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Measurement, Prediction, and Modeling of Bit Wear During Drilling Operations

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Abstract

Modelling wear of drill bits can increase the efficiency in the drilling operations. Related to the subject, it is aimed to investigate the wear mechanism of drill bits. Wear in drill bits is influenced by many factors related to the drilling and rock properties. The type and intensity of wear are dependent on several complicated factors that are required to be considered in anticipating the rate of wear in the field and laboratory conditions. The laboratory tests have been performed in order to specify the relationships between the bit wear rate and the physico-mechanical properties, drillability, abrasive properties, and brittleness of rocks. Statistical analysis has been used to obtain equations for estimating the bit wear rate based on the rock properties. In this work, an ensemble technique is used to estimate the confidence interval and the prediction intervals for the regression models. This paper summaries the rock properties and bit wear mechanism, and argues the options to determine the bit wear rate. The test models indicate that the rock properties can give an idea of bit wear. They also show a good correlation between the bit wear rates. Also some models are developed to represent the wear quantification, and an approach is suggested in order to estimate the bit wear rate. The results obtained from studying the developed models provide a good agreement with the performance evaluation of an efficient drilling, which provide an indirect evaluation of drill bit wear rate during a drilling process, which can help to reduce the specific energy consumption and lower costs for the exchange of drill bits.

1. Introduction

Drilling of rocks is one of the most demanding operations in surface mining and underground engineering. In the recent years, underground mine, open-pit mining, and quarries and tunnel drilling process have increased for the excavation purposes, which cannot be carried out without the use of drill tools. Therefore, drill tools are considered to be an important issue in a drilling process because the cost of drilling tools is quite high in the total project cost. Thus bit wear prediction is considered as an important issue in planning and designing a drilling process. Drill bit wear is one of the most important input parameters for the tunnel project designes. This is done using the development models.

In the civil and mining engineering industrial applications, the bit wear rate is usually observed depending on the drilling time or the performance time of drilling rig, and it shows a typical behavior, which is similar to the dependence of drill bit wear on the drilled length [1].

The bit wear defines the rate of material removal from the bit. The bit wear is an important parameter used to calculate the bit consumption and wear costs [2, 3]. The bit wear in rock drilling is a major factor involved in determining the drilling cost, and may determine the drilling method for a given rock [4].

Many researchers have reported many studies related to the bit-rock interactions. One of the main factors affecting the drilling process is bit wear. A serious wear on the bit leads to the delay in a

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drilling process, which certainly brings about increased project costs. Fay [5], Willis and Johnson [6] have reported that the bit wear is one of the main factors affecting the drilling costs and penetration rate. Therefore, the key aspect to decrease the drilling costs is to determine the interactions between the rock properties and the rock bit according to a particular drilling process.

Singh and Alam [7] have revealed that one of the important points about rock excavation is that the drilling tools are in interaction with different types of geological structures. Some of the dominant rock properties such as uniaxial compressive strength (UCS), tensile rock strength, elasticity modulus, abrasivity, and rock structure affect the drill performance during a rock excavation.

The high production rate and efficiency of drilling machines is essential for the profitability and productivity in modern mining sites. However, bit wear severely affects the advance rate of the machines in the drilling conditions, resulting in the increasing cost and project delay. Some research works have been performed to get a proper drilling bit with an optimum shape and optimum abrasive material in order to extend its life under different drilling conditions [8].

The form of bit wear widely depends on the bit temperature. The bit velocity is the main parameter involved in influencing the bit temperature. Therefore, a practical approach is to keep the bit temperature below the critical value at a higher velocity [9]. Thuro [10] has shown that some specific rock properties and geological factors significantly influence the bit wear and drilling rate. Ersoy and Waller [11] have demonstrated that bit wear depends on the size of drill cuttings. A larger size of the drill cuttings causes a rapid wear in impregnated diamond core drilling bits, thereby reducing the penetration rate.

Howarth and Rowlands [12] have stated that the rock hardness cannot be determined and described by a single physical property. They also pointed out that the petrographic properties can be used in order to determine the wear tool. Warren [13], Burgess [14], Falconer and Normore [15], Kuru and Wojtanowicz [16] have carried out research works on a torque model in order to demonstrate the effect of tooth wear on drilling. This model is based on a mechanical efficiency log that uses the penetration rate data, and rotation speed and measurement while drilling the torque and weight on bit.

Rabinowicz [17] has stated that the previous methods for determining the wear are based on the empirical equations. Ning and Ghadiri [18] have developed a wear model for materials under a shear loading. The surface damage in consideration here is the elastic-plastic damage by the propagation of the lateral cracks as the particles are loaded and slid against each other by shearing. Hutchings [19] has investigated abrasive wear involving the removal of material by plastic deformation. This model is based on assuming that the abrasive particles are represented as a cone of semi-angle being dragged across the surface of the material under an indentation pressure. Rabinowicz [20] has developed an abrasive wear model in order to improve the quantification of the two-body abrasive wear. This model figures the process of an abrasive grain sliding over a distance, while the grain is pressed upon a given surface with a force.

Abrasive wear is the dominant type of wear occurring in drilling due to the drilling mechanism of the bit cutters against rock formation. The wear type causes a serious damage to the drill bit, and therefore, many engineers have assessed means of wear quantification to understand the material resistance against it and how it can be minimized. Various wear models have been assumed; however, most of them are only relevant to specific cases [21].

Mori *et al.* [22] have studied the development of the materials that are highly resistant to wear and chipping to prolong the life of the roller cone insert bits during drilling hard abrasive rocks. The test results showed that these manufactured insert samples achieved more than eight times the wear resistance of traditional inserts.

Dupriest and Koederitz [23] have stated that the specific energy displays a gradual slow rise, which is an indication of a continuous bit wear. This mean that bit wear is an effective specific energy. In other words, dramatic increases of the specific energy values correspond to a severe bit wear.

A drilling process is widely influenced by the bit rock interactions. A theoretical model has been advanced in order to calculate the forces applied to the drill bits [24].

The drilling performance depends upon the drill bit life. The drill bit consumption is wear due to the rock/bit interaction. A worn bit decreases the penetration rate because the drill bit cost is expensive [25]. According to Cunha [26], the drilling costs may constitute up to 40% of all the costs.

There are many methods available for the bit quantification. Each model depends on the field values and the bit wear types [27]. Alemdag *et al.* [28] have emphasized that the theoretical and empirical analysis models are reliable. Saai *et al.*

[29] have measured the wear resistance of drill bits for underground drilling. Their study expressed that an increase in the impact speed accelerates the weight loss. Adebayo [30] has concluded that the high strength and abrasive rock parameters decline the drilling performance. These parameters lead to a low penetration and a high wear rate. Piri *et al.* [31] have investigated the wear resistance of drill bits with tungsten carbide coating. Saeidi *et al.* [32] have used an image processing technique in order to monitore bit wear in rotary drilling in mining. Drilling is still very demanding in many areas around the world. The hydraulic rotary percussive drilling hammers is the most common technique for drilling, and the button bits are used. Drilling occurs due to the compression and rotation of the drill string. The button bits are used, in general, to drill a wide variety of rocks, from soft to extremely hard, since the wear of drill bits is considered as a project cost and project delay.

Various methods have been efficiently implemented in the drill wells using various drill bits in order to gain a paramount increase in the drilling performance and to lower the drilling costs associated with the drilling operation. Numerous attempts have been made to improve the manufacture of drill bits using optimum materials and design methods. Since the common bits are used in drilling, the majority of the research works are related to these particular bit types.

For many years, several abrasivity measurement techniques have been introduced in order to permit the engineers to forecast the bit life since the wear life of the rock cutting tools often has a linear trend with the measured rock abrasion [33].

In a literature review, it was seen that the previous studies generally focused on investigating the effects of the abrasivity rocks on the cutter wear, tool geometry, angle change of the cone, cutting efficiency, specific energy, and theoretical model using different laboratory test methods without carrying out any further investigations on the drill button bit wear rate. The bit wear rate is measured in accordance with the weight loss. The amount of drill bit wear is affected by many factors related to the properties of rocks. In this research work, efforts were made in order to develop the possible correlations of the drilling bit wear rate with the dominant globally recognized rock tests including the physical-mechanical property, drillability, abrasivity, and brittleness index measurement methods since the work was carried out in the field and the laboratory in order to see how rock properties affect the bit wear. The field data are more reliable than the laboratory test results. The field and laboratory experiments present the most direct method to predict the bit wear rate for drilling machines using the real field data. The main rock properties and bit wear mechanisms are argued for the options available to determine the bit wear rate. Thus we developed new regression models for prediction of the bit wear based on the rock properties. The developed models were confirmed using the statistical approaches. These models are thought to be helpful for the prediction of drill bit wear during the drilling operations. Additionally, the types of button tip wear is mentioned. The conclusions are discussed with respect to the literature.

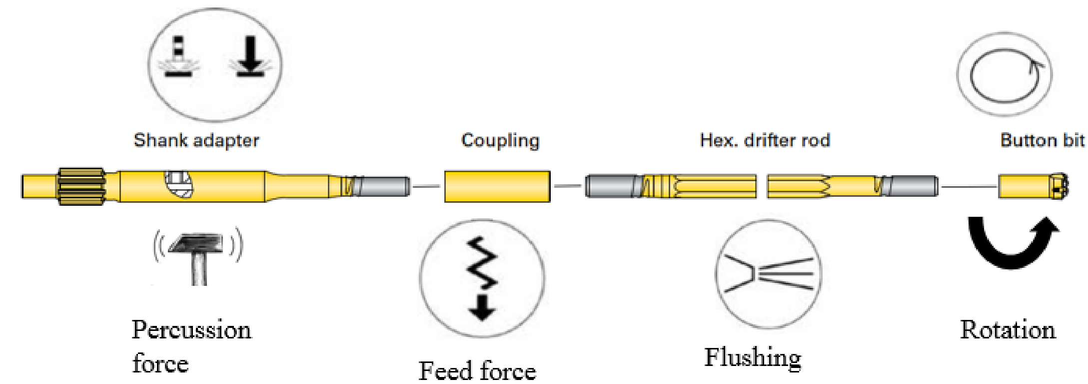
2. Materials and Methods

2.1. Field studies

This work involved the investigations made on two highway tunnels, namely Macka and Caykara) in the Eastern Black Sea Region in Turkey. The bit wear rates were calculated on the Sandvik DT820 (Macka tunnel) and Atlas Copco Rocket Boomer 282 (Caykara tunnel) drilling machines using the semi-ballistic-button bits, which offer a very good penetration, and it is sufficient for most rock formations including the soft and hard rocks. Two button bits were used for all the tests. The button bit diameter was 45 mm. The number of buttons on the bit body was 9 (6 gauge buttons and 3 front buttons). The flushing hole numbers were 4 (side 1 and front 3). The drill properties are given in Table 1 [34].

Table 1. Drill bit roperties [34].

Diameter (mm)	Number of buttons	Buttons x button diameter (mm)		Gauge buttons angle	Flushing hole		Weight approx. kg	Type
		Gauge	Centre		Side	Centre		
45	9	6x9	3x8	40°	1	3	0.8	R32 Threaded



Each semi-ballistic-button bit was drilled by 10 bores in an excavation surface, which had 3-m lenghts (totally, 10 × 3 = 30 m in an excavation face). The tests were performed on 11 different excavation surfaces (totally, 10 × 3 × 11 = 330 m for a bit) by weighing the drill bit in each tunnel excavation. After the tests, the surface of the drill bits was cleaned and weighed. The weight loss abrasion was measured as the drill bit wear. The percent weight loss was defined as the difference between the weight after and before the test divided by the initial weight drill bit. Some parameters were kept constant for all drillings during bore hole such as the rotational pressure (55 bar), water pressure (10 bar), and machine operator. The feed force (bar) and percussion force (bar) differed between the machines (Table 2). In this work, the amount of water was kept constant in the field tests during the drilling process because water lowered both the temperature of the drill bits and the rock cuttings from the bore surface.

Table 2. Characteristics of machines and drill bore.

Parameters	Atlas Copco Rocket Bommer 282	Sandvik DT820
Feed force (bar)	100	80
Percussion force (bar)	200	100
Rotational pressure (bar)	55	55
Water pressure (bar)	10	10
Bit diameter (mm)	45	45
Button number	9	9
Water flushing number	3	3
Bit type	Ballistic button	Ballistic button
Bore length (m)	3	3
Bore number	20	20

2.2. Laboratory studies

In the present work, the rock blocks were taken from 11 different points of the tunnel excavation surface for the experimental studies (6 point Maçka Tunnel, 5 point Caykara Tunnel), five of which were dasitic, three were basalt, and three were of basaltic crystal lithic tuff rock type. Each rock block was controlled for the standard testing of the samples free from fractures and cracks. The NX-size core specimens for the experimental testing were prepared in the laboratory using the core drill machines and sawing machines. The rock cores were prepared in accordance with the procedure suggested by ASTM [35].

The UCS tests were carried out on the trimmed core samples with a length to diameter ratio of 2:2.5. The stress rate was applied within the limit of 0.5-1 MPa/s, and at least five core samples from each rock type were subjected to the UCS tests [36, 37].

The Brazilian test is a simple indirect testing method used to obtain the tensile strength of rocks. The test was performed on the core samples (NX: 54.7 mm) having a length to diameter ratio of 1:2. A loading rate of 200 N/s was applied. The test was conducted on at least ten samples from each rock type, and the results obtained were averaged [36].

The point load strength test was performed on the cores having a length to diameter ratio of 1:2. The load rose steadily, and the failure of test occurred within 10-60 s. The test was repeated at least ten times for each rock type, and the average value was recorded as the point load strength. The results obtained were normalized according to the standard equivalent diameter of 50 mm [36].

P-wave velocities were performed on the trimmed core samples by direct transmission using the Pundit-plus model equipment. After testing the P-wave velocities of each sample, the UCS tests were carried out for that sample.

Several Schmidt rebound hammer types are used worldwide. Nowadays, the most widely used method for measuring the surface hardness of the test is the Schmidt rebound hammer. The Proceq Silver Schmidt instrument offers a wide measuring range, and the latest model PROCEQ Silver Schmidt provides unprecedented benefits for the users [38]. The tests were performed in accordance with the ISRM [39] methods.

The Cerchar abrasivity index (CAI) was performed using an original Cerchar apparatus. The Cerchar test was applied to the sawn specimens. Rockwell hardness of HRC 54/56 and the HRC 40/42 steel stylus were used for the tests. The tests were recorded as CAI [40].

The Drilling rate index (DRI) was determined by the Sievers'J-miniature drill (SJ) test and the brittleness value (S_{20}) test. The NTNU/SINTEF drillability testing methods of rocks were carried out in compliance with the standard test procedure Dahl *et al.*, [41] method.

In the literature, there are many different ways to determine the brittleness of rocks; however, description of the brittleness concept differs from author to author [42, 43]. In this work, the brittleness of rocks was determined from three different models (B_1, B_2, and B_3), which were calculated for the test results. The brittleness concepts used from the compressive strength and tensile strength are given as follow. In this case, the brittleness may be represented by the following equations (Equations 1-3):

$$B_1 = \frac{\sigma c}{\sigma t} \tag{1}$$

$$B_2 = \frac{\sigma c - \sigma t}{\sigma c + \sigma t} \tag{2}$$

$$B_3 = \frac{\sigma c \times \sigma t}{2} \tag{3}$$

where B_1, B_2, and B_3 are the brittleness determined from the compressive and tensile strengths, σc is the uniaxial compressive strength, and σt is the tensile strength.

3. Results and Discussion

In this work, the analysis of the recently drilled tunnels from NE of Turkey was carried out in order to investigate the bit abrasion loss. In all the experiments, the amount of weight loss on drill bits was calculated by measuring the weight of the button bit before and after the tests. Two button bits were used in the tunnel face. The bits had the same total travel distance during penetration but different weight losses of button bits were measured. Due to the different rock properties, the weights of the button bits were different. The bit wear rate varied from 90 to 177 mg/m for the basalt and basaltic crystal lithic tuff, respectively.

The results of the drill bit wear and rock properties were analyzed using the methods of least squares regression, confidence interval, and prediction interval.

An interval forecast always comprises the upper and lower limits between which a future unknown value (e.g. a point forecast) is expected to lie with a prescribed probability. In the real world applications, the prediction interval is of more practical use than the confidence interval because the prediction interval is concerned with the accuracy with which we can predict the targets or the observed values, not just the accuracy of our prediction of the true regression. The confidence intervals are enclosed in the prediction intervals, and are concerned with the accuracy of our estimate of the true regression [44, 45].

The linear curve fitting predictions were used in order to define the relations among the variables; the best fitting predictions are shown in Figures 1-4. As shown in these figures, a very high correlation was obtained between the bit wear rate and the rock properties for the testing methods within 95% confidence interval and 95% prediction interval. According to these figures, the prediction interval is always bigger than the confidence interval.

Keeping in view the dataset results, the best fit correlation functions were obtained in the positive linear regression analysis in the cases of UCS, Brazilian tensile strength, point load index, Schmidt rebound hardness, and P-wave velocity. However, in the case of the bit wear rate against the apparent porosity, the best fit correlation was found by applying the liner regression analysis.

The physical-mechanical properties of rocks show a high relationship with the bit wear rate. As displayed in Figure 1, there is an increase in the bit wear utilized at the selected tunnel face with the corresponding increase in the uniaxial compressive strength, Brazilian tensile strength, point load index, Schmidt rebound hardness (original Schmidt and Proceq Silver Schmidt), and P-wave velocity. However, there is a decrease in bit wear with the corresponding increase in the apparent porosity.

By calculating the 95% confidence interval and 95% prediction interval for the mean bit wear rate for all values of the mean physical-mechanical properties of the rocks within the range of observations, we get a 95% confidence interval and a 95% prediction interval for the regression line; this can be seen in Figure 1. This figure was plotted to compare the bit wear rate with the mechanical properties of rocks. As it can be seen in this figure, the bit wear rate has a much higher wear rate in drilling highly strong rocks. The best fit correlations of the bit wear rate with UCS was established when the regression analysis was applied. A very good correlation between the bit wear rate and the UCS of rocks can also be seen in Figure 1. The relation follows a linear model. The equation of the line is:

$$BWR = 1.457UCS + 17.367 \quad r=0.92 \tag{4}$$

where BWR is the bit wear rate (mg/m) and UCS is the uniaxial compressive strength (MPa).

The highest bit wear rate was measured on the basaltic crystal lithic tuff having a uniaxial compressive strength of 106 MPa. This reveals that the wear of drill bit is influenced by the rock properties. UCS varied from 51 MPa to 106 MPa. The strength characteristics of these rocks varied from medium to high strength. It was also found that the Brazilian tensile strength model had a high correlation among the produced models. Accordingly, two different Schmidt rebound hammers, classic and silver, were introduced, and the experimental results obtained by these two methods were compared with the results of each other. The Silver Schmidt (Q) values were found to be higher than the classic Schmidt values.

The results obtained from this work were in complete accordance with the research work of Adebayo and Akande [46], where the wear rate of button drill bit increased with the corresponding rise in the uniaxial compressive strength of rock. Piri *et al*. [31] have found a strong correlation between the drill bit wear and the rock strength. Piri *et al*. [47] have concluded that the higher the hardness, compressive strength, and abrasiveness of the rock are, the faster will be the bit wear.

Moreover, according to Majeed *et al*. [48], the bit life increases with decrease in the Brazilian tensile strength of rocks, and vice versa. The results of the current work (Figure 1) generally match up with the findings of the earlier research works [2, 49-52] in the analogy that the tool consumption has a relationship with the rock strength. On the other hand, Ramazan [53] has found a negative relationship between the cutter wear and UCS, and point load strength and Schmidt hammer values of rocks. He reported that the wear in the cutters decreased with increase in the rock strength. On the other hand, he obtained that the relationships were only for very low-strength and easily-cut tuffs.

Figure 1 shows a plot of the bit wear rate versus the apparent porosity values. The physical property values obtained for the apparent porosity varied from 0.68 to 2.85 for the basalt and basaltic crystal lithic tuff, respectively. The bit wear rate exhibits an inverse relationship with the apparent porosity value. As shown in this figure, there is an inverse relationship between the bit wear rates and the apparent porosity values. The equation of the line is:

$$BWR = -31.02n + 182.11 \quad r = 0.8 \tag{5}$$

where BWR is the bit wear rate (mg/m) and n is the apparent porosity (%).

As shown above, the correlation coefficients of the bit wear rate for the apparent porosity are very good.

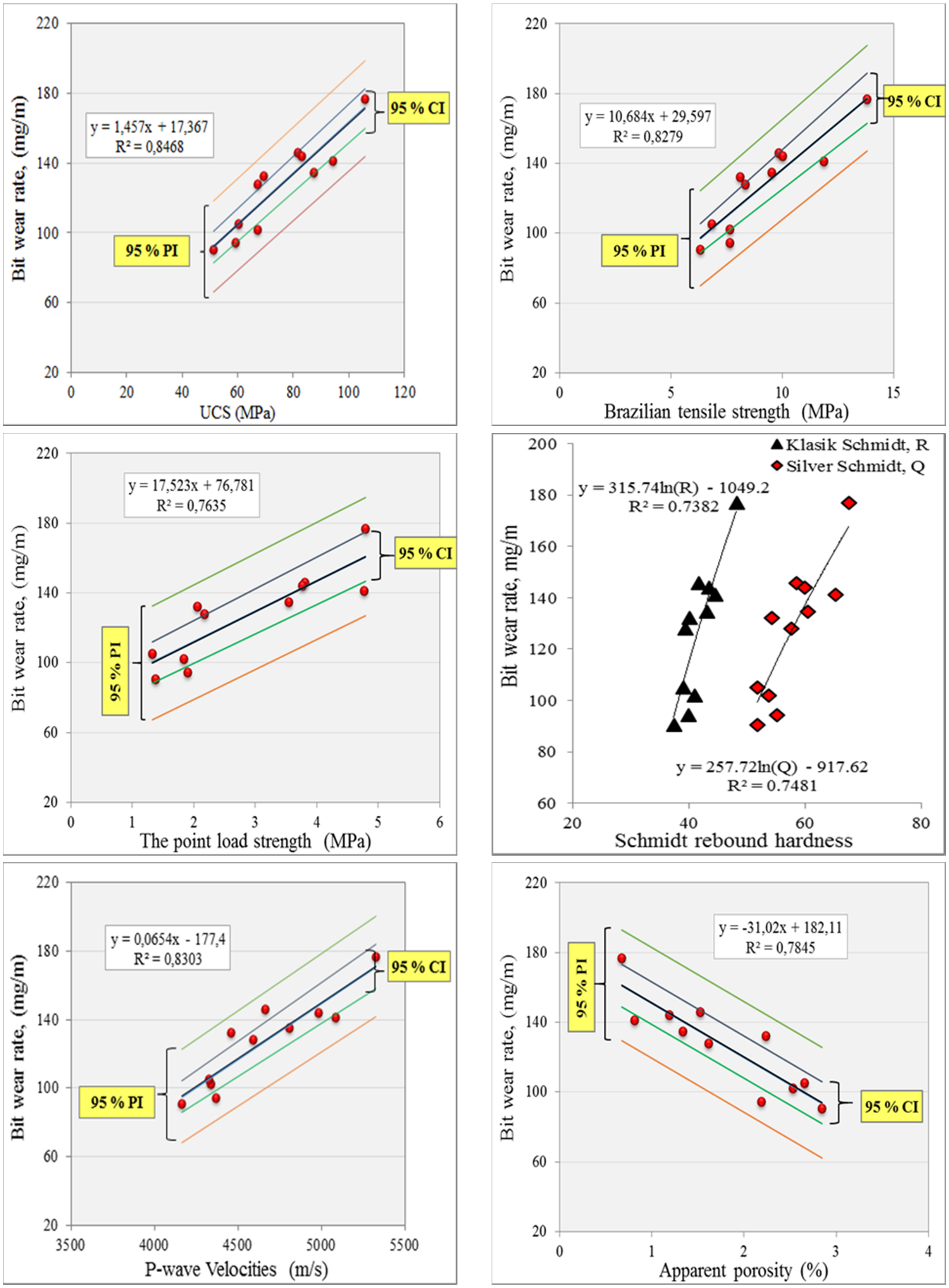


Figure 1. Bit wear rate correlation with the physical-mechanical property tests within a 95% confidence interval (CI) and 95% prediction intervals (PIs).

In this work, the expectations of developing correlations of the bit wear rate with the NTNU/SINTEF drillability methods were carried out. The drillability values obtained from the drilling rate index (DRI) varied from 28 to 58 for the basaltic crystal lithic tuff and dacite, respectively. The contrast with the 95% confidence interval (CI) for the mean bit wear rate for a mean drilling rate index of rocks is noticeable. The 95% prediction intervals (PIs) for the range of observed levels of mean drillability properties of rocks are shown in Figure 2, and again these widen on moving away from the drilling rate index of rocks. Figure 2 shows a negative linear relationship of a reasonable strength between the bit wear rate and the DRI values of the included rock units. The equation of the line is:

$$BWR = -2.430DRI + 235.48 \quad r=0.89 \quad (6)$$

The Cerchar abrasivity index is universally accepted for wear prediction and estimation of the cutter consumption [4, 33]. Figure 3 illustrates a relationship between the bit wear rate and the Cerchar test values for the HRC 54/56 and HRC 40/42 pins with a sawn surface condition for 11 rock units taken from the tunnel surface during the drilling operations. As expected, there is an increasing linear positive relationship of a reasonable strength between the bit wear rate (mg/m) and the CAI values, which indicates that as the rock abrasiveness increases, the bit wear rate is increased in a direct proportion. As expected, the CAI values with HRC 40/42 pins are higher than the CAI values with HRC 54/56 pins for the sawn specimens. The bit wear rate exhibits a high quality correlation with CAI for the HRC 40/42 and HRC 54/56 pins. It was found that, in practice, the generated models were reliable and accurate enough in order to predict the drill bit wear of intact rocks. The abrasion property values for the Cerchar abrasion index (HRC 40-42) ranged from 2.41 to 3.44 for the basalt and basaltic crystal lithic tuff, respectively. The abrasion property values for the Cerchar abrasion index (HRC 54/56) ranged from 1.36 to 2.3 for the basalt and basaltic crystal lithic tuff, respectively.

Figure 3 was plotted in order to compare the bit wear rate and the Cerchar test values for HRC 54/56 and CAI HRC 40/42. A very strong correlation can be seen between the bit wear rate and the CAI HRC 54/56 and HRC 40/42 pins. This relation follows a linear model. The bit wear rate increases with increasing CAI. The equation of the line is:

$$BWR = 82.523_{CAI54/56} - 118.05 \quad r = 0.8 \quad (7)$$

$$BWR = 77.878_{CAI40/42} - 18.049 \quad r = 0.95 \quad (8)$$

where BWR is the bit wear rate (mg/m) and CAI 54/56 and CAI 40/42 are the Cerchar abrasivity indices. As shown above, the correlation coefficients of the bit wear rate for CAI are very good.

Up to the present time, in the literature, there are very limited research works correlating the bit wear rate with CAI, which, in general, corresponds to the correlation suggested in this work. Plinninger [2, 54] proved a model for estimation of the button bit lifetime variation on the CAI values. Majeed *et al*. [48] have proposed a logarithmic function for the assessment of drill bit consumption based on the CAI values. Bilgin *et al*. [4] have performed a study on the influence of wear coefficient and the CAI test results based on different field experiences. Their study indicated that the relationship between CAI and the wear coefficient may be used for estimation of the cutter consumption. Ramazan [53] has found a positive relationship between the cutter wear and CAI values of rocks. He also reported that the abrasion rate increased with increasing effective bit wear rate.

The brittleness indices calculated using three different models were correlated with the bit wear rate in order to investigate the effect of the brittleness of the drilled rocks on the bit wear rate. A moderate relationship was obtained between the bit wear rate and only one brittleness index value (B_3) (Figure 4). The equation of the line is as in Equation (9).

$$BWR = 0.140B_3 + 76.648 \quad r = 0.91 \quad (9)$$

where BWR is the bit wear rate and B_3 is the brittleness index.

The calculated brittleness index value was obtained from a suggested model based on the uniaxial compressive strength and the Brazilian tensile strength of rocks. As it can be seen in Figure 4, increasing the brittleness values leads to an increase in the bit wear rate. The correlations were very high, all the samples were within a 95% PI. Similar correlations were found between the mechanical properties and Cerchar abrasivity index and bit wear rate results.

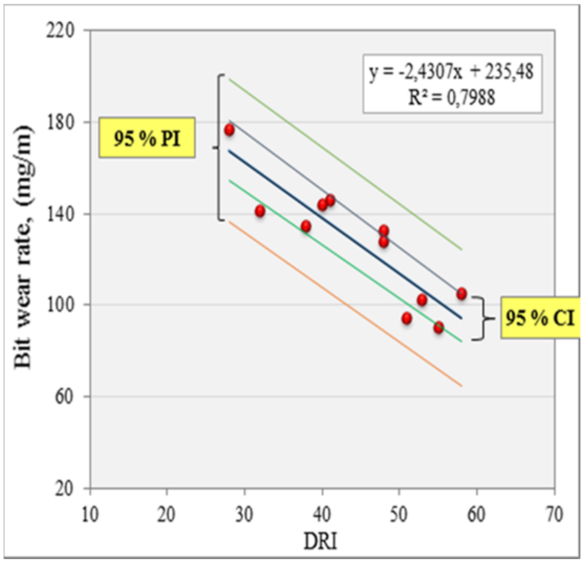


Figure 2. Correlation between the bit wear rate and the drillability tests within a 95% CI and 95% PIs.

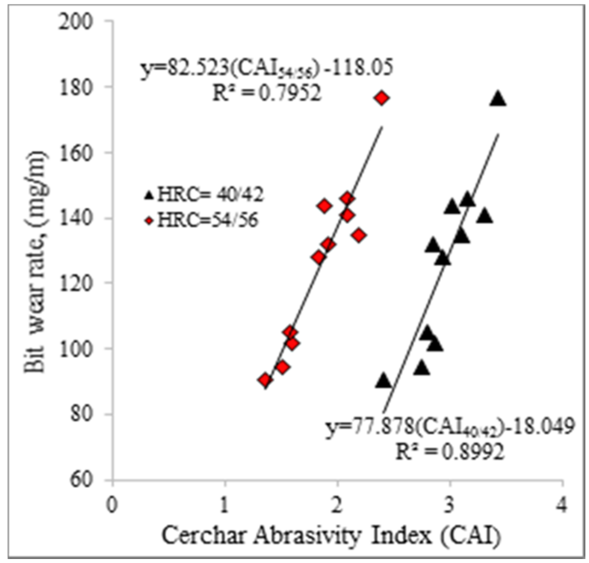


Figure 3. Correlation between the bit wear rate and the Cerchar abrasivity index.

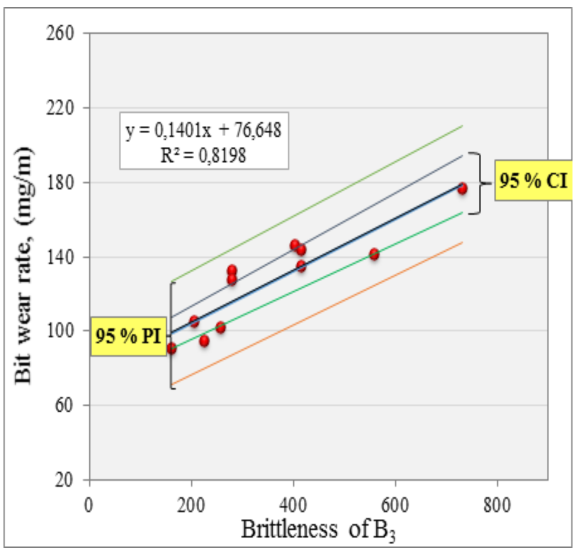
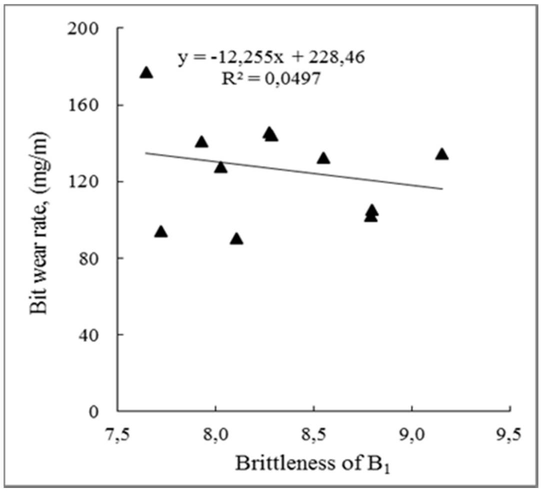


Figure 4. Correlation between the bit wear rate and the brittleness of the B_3 tests within a 95% CI and 95% PIs.

In the earlier studies, Yasar *et al*. [55] have found a positive strong relationship between the brittleness of the B_3 concepts and the cutter force and normal force of rocks. In this study, a positive strong linear correlation was found between the bit wear rate and the brittleness of B_3, which was similar to the results of the previous resource models. However, Ramazan [53] has fond a moderate relationship between the cutter wear and brittleness (B_3) of rocks, opposed to the results of this work. He found a negative correlation between the cutter wear and brittleness of the B_3 value, studied pyroclastic rocks on cutter wear in roadheaders with a low UCS strength. Al-Ameen and Waller [56] indicated that the broken rock potential causing abrasive wear is dependent on a combination the surface roughness of rock, mineral hardness, and rock strength.

On the other hand, the other brittleness (B_1 and B_2) concepts of rocks were correlated with the bit wear rate (Figure 5). As it could be seen in this figure, strong relationships (with a high R^2 value) were not found in the correlation results because the range of variation of B_1 and B_2 was small, and the rocks with different strengths may have the same stress ratio of B_1 and B_2 [57]. Kahraman [58] has reported that there is a variation between the formulations of brittleness. Thus the formulations have been used separately in the rock properties depending on its practical use. In the earlier studies, Goktan [59] has found no relation between the rock brittleness of B_2 and the cutting efficiency of chisel picks. Altındag [60] has found no meaningful correlations between the brittleness of B_1 and B_2. Kahraman [58] has investigated that there is no relationship between the brittleness of B_1 and B_2 and the penetration rate of the percussive drills.



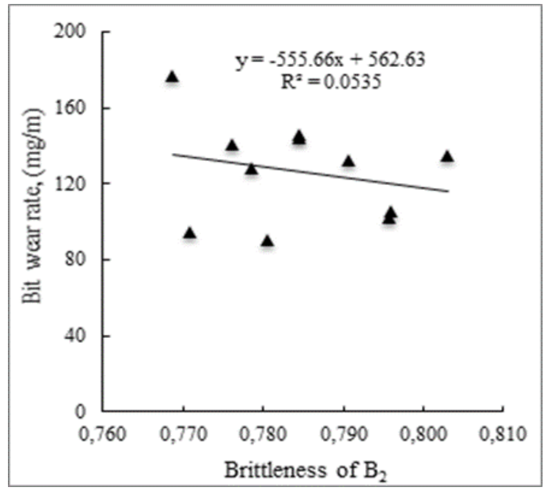


Figure 5. Correlation between the bit wear rate and the brittleness of B_1 and B_2.

The gauge buttons of drill bit are exposed to axial forces (Figure 6). In these wear types, the bit penetrates deeper into the rock mass and creates a lot of rock detritus, and thus both gauge buttons and bit body are exposed to the abrasive material. The tool body wears faster than the gauge buttons. Thus the gauge buttons may come loose due to missing the embedding or gauge button breakage.

In the previous studies, the researchers have investigated the classification system of the bit wear type, and according to these studies, classification of the bit wear type can be used as a fingerprint of the wear process. The wear of the bit body is a typical event for drilling the weak and abrasive rock types. When embedding is not sufficient, they may displace or easily undergo button breakage [2, 54].

Figure 6. Gauge buttons of drill bits.

The wear flat generated on the center of the button bits in the mode of abrasive wear is shown in Figure 7. The button bits were thoroughly observed at various stages of the button movement after each excavation tunnel surface in order to analyze the progress of the wear flat diameter on the button.

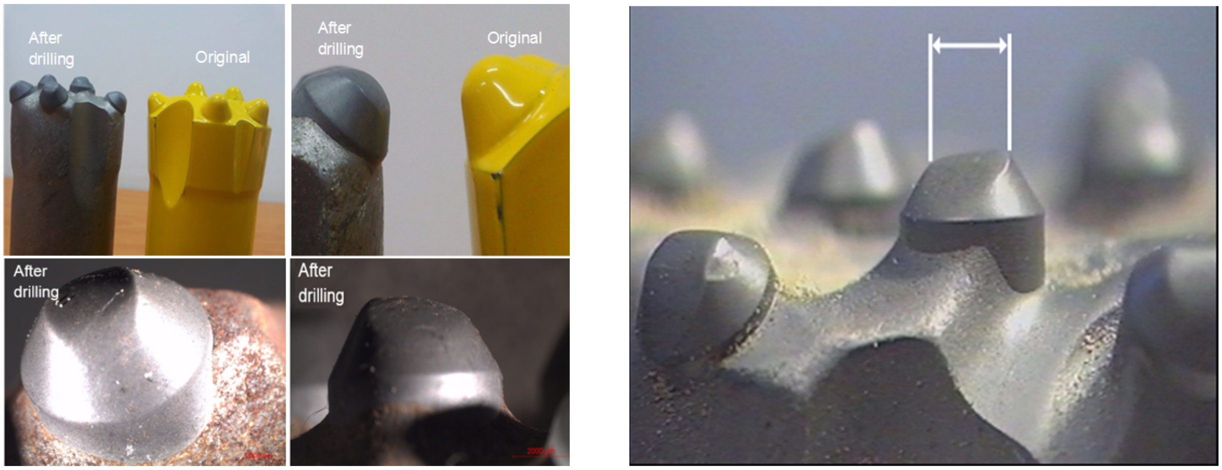
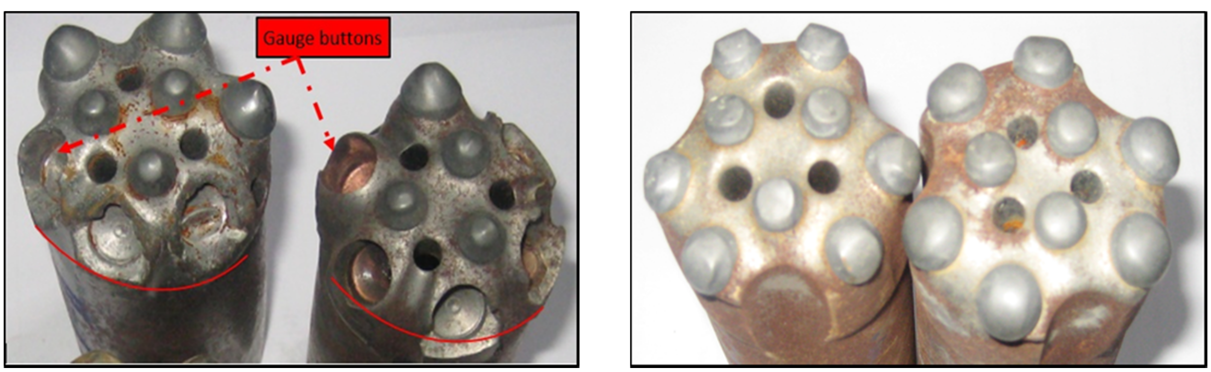


Figure 7. Button tip wear in button bits.

A good cemented button has always been able to handle that type of load with a minimal risk of breakage because it has a significantly higher resistance to that type failure. The good cemented carbide bits reached proved to exceed the average bit life (Figure 8a).

Cemented carbide is one of the most successful composite engineering material. Its unique combination of strength, hardness, and toughness satisfies the most demanding applications [61]. When drilling in non-abrasive materials, where carbide wear is minimal, the extended drilling intervals are possible [62].

The gauge buttons of a drill bit are usually exposed to the axial forces. When the bit wears, the load angle changes and the risk for button breakage increases (Figure 8b). Wear to the cemented carbide button on the periphery of the bit is very high, causing a reduced taper to develop, which diminishes the clearance of the bit [61]. In some materials such as hard sand stone and quartzite, the wear tends to be greater on the bit circumference. Thus when the buttons are sharpened, the diameter across the gauge buttons will be less than the diameter of the bit shoulders and the bit will tend to bind to the hole [62].



(a) **(b)**

Figure 8. Failure of gauge button.

Tool wear is an important parameter in the project cost and production efficiency, and thus the shape and geometry of the tool bits are important parameters for determining the efficiency of the rock tool for the penetration rate. Cemented carbide and hardened steel made the tool bit and body material, respectively. The cemented carbide is for the tip and hardens steel for the tool body since carbide tips are suitable for a combination of hardness, thermal resistance properties, high compressive strength, and high impact resistance. The cemented carbide structure has very hard tungsten carbide grains glued together with cobalt [63, 64]. Bellin *et al*. [65] have shown that using sintered grains of fine diamond provide a more resistance against abrasion and gives a lower wear rate, while coarse grains of the material have better toughness against impact and a higher wear rate.

The drill bit wear depends on the rock drilled through, and it is affected by the rock minerals and the amount of crushed rock in the bore hole. A decreased rotational speed would also have the effect of wear bits because a too high speed will result in an excessive wear on the drill string.

The wear rates of the drill bits differ between the rock properties. When the hardness of a rock is increased, the wear of the bits is increased. During a strong rock drilling, the bit is rapidly worn off, exposing the diamonds, which leads to a large material loss of the sample during that run and a large wear rate.

The design of the drill bit and the shape of the buttons has an important effect on the drill bit wear. A too fast wear of the bits show a wrong selection, resulting in an increase in the project time and thus the processing cost.

4. Conclusions

In this work, the effects of the physico-mechanical properties, drillability, abrasivity, and indirect brittleness test on the bit wear rate during drilling operations were investigated. For this purpose, some specimens were obtained from two drilled tunnels in Turkey and tested in the laboratory. The physico-mechanical properties, drillability, abrasivity, and brittleness of rocks were obtained from the laboratory tests. The bit wear rate and the laboratory test results were statistically analyzed using a simple regression analysis method. The following conclusions were made:

- The test results show a harmony with a 95% confidence interval and 95% prediction intervals and the significance level of $P < 0.05$.
- A strong positive linear correlation was obtained between the bit wear rate and the mechanical properties of rocks including the UCS, Brazilian tensile strength, point load index, Schmidt hammer (classic and silver), and P-wave velocity. These relationships showed that the bit wear rate increased with increase in the rock strength. Similarly, anincreasing linear positive relationship was found between the bit wear rate and the CAI values and indirect brittleness of B_3, which indicated that as the rock abrasiveness and brittleness increase, the bit wear rate is increased in a direct proportion. The rock abrasiveness and rock strength have a significant influence on the bit wear. However, a strong negative relationship was found between the bit wear rate and the drilling rate index and the apparent porosity values of rocks. These relationships show that the bit wear rate in the drillings decrease with increase in the apparent porosity and DRI of rocks. This work provided a good agreement between the trends of the bit wear and the rock properties. A reliable correlation was not found between the bit wear rate and the brittleness (B_1 and B_2) values.
- The bit wear rate of the drilling machines is one of the important parameters involved in the mechanical drilling projects. All the drilling tools are affected by various types of rocks and the geological surroundings including the rock strength, tensile strength, abrasiveness, and rock structure.
- The results obtained from this research work showed that the bit wear rate was not related to the abrasive mineral content alone, and the test was largely influenced by the type and degree of the cementation materials (rock strength).
- The amount of bit wear rate depends on the properties of rocks, abrasive mineral content, tool material composition, and operational conditions. The button type and design also considerably affect the tool wear.
- The wear of drilling bits was examined in different rock types. These results obtained showed that the increased strength of rocks and abrasiveness increased the bit wear rate.
- In this work, several drill bit wear models including the linear and non-linear ones were developed, and then the best possible variants were selected among them. Additionally, the developed models were compared with each other and other models in the literature. It can be stated that the models developed using the accessible equations are precise enough in order to estimate the drill bit wears.
- The models developed in this work are suitable for estimating the drill bit wear; however, the Cerchar abrasion index and the uniaxial compressive strength of the rock models are the most accurate ones among them. Further, these models can be used for similar rock types in order to estimate the rock brittleness; however, the results obtained are open to be improved and generalized. Moreover, the failure of the gauge buttons and center button bits was investigated, while the gauge buttons and bit body were exposed to the abrasive material and rock detritus. The bit body wears faster than the gauge buttons. Thus the gauge buttons may be displaced due to the lack of embedding of the buttons. A good cemented button decreases the bit wear and increases the average bit life.
- The success of a project management has links with the cost, time, and quality. The tool wear is an important parameter involved in a project efficiency and the shape and geometry of the tool bits are important parameters involved in determining the efficiency of the rock tool for penetration rate.

- This work provided some beneficial models in order to help the engineers and contractor on their future plans and the cost estimation of the drilling project. The effects of rock properties on the bit wear rate contribute to the success of selecting the drill bit.

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اندازه گیری، پیش بینی و مدل‌سازی سایش در طول عملیات حفاری

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چکیده:

مدل‌سازی سایش دکمه‌های سرمته می‌تواند باعث افزایش کارایی در عملیات حفاری شود. مرتبط با این موضوع، هدف آن بررسی مکانیسم سایش دکمه‌های سرمته است. سایش در دکمه‌های سرمته تحت تأثیر بسیاری از عوامل مربوط به حفاری و خواص سنگ است. نوع و شدت سایش به عوامل پیچیده‌ای بستگی دارد که لازم است برای پیش‌بینی میزان سایش در محیط کارگاه و شرایط آزمایشگاهی در نظر گرفته شود. آزمایش‌های آزمایشگاهی به منظور مشخص کردن روابط بین نرخ سایش دکمه و خصوصیات فیزیکی-مکانیکی، قابلیت حفاری، خواص سایشی و شکنندگی سنگها انجام شده است. از آنالیز آماری برای بدست آوردن معادلاتی برای تخمین میزان فرسایش دکمه بر اساس خصوصیات سنگ استفاده شده است. در این کار، از یک تکنیک کلی برای تخمین سطح اطمینان و سطح پیش‌بینی برای مدل‌های رگرسیون استفاده شده است. در این مقاله خلاصه‌ای از خواص سنگ و مکانیسم سایش دکمه آورده شده است و گزینه‌های تعیین نرخ سایش دکمه‌های سرمته بررسی می‌شود. مدل‌های آزمایشی نشان می‌دهد که خصوصیات سنگ می‌تواند ایده‌ای در مورد سایش ارائه دهد. آنها همچنین ارتباط خوبی میان میزان سایش دکمه نشان می‌دهند. همچنین برخی از مدل‌ها برای نشان دادن مقدار سایش تولید شده‌اند همچنین به منظور تخمین میزان سایش دکمه روشی ارائه شده است. نتایج به دست آمده از مطالعه مدل‌های توسعه یافته، مطابقت خوبی با ارزیابی عملکرد یک حفاری کارآمد فراهم می‌کند و یک ارزیابی غیر مستقیم از میزان سایش دکمه‌های سرمته را در طی فرایند حفاری ارائه می‌دهد، که می‌تواند به کاهش مصرف انرژی ویژه و کاهش هزینه‌های تعویض سرمته منجر شود.

کلمات کلیدی: سرعت سایش دکمه سرمته، ماشین آلات حفاری، دکمه سرمته، حفاری موثر، مدل‌های توسعه یافته.