$, ϕ, and BTS. The general form of the proposed linear relationship is given as follows:

$$Wr = a + (b \times BTS) + (c \times \phi) + (d \times EqQtz) \quad (4)$$

where Wr is the wear rate of diamond wire ($\mu m/m^2$), a is the intercept of the regression, and b, c, and d are the coefficients of BTS, ϕ, and $EqQtz$, respectively.

Secondly, based on the Equation (4) obtained, the probabilistic analysis was performed in order to assess the impact of the independent parameters on the wear rate. In fact, the statistical analysis was performed on a limited dataset, and generalization of the results obtained to other data may lay in unreliable estimations. To overcome this issue, the application of probabilistic simulation can be useful.

The probabilistic analysis is based on the generation of multiple attempts to calculate the expected values for a random variable [28]. In this method, unlike the statistical analysis, the distribution functions are used to define the input and output parameters. The distribution functions for the input parameters were obtained based on the variation in the parameters, and the Monte Carlo simulation was utilized to define the output distribution function. In this research work, by utilizing the Monte Carlo simulation, the impact of three normal distribution functions (representing BTS, ϕ, and $EqQtz$) on the measured wear rate was evaluated. Finally, the results obtained from the probabilistic analysis, i.e. the impact of the independent parameters on the wear rate, were considered as the correction factors in Equation (3).

Herein, an open access dataset published by Mikaeil et al. [29] is used to calculate the proposed correction factors. The dimension stone block samples were collected from 15 different andesite quarries located in Ankara (Turkey). There was an emphasis on using the blocks that were big enough and free of discontinuities such as fractures, alteration zones, and partings. The rock samples were divided into two groups. The first group of rocks were prepared and tested to determine the mentioned physical and mechanical properties according to the ISRM standards [13].

In order to determine the wear rate of the diamond wire saw, a field study including block cutting operations using a diamond wire cutting machine was carried out. At least, three cutting operations were performed for each andesitic dimension stones on site, and their averages were taken and recorded as a representative on-site measurement. Some of the machine parameters, given in Table (1), were fixed in order to achieve more correct results.

To measure the wear rate of diamond wire, bead dimensions of the wire were measured before and after performing the tests. The wear rate was recorded as the difference in the diameter measurements using a three-digit digital micrometer. The wearing measurements were carried out containing at least 1/4 of the wire length used and taking at least four measurements from the different sides of a bead. Then the unit wear values of the beads were identified as the amount of wear per square meter ($\mu m/m^2$). The results obtained from the laboratory tests are shown in Table (2).

Table 1. Fixed parameters of machines and equipment employed in this work [29].

Parameter	Unit	Value
Number of beads per meter	-	37
Power of machine	kW	37.3
Speed of machine	rpm	750
Voltage	V	380
Stretching amperage	A	25
Pullback force	MPa	3.6
Pulley diameter	cm	80

Table 2. Basic descriptive statistics for original database [29].

Parameter (unit)	Ranges	Avg.	SD	Var.
BTS (MPa)	3.56–9.83	7.15	2.31	5.35
ϕ (µm)	51–140	103.4	29.75	885
EqQtz (%)	1–7	3.5	1.55	2.39
Wr (mm/m^3)	(15–168) × 10^{-4}	0.0062	0.0054	0.00003
Cr (m^2/h)	0.33–3.33	1.65	0.925	0.856

5. Calculation of correction factors

An integrated approach based on the statistical analysis and probabilistic simulation was utilized to calculate the proposed correction factors of Equation (3). In what follows, the main procedure for the calculation of the correction factors is discussed.

In the first step, the correlation between each independent parameter and the actual wear rate was investigated. As it can be seen in Figure (1), BTS and wear rate have a linear relationship with $R^2 = 0.38$. Throughout the rock cutting, as BTS increases, the wear rate of diamond wire increases. Likewise, in this particular project, the wear rate of diamond wire is related to $EqQtz$ through a linear relation with $R^2 = 0.75$. Furthermore, the statistical analysis showed that ϕ had the greatest correlation with the wear rate (Figure 2). During the rock cutting process, as for ϕ, the measured wear rate decreases drastically. The relationship between ϕ and the actual measured wear rate was obtained with $R^2 = 0.97$, as shown in Figure (3). The equations obtained between the wear rate and each rock parameter are given in Table (3).

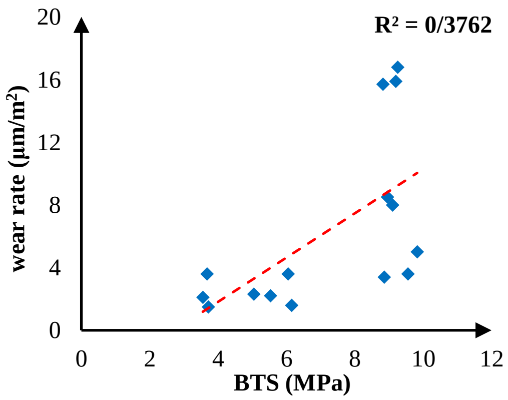

Figure 1. Linear relation between measured wear rate and BTS.

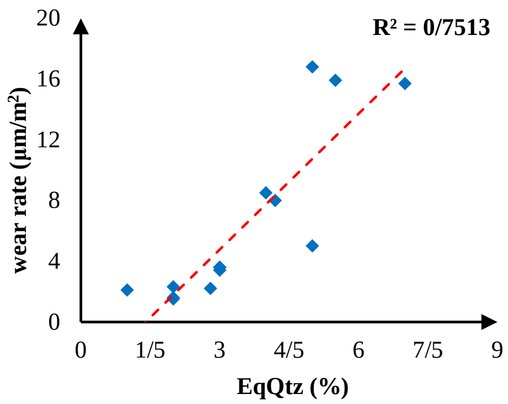

Figure 2. Linear relation between measured wear rate and EqQtz.

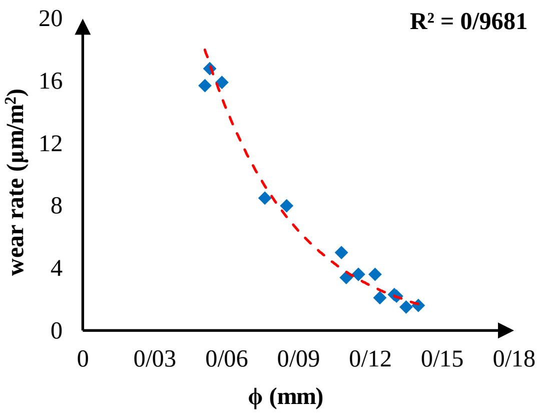

Figure 3. Exponential relation between measured wear rate and Grain size.

Table 3. Relations between rock properties and measured wear rate with achieved equations.

Equation	An empirical equation	R^2	F-ratio	Tab. F-ratio	t-value	Tab. t-value	P-value
(5)	$Wr = -3.86 + 1.41BTS$	0.38	7.84	6.413	7.027	±2.16	0.008
					2.80	±2.16	
(6)	$Wr = -4.18 + 2.98EqQtz$	0.75	15.31	6.413	3.081	±2.16	0.001
					3.912	±2.16	
(7)	$Wr = 69.56\exp(-26.5\phi)$	0.97	432.2	6.413	-20.789	±2.16	0.001
					7.261	±2.16	

The validation of Equations 5-8 was checked by considering the P-value, t-test, and F-test. The P-value for each equation tests the null hypothesis that the coefficient is equal to zero. A low P-value (less than 0.05) indicates that the null hypothesis can be rejected. In Table 3, it can be seen that all equations have a P-value less than 0.01, and therefore, it can be stated that the null hypothesis can be rejected. In order to test the significance of the R-value, the t-test was applied. This test compares the computed t-value with a tabulated t-value using the null hypothesis. According to this hypothesis, if the computed t-value is greater than the tabulated t-value, the null hypothesis is rejected. In this case, R is significant; otherwise, it is not significant. In Equations 5-8, a 97.5% confidence level was chosen, and a corresponding critical t-value of ±2.16 was obtained for the models. As it can be seen in Table 3, the computed t-values are greater than the tabulated t-value for all models, which can infer that all models are valid.
On the other hand, to test the significance of the regressions, the analysis of variance was applied. Similar to the t-test, this test compares the computed F-value with a tabulated F-value using the null hypothesis. According to this test, if the F-value is greater than the tabulate F-value, the null hypothesis is rejected, which means that there is a real relationship between the dependent and independent variables. In this test, a 97.5% level of confidence was chosen, and a corresponding tabulated F-value of 6.413 was obtained. Since the tabulated F-value is less than the computed F-value for all models, it can be concluded that the models are valid.
After performing the simple regression analysis, one of the commercial software packages for standard statistical analysis (SPSS) was utilized to perform the multivariable linear regression analysis between the rock parameters and the wear rate. The results of this regression analysis are presented in Table 4. Based on the multivariable linear regression analysis, Equation (8) can be suggested for the estimation of the wear rate of diamond wire.

$$Wr = -0.27BTS + 0.47EqQtz - 0.167\phi + 23.784 \quad (8)$$

Table 4. Results of multivariable linear regression analysis for rock abrasivity prediction.

Model	Parameter	Coefficient	Std. error	F-ratio	Tab. F-ratio	t-value	Tab. t-value	R
Eq. 8	Constant	23.784	0.004	72.438	11.56	5.603	±1.65	0.976
	BTS	-0.270	0.0002			-1.194		
	EqQtz	0.471	0.001			1.912		
	ϕ	-0.167	0.0003			-6.746		

The validation of Equation 8 was carried out by considering the correlation coefficient, t-test, and F-test. The correlation coefficient of the obtained equation ($R = 0.976$) is good but this index is not solely able to verify the validation of the model. Hence, the other tests must be performed. In the model, a 95% confidence level was chosen, and a corresponding critical t-value of ±1.65 for the model was obtained. As it can be seen in Table 4, the computed t-values are greater than the tabulated t-values for the model, suggesting that the model is valid. In this test, a 99% level of confidence was chosen. Since the computed F-value (72.44) is greater than the tabulated F-value (11.56) for the models, it can be concluded that the model is valid. Afterwards, the probabilistic analysis was performed in order to assess the impact of the rock parameters on rock abrasivity. As discussed in the previous section, the inputs of the probabilistic analysis are distribution functions. In this work, three normal distribution functions were supposed for the three input parameters (BTS, ϕ, and $EqQtz$) as the input distribution function of analysis, and their impact on the output was considered using the Monte Carlo simulation. The distribution functions of the input parameters are illustrated in Figures 4-6.

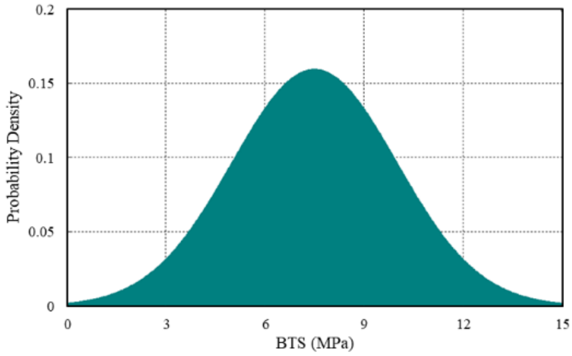

Figure 4. Normal distribution function used for Brazilian tensile strength.

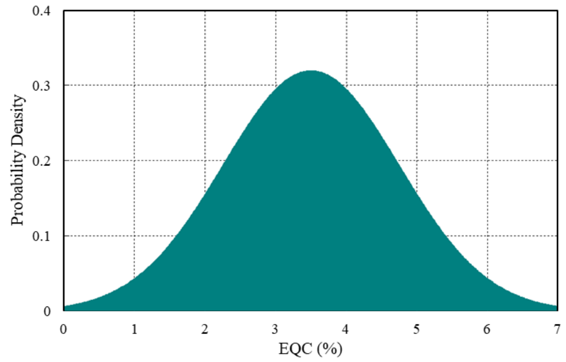

Figure 5. Normal distribution function used for equivalent quartz content.

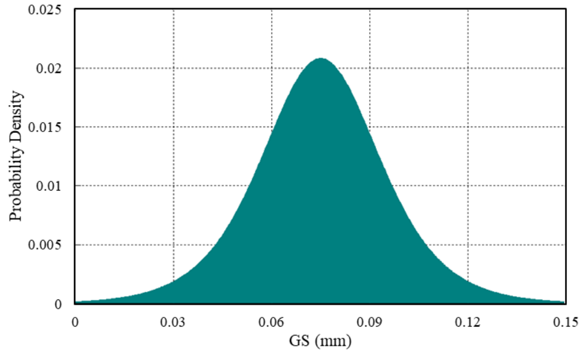

Figure 6. Normal distribution function used for grain size.

The results of the probabilistic analysis are demonstrated in Figure 7. It can be seen that the major and minor influencing parameters on the wear rate of diamond wire are ϕ and $EqQtz$, respectively. Furthermore, it has been inferred that BTS and ϕ have an inverse impact on the wear rate, while a direct impact of $EqQtz$ on the output is observed.

According to the results obtained, the values of -0.36, 0.30, and -0.89 were considered as the correction factors for BTS, $EqQtz$, and ϕ, respectively. After substituting the correction factors, the general form of the modified Schimazek's F-abrasiveness factor (MSF_a) was achieved as Equation 9.

$$MSF\_a = \frac{EqQtz^{0.3}}{BTS^{0.36} \times \phi^{0.89}} \quad (9)$$

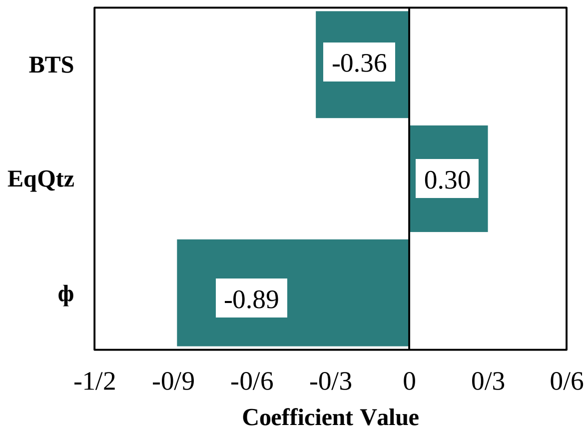

Figure 7. Impacts of input parameters of probabilistic analysis on Equation 8.

6. Comparison of MSF_a performance with previous models

The purpose of the study described in this section was to compare the performance of MSF_a with the previous studies. Ataei et al. [28-29] have presented two different approaches in order to provide a modification for SF_a.

Ataei et al. [28] have stated that considering an equal importance for all parameters in SF_a is not correct. Thus they developed a classification system (CSF_a) to classify rock abrasivity. Actually, CSF_a was developed based on the same parameters as incorporated in the original form of SF_a for the carbonate rocks. Based on the proposed classification, abrasiveness of carbonate rocks can be classified into five different categories including very low, low, medium, high, and very high. The proposed rock abrasivity classification is presented in Table 5.

Table 5. Rock abrasivity classification [28].

Equivalent quartz content	0-1.5	1.5-3	3-4.5	7-10	> 10
	very low	low	medium	high	very high
Rating	3.9	9.75	19.5	29.25	39
Median grain size	0-0.02	0.02-0.6	0.6-6	6-20	> 20
	very low	low	medium	high	very high
Rating	3.15	7.875	15.75	22.05	31.5
Brazilian tensile strength	0-2	2-4.5	4.5-7	7-9	> 12
	very low	low	medium	high	very high
Rating	2.95	7.375	14.75	20.65	29.5

More recently, Ataei et al. [29] have utilized a knowledge-driven method in order to modify SF_a. They tried to modify SF_a considering the weights of its applied parameters. In that research work, the Fuzzy Delphi Analytical Hierarchy Process (FDAHP) was applied to calculate the weight of the dominant parameters in rock abrasivity. For this purpose, several questionnaires were distributed and the expert opinions were collected. The modified Schimazek's F-abrasiveness factor by Ateai et al. [29] (MF) is as presented in Equation 10. In contrast to CSF_a, which was developed only for carbonate rocks, MF was proposed for all types of rocks.

$$MF = \frac{BTS^{0.29} \times \phi^{0.31} \times EqQtz^{0.4}}{100} \qquad (10)$$

In this section, the performance of MSF_a (Equation 9) is compared with the original form of SF_a (Equation 1), CSF_a (Table 5), and MF (Equation 10). A comparison between the measured wear rate and SF_a, MSF_a, CSF_a, and MF can be found in Table (6).

Table 6. Comparison between measured wear rate and rock abrasivity using suggested and existing indices.

Andesite rock	**BTS**	**ϕ**	**EqQtz**	**Wr**	**Cr**	**SF_a**	**This study**	**Ataei et al. (2012)**	**Ataei et al. (2017)**
	(MPa)	**(mm)**	**(%)**	**(μm/m²)**	**(m²/h)**	**Eq. 1**	**Eq. 9**	**Table 5**	**Eq. 7**
Type-1	3.72	0.135	2	1.5	3.3	0.0100	4.547	19.15	0.0104
Type-2	5.05	0.13	2	2.3	3.29	0.0131	4.217	26.525	0.0112
Type-3	9.55	0.115	3	3.6	1.75	0.0329	4.231	32.425	0.0153
Type-4	8.86	0.11	3	3.4	1.8	0.0292	4.520	32.425	0.0147
Type-5	3.56	0.124	1	2.1	2.81	0.0044	4.045	19.15	0.0076
Type-6	9.83	0.108	5	5	1.58	0.0531	5.161	32.425	0.0185
Type-7	6.15	0.14	2	1.6	2.23	0.0172	3.681	26.525	0.0121
Type-8	8.82	0.051	7	15.7	0.33	0.0315	11.535	32.425	0.0163
Type-9	9.25	0.053	5	16.8	0.62	0.0245	9.909	32.425	0.0146
Type-10	9.2	0.058	5.5	15.9	0.64	0.0293	9.432	32.425	0.0156
Type-11	8.95	0.076	4	8.5	0.85	0.0272	6.813	32.425	0.0148
Type-12	9.1	0.085	4.2	8	0.74	0.0325	6.224	32.425	0.0157
Type-13	3.68	0.115	3	3.6	1.2	0.0127	5.942	19.15	0.0116
Type-14	5.53	0.131	2.8	2.2	2.1	0.0203	4.486	26.525	0.0132
Type-15	6.05	0.122	3	3.6	1.49	0.0221	4.724	26.525	0.0136

Furthermore, the correlation between the wear rate and different rock abrasivity indices are presented graphically through Figures 8-11. As it can be seen in Figure 8, the original forms of SF_a and wear rate have a linear relationship with $R^2 = 0.14$, which is a very weak correlation. In this case, it can be stated that SF_a should not be used to predict rock abrasivity (especially for andesite rocks).

Figure 9 shows that CSF_a is related to the actual wear rate of diamond wire through a linear relation with $R^2 = 0.35$, in which it can be inferred that CSF_a has slightly improved the performance of SF_a.

On the other hand, the relationship between MF, developed by Ateai et al. [29], with the wear rate was found to be very weak with a coefficient determination (R^2) of 0.27, as demonstrated in Figure 10. Similar to CSF_a, the performance of SF_a has been slightly improved by MF but the improvement is very low. However, the results obtained were a bit confusing. It was expected that MF would show better results rather than CSF_a because MF was developed for all type of rocks and CSF_a was just proposed for the carbonate rocks, in which, in the case of this work, the characteristics of andesite rocks are totally different from the carbonate ones.

In addition, during the calculation of CSF_a for andesite rocks, it was found that this classification system had some shortcomings. In fact, CSF_a does not consider all possible ranges of $EqQtz$ and BTS. For instance, CSF_a classifies $EqQtz$ into five groups including (0-1.5), (1.5-3), (3-4.5), (7-10), and (more than 10%). As it can be seen, CSF_a cannot be applied to rocks with $EqQtz$ ranging from 4.5% to 7%. A similar issue can be seen for classifying BTS over the range of 9-12 MPa.

Therefore, it can be inferred that CSF_a and MF are not reliable for predicting rock abrasivity. In addition, the relationship between MSF_a and the actual wear rate is depicted in Figure (11). As it could be seen, a linear relationship between the actual wear rate and MSF_a was obtained with $R^2 = 0.93$. According to the results obtained, the performance of SF_a, CSF_a and MF is nearly the same, whereas MSF_a shows a higher prediction performance in comparison with them.

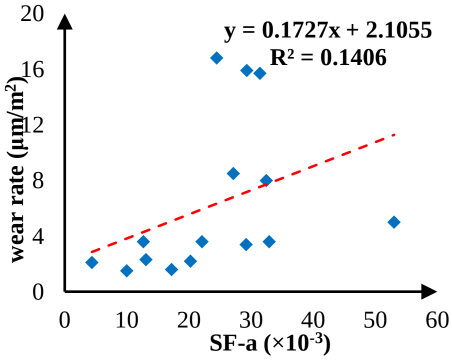

Figure 8. Correlation between SF_a (Equation 1) and wear rate.

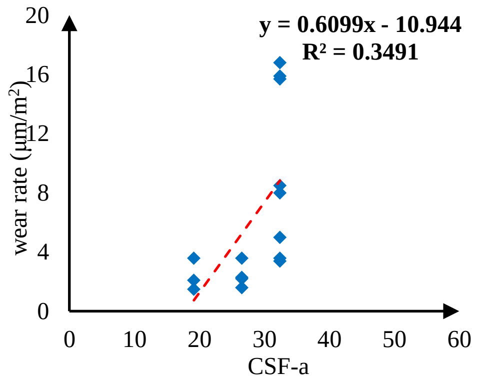

Figure 9. Correlation between CSF_a (Table 5) and wear rate.

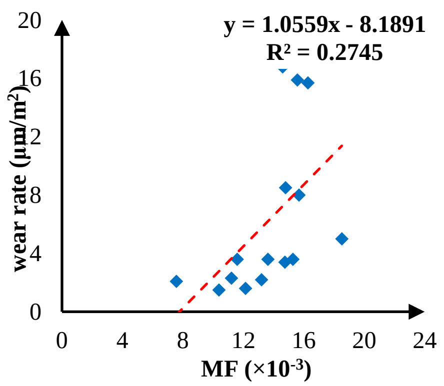

Figure 10. Correlation between MF (Equation 10) and wear rate.

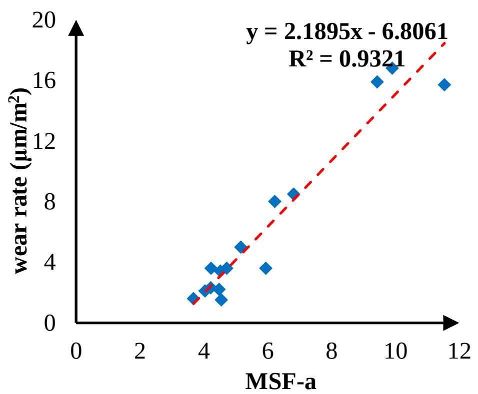

Figure 11. Correlation between MSF_a (Equation 9) and wear rate (present study).

Finally, the validation of MSF_a was verified by the results obtained from cuttability of the andesite rocks. To do so, the relationship between the cutting rate of andesite rocks and different rock abrasivity indices was studied. As it could be seen in Figure 12, a weak relationship between SF_a and the actual cutting rate was obtained with $R^2 = 0.31$. According to this relationship, as rock abrasivity increases, rock cuttability drastically decreases, which is meaningful. Similar relationships were found between rock cuttability and both CSF_a and MF. The relationships between CSF_a and MF and the cutting rate were found to be very weak with the determination coefficients (R^2) of 0.34 and 0.39, respectively, as demonstrated in Figures 13 and 14.

The relationship between MSF_a and the actual cutting rate is illustrated in Figure 15. As it could be seen, a power relationship between the actual cutting rate and MSF_a was obtained with $R^2 = 0.83$. It can be concluded that not only the actual wear rate but also the cutting rate of andesite rocks can reliably be predicted using MSF_a.

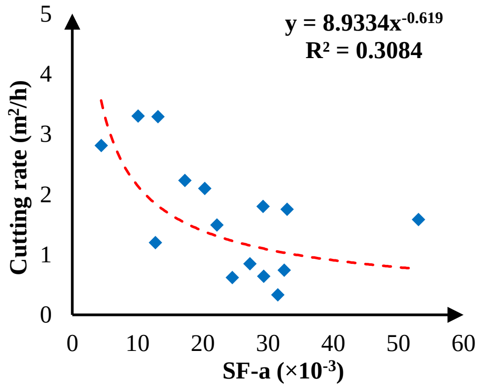

Figure 12. Correlation between SF_a (Equation 1) and cutting rate.

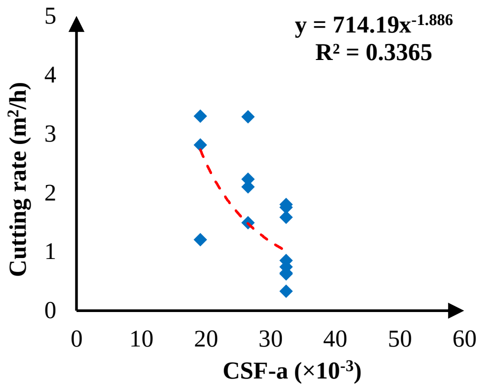

Figure 13. Correlation between CSF_a (Table 5) and cutting rate.

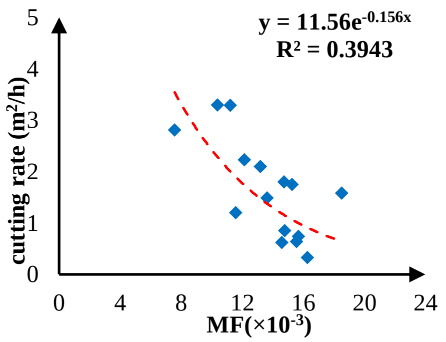

Figure 14. Correlation between MF (Equation 10) and cutting rate.

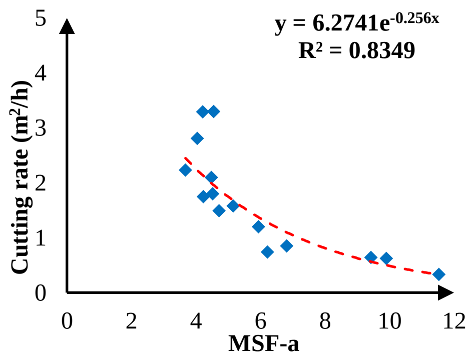

Figure 15. Correlation between MSF_a (Equation 9) and cutting rate (present study).

7. Conclusions

According to the results obtained for the wear rate of diamond wire, the performance of SF_a, CSF_a, and MF was nearly the same ($R^2 = 0.14$, 0.35, 0.27, respectively), whereas MSF_a showed a higher prediction performance in comparison with them ($R^2 = 0.93$). In addition, less and more similar results were observed between the cutting rate and different forms of Schimazek's factor. MSF_a showed a higher performance ($R^2 = 0.83$), whereas the performance of SF_a, CSF_a, and MF was nearly the same (, respectively). The performance of MSF_a was compared with the original form of SF_a, CSF_a (developed by Ataei et al. 2011), and MF (developed by Ataei et al. 2017). For this purpose, the performance of the mentioned factors was checked not only by the wear rate of diamond wire but also by the cutting rate of wire sawing process of andesite rocks. It should be noted that the suggested method is especially useful for the rock sawing industry and especially for the cases of andesite rocks. Moreover, a large number of different rock types should be further tested in order to develop a more comprehensive factor for all types of rocks. More attempts are underway to propose more general forms of rock abrasivity to overcome the previous shortages.

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اصلاح شاخص سایندگی شیمازک به منظور ارزیابی سایندگی سنگ‌های آندزیت در فرایند برش سنگ

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چکیده:

یکی از تأثیرگذارترین پارامترها در طراحی بهینه و برآورد هزینه فرایند برش سنگ، میزان سایندگی سنگ است که می‌تواند منجر به افزایش قابل توجه هزینه‌های عملیاتی شود. به منظور محاسبه و ارزیابی میزان سایندگی، روش‌های مختلفی ارائه شده است که می‌توان به آزمایش‌های مستقیم و ارزیابی غیرمستقیم اشاره کرد. یکی از مهم‌ترین و رایج‌ترین شاخص‌های ارزیابی میزان سایش سنگ، شاخص سایندگی شیمازک (SF_a) است که از حاصلضرب مقاومت کششی (BTS)، محتوای کوارتز معادل (EqQtz) و ابعاد دانه‌های سنگ (ϕ) حاصل می‌شود. شاخص SF_a تابعی از سه پارامتر مذکور بوده و میزان اثرگذاری هر سه پارامتر، یکسان در نظر گرفته شده است. با در نظر گرفتن فرمول این شاخص، مشخص شده که تساوی ضرایب پارامترها صحیح نیست؛ زیرا هر پارامتر در فرایند سایش سنگ نقش متفاوتی را ایفا می‌کند. هدف اصلی این پژوهش، اصلاح شاخص SF_a با معرفی ضرایب تصحیح است. برای محاسبه این ضرایب، از روش ترکیبی مبتنی بر تحلیل‌های آماری و شبیه‌سازی احتمالاتی بر روی داده‌های حاصل از ۱۵ نمونه سنگ آندزیت مختلف استفاده شد. بر اساس نتایج به‌دست‌آمده، مقادیر ۰/۳۶- ، ۰/۳ و ۰/۸۹- به ترتیب به‌عنوان ضرایب تصحیح پارامترهای BTS، EqQtz و ϕ پیشنهاد شد. همچنین عملکرد شاخص سایندگی شیمازک اصلاح‌شده (MSF_a) از دیدگاه میزان سایش سیم‌برش الماسه و نیز سرعت برش در فرایند برش با اره برای سنگ‌های آندزیت بررسی شد. نتایج حاصل نشان می‌دهد که شاخص MSF_a بر اساس داده‌های موجود، سازگاری مناسبی با شرایط واقعی داشته و نسبت به شاخص SF_a بهبود یافته است. از سوی دیگر، میزان سایش و سرعت برش سنگ‌های آندزیت با استفاده از شاخص ارائه‌شده قابل پیش‌بینی است. البته باید اشاره نمود که این مطالعه در مورد انواع محدودی از سنگ‌های ساختمانی انجام شده و مطالعات آتی برای انواع مختلف سنگ پیشنهاد می‌شود.

کلمات کلیدی: سایش، شاخص سایندگی شیمازک، فرایند برش سنگ، نرخ برش، سنگ‌های آندزیت.