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A laboratory study of rock properties affecting the penetration rate of pneumatic top hammer drills

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Abstract
Having collected rock samples from eight mines and one high way slope, the researchers did some tests on the samples to determine dry density, Uniaxial Compressive Strength, tensile Strength (Brazilian Test), elastic modulus, Schmidt hammer rebound number. In addition, a thin section of each rock was studied to calculate the mean size of rock grains, quartz content, hardness and abrasivity. The rock samples were finally drilled using an actual pneumatic top hammer drilling machine with a 3½ inche diameter cross type bit. Regression analyses showed that Brazilian tensile strength (R^2=0.81), uniaxial compressive strength (R^2=0.77) and Schmidt hammer rebound (R^2=0.73) have the most significant effect on drilling rate and have a relatively appropriate correlation with drilling rate.

Keywords: *Drillability, rock material, physical and mechanical properties, pneumatic top hammer drills.*

1. Introduction

In open pit mining and some contraction works, drilling has a significant role in the whole operation. Considering the high operation costs, 10-14% of total costs[1,2], as well as the most expensive machinery, full recognition of the rock and machine parameters involved in the drilling, optimizing the efficiency of drilling process would be necessary. Up to now, the most common drilling methods, which have been developed for bench blasting, are rotary drilling and rotary percussive drilling [3]. Depending upon where the hammer is located, rotary percussive rigs are classified into two large groups:

a. Top hammer: in these drills, two of the basic actions, rotation and percussion, are produced outside the blast hole, and are transmitted by the shank adaptor and the drill steel to the drill bit. The hammer can be driven hydraulically or pneumatically. The most common range of diameters in surface applications of these rigs is 50 to 127mm.

b. Down-the-hole hammer; the percussion is delivered directly to the drill bit, whereas the rotation is performed outside the hole. The piston is driven pneumatically, while the rotation can be hydraulic or pneumatic. The most common range of diameters in surface applications of these rigs is 75 to 200mm.

The pneumatic top hammer drills are used in short blast holes with a length between 3 and 15m, especially with small diameter and in hard rocks and difficult access areas. In many small and medium mines such as limestone, gypsum, salt and building materials and some short construction works this system is widely used and is more useful than hydraulic drills because of some advantages such as simplicity, reliability, easy repair and low capital cost.

Since 1960, many researchers have studied the top hammer and down the hole drilling and some relationships between drilling rate and various mechanical and physical rock properties have been presented. In this study, the influence of effective mechanical and physical properties of rocks on penetration rate of pneumatic top hammer drills has been studied in field and laboratory.

2. Effective parameters influencing the rock drillability and penetration rate of drilling

In previous investigations, many researchers have widely studied the effective parameters on penetration rate of drilling system [4-34]. The initial works done on drilling were reviewed by Singh [4]. He reported that Guss and Davis (1927) [5] and Simon (1956) [6] had found that the penetration rate of drilling is a function of hardness, toughness and strength of rocks. Hartman [7] used the volume created in percussive drill as a quantity for estimation of rock drillability. Paone et al. [11] observed that compressive strength, tensile strength, Young's modulus, shore hardness and coefficient of rock strength (CRS) affect the drilling rate. Selmer-Olsen and Blendheim [12] showed that the rate of percussive drilling has a strong relationship with Drilling Rate Index (DRI) of rocks. Hustrulid and Fairhurst [13-16] did a comprehensive theoretical and experimental study on percussive drilling and finally presented a drilling model based on blow energy, blows per minute, coefficient of energy transfer from drill bit to rock, apparent specific energy and cross-sectional area of hole. Tandanand and Unger [19] used the coefficient of rock strength in their presented drilling model. Rabia and Brook [20, 21] proposed that an empirical equation containing rock impact hardness and Shore hardness correlates with drilling rate of down-the-hole drills for wide range of rock types. Howarth [29, 30] emphasized on effects of many rock parameters such as texture, mineral content, compressive strength, density, Young's modulus, Schmidt hammer rebound, tensile strength, P-wave velocity, porosity, water content on drilling rate, and particularly correlated the drilling rate with texture coefficient. Bilgin et al [35] analyzed the drilling performance of rotary drills in five Turkish surface coal mines based on machine parameters and some rock properties such as compressive strength, tensile strength, Schmidt hammer rebound, drilling index and point load index. Ersoy and Waller [36] developed a model for the prediction of polycrystalline diamond compact (PDC) and impregnated drill bits based on laboratorial studies. For this purpose they classified many effective rock parameters and used texture coefficient, quartz content, compressive strength, tensile strength, Young's modulus, Mohs hardness, Shore hardness, Cerchar abrasivity index and Schimazek's F-abrasivity factor in their studies. In another research, Ersoy and Waller [37] correlated the penetration rate of pin, hybrid and impregnated drill bits with texture coefficient of five different rock types. Shimada & Matsui [38] used compressive strength, tensile strength (Brazilian test), Young's modulus, Shore hardness and especially rock impact hardness number (RIHN) in their laboratorial and field investigation on rotary percussive drills in 13 rock types in Japan. Serradj [39] related the drillability of rocks to the Protodyakonov index (PI) and uniformity coefficient (UC). Thuro & Spaun [40] presented the major correlation of compressive strength, tensile strength and Young's modulus with measured drilling rates. Also, they introduced a new property for toughness, referring to drillability named "desrtruction work". They concluded that destruction work of rock has an excellent correlation with drilling rate. Thuro [41] did a comprehensive study on drillability prediction in rotary percussive drilling in tunneling. He classified the effective operational factors and rock properties on drilling excellently and finally presented some correlations between drilling rate and bit wear and porosity, destruction work, equivalent quartz content, density and joints spacing. Kahraman [42], as one of the active drilling researchers, developed penetration rate models for rotary, down the hole and hydraulic top hammer drills using multiple curvilinear regression analysis. During research, he measured compressive strength, tensile strength, impact strength, point load strength, wave velocity, Young's modulus, density and quartz content as the most important rock parameters influencing the drilling rate. In another research, Kahraman et al [43] did a very comprehensive study for presenting a new drillability index for prediction of penetration rate of rotary drilling. They reached some good correlations between drillability index and compressive strength, tensile strength, point load index, Schmidt Hammer rebound, impact strength, P-wave velocity, elastic modulus and density. Osanloo [44] investigated the rock cohesion force, porosity, density, texture, compressive strength, RQD, elasticity, plasticity, rigidity, hardness and structure of rock mass effects on drilling. Li et al [45] analyzed the piston rebound common to both the Schmidt Impact Hammer and down-hole hammer drills and established a quantitative relationship between the amount of rebound of the piston and the impact resistance index (K). Plenninger et al [46, 47] did a study on the relationship between rock abrasivity and bit wear prediction. Using a criterion based on maximum feed rate at minimum specific energy (SE_{drill}), Ersoy [48] evaluated the optimum performance of polycrystalline diamond compact (PDC) and tungsten carbide (WC) bits. Kahraman et al [49] investigated the dominant rock properties influencing the penetration rate of hydraulic top hammer drills –with button bit- comprehensively. They correlated the drilling rate with theoretical specific energy, compressive strength, Brazilian tensile strength, point load index, Schmidt Hammer rebound, impact strength, P-wave velocity, elastic modulus and density in eight rock types. Izquierdo and Chiang [50] developed a methodology for estimating of rock specific energy in down the hole drilling. They presented two experimental models; one model for the simulation of thermodynamic cycle of DTH hammers and another model for stress wave propagation analysis to estimate the effective energy delivered to rock. Tanaino [51,52] investigated the dependence of specific energy and drilling rate of roller cutter machine and down the hole pneumatic puncher on compressive strength of rocks. Akun and Karpuz [53] correlated the penetration rate of surface-set diamond drilling with compressive strength, RQD, discontinuity frequency and specific energy. Schormair et al [54] studied on influence of rock anisotropy on drilling rate and crack propagation in rock using experimental investigations and numerical modeling. Singh et al [55] used Protodyakonov index, impact strength index, shore hardness, Schmidt hammer number for prediction of drillability and wear factor of rocks using Artificial Neural Networks (ANN). Hoseinie et al [56,57] developed a new classification system named Rock mass Drillability index (RDi). They used compressive strength, Mohs hardness, Texture (grain size), joint spacing, joint filling and joint dipping in their classification. They presented a good correlation between RDi and penetration rate of DTH drilling.

3. Laboratory studies

3.1. Testing rock properties

The main factors used in predicting the penetration rate of drilling systems are characteristics of rocks. Therefore, a testing program was done to determine the physical and mechanical properties to investigate the dependence of drilling rate on rock. Considering the revision of previous studies, especially the studies done by Kahraman et al [43, 49] and Thuro [41], the most important rock properties which were chosen in this study are dry density, uniaxial compressive strength, Tensile strength (Brazilian test), Schmidt hammer rebound number, Yuong's modulus, mean hardness of rock, mean grain size, equivalent quarts content and Schimazek's F- abrasivity. The rock samples which were studied in this research were collected from eight mines and one high way's slope.

3.1.1. Mineralogical and petrographic properties

A typical thin section belonging to each rock type was prepared for petrographical analyses and the determination of textural rock characteristics. Primary and secondary minerals were identified and their grain sizes were evaluated. The results of the petrographical analysis of thin sections are given in Table 1.

3.1.2. Physical and mechanical properties

Standard samples were prepared from the total samples of rocks. Then, standard tests were completed to measure the above mentioned parameters following the suggested procedures by the ISRM standards [58].The bulk dry density of rocks was determined on cylindrical rock cores with 54mm diameter and 50mm length. The uniaxial compressive strength (UCS) tests were done on testing machine with a capacity of 2000 kN at a loading rate of 1 KN/sec. Cylindrical NX specimens with a length to diameter ratio of 2.5:1 were used. Tensile strength was determined using the Brazilian testing (BTS) method. NX disc specimens with a thickness to diameter ratio of 1:2 were used. Schmidt hammer rebound tests were carried out on fresh surfaces of outcrops of rocks by using a calibrated L-type Schmidt hammer in the field. For estimation of elasticity of each rock type, tangent Young’s modulus was measured at a stress level equal to 50% of the ultimate uniaxial compressive strength of each rock type.

There is no single physical property to quantify and describe the "hardness" as if it is the uniaxial compressive strength for stress. Also, a lot of petrographical parameters such as rock texture and mineral fabric were discussed to be used for predicting the tool wear and drillability. But, the structural methods are very time consuming and thus were not applied in practice [41].

It is clear that, tool wear is predominantly a result of the mineral content harder than steel (Mohs hardness ca. 5.5), especially quartz (Mohs hardness of 7).

Table. 1. Results of petrographical analysis of thin sections

Location	Formation	Mineral Content	Texture	Mean grain size (mm)
Sungun Copper Mine	Monzonite	Quartz, cerussite, zircon muscovite, opaque minerals.	Granublastic	0.51
Ooch Mazi Mine	Granite	Feldspar, andesine, biotite, amphibole, pyroxene, chlorite, opaque minerals.	Granular	6.56
Souphiyan Mine-75	Limestone	Calcite, organic material, hematite, rock fragments.	Sprite	1.52
Souphiyan Mine-17	Limestone	Calcite, hematite, opaque minerals.	Sprite	1.35
Khalkhal Mine	Travertine	Calcite, organic material, void.	Sprite	1.27
Sardat Abaad Mine	Travertine	Calcite, hematite, opaque minerals, void.		1.12
Khajemarjan Mine	Silica	Quartz, andesine, microcline, muscovite, apatite, zircon, rock fragments, opaque minerals.	Granular	2.45
Razgah Mine	Nepheline Cyanide	Alkali feldespate, plogiyoclaz, Nepheline, augite, olivine, apatite, opaque minerals.	Granular	3.77
Pasdaran High Way	Limy-Sandstone	Calcite, Quartz, rock fragments	Granular	1.3

To include all minerals of a rock sample, the equivalent quartz content has been determined in thin sections by modal analysis - meaning the entire mineral content referring to the abrasiveness or hardness of quartz (Eq.1). Therefore, each mineral amount is multiplied with its relative Rosiwal abrasiveness to quartz (with quartz being 100) [41].

$$equ = \sum_{i=1}^{n} A_i \times R_i \qquad (1)$$

Where, A is mineral amount (%), R is Rosiwal abrasiveness (%) and *n* is number of minerals. An appropriate correlation between Mohs hardness and Rosiwal abrasiveness is given in Figure 1. When the Mohs hardness is known, the abrasiveness of minerals can be estimated by this chart accurately.
After the estimation of each mineral proportion, mean hardness of each rock was calculated based on the hardness of contained minerals using following equation:

$$\text{Hardness}_{mean} = \sum_{i=1}^{n} A_i \times H_i \qquad (2)$$

Where A is mineral amount (%), H is Mohs hardness, and *n* is number of minerals in rock.

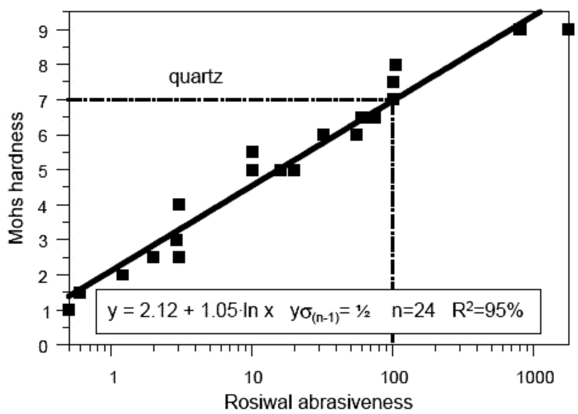

Figure 1 .Correlation between Rosiwal abrasiveness and Mohs hardness [41].

F-abrasivity factor is defined as [37, 59]:

$$F = \frac{(EqQtz \times \varphi \times BTS)}{100} \qquad (3)$$

Where, F is the Schimazek's wear factor (N/mm), EqQtz is the equivalent quartz volume percentage, is the grain size (mm) and BTS is the indirect Brazilian tensile strength. It has been suggested that if the grain size is less than 0.025 mm, the grains have little influence on abrasivity. Tensile strength is taken as a measure of the bond strength between grains.

Mean hardness and Schimazek's F-abrasivity of tested rocks were calculated using Equations 2 and 3. The measured physical and mechanical properties of rocks are summarized in Table 2.

Table. 2. Physical and mechanical properties of studied rock

Formation	UCS (MPa)	BTS (MPa)	Dry Density (gr/cm^3)	Schmidt hammer rebound	Young's modulus (GPa)	Mean Mohs hardness	Equivalent quarts content (%)	Schimazek's *F*- abrasivity (N/mm)
Monzonit	57	4.21	2.58	50.9	51.23	4.75	52.81	1.13
Granite	87.5	5.36	2.65	58.1	60.84	5.42	32.5	11.44
Limestone	40	5.45	2.79	52.3	58.82	3.05	3.4	0.25
Limestone	51	2.23	2.59	54.1	44.1	3.15	4.2	0.14
Travertine	50.5	2.4	2.46	54.3	48.83	2.6	1.93	0.05
Travertine	53	1.45	2.55	50.2	70.19	2.7	3.85	0.06
Silica	112	4.18	2.58	54	43.28	6.35	72.45	7.42
Neph. Cyanide	76	4.46	2.49	57.2	51.59	5.85	37.59	6.32
Santstone	14	0.78	2.24	45.5	9.28	2.1	1.62	0.016

3.2. Drilling tests

After testing the important rock parameters, drilling tests were done on intact rock samples. For this purpose, all massive samples were fixed in ground using concrete. The concrete prevents the rock blocks from displacement under the bit load and its rotation. Using this approach, the drilling machine could drill the blocks in a suitable and stable condition without any movement. A pneumatic top hammer drill machine with 35 bar pull down pressure, 2200bpm blow frequency, 40 bar rotational pressure and a new 3½ inches diameter insert cross type bit was used in drilling studies. In each sample, five holes with 15cm depth were drilled and the average of drilling times of those holes was recorded as the drilling rate in each rock type Table 3) Figure 2 shows the drilling machine while drilling the samples.

Table.3. Penetration rate of each formation resulted from drilling testes

Formation	Penetration Rate (m/min)
Monzonite	0.52
Granite	0.32
Limestone	0.34
Limestone	0.44
Travertine	0.58
Travertine	0.81
Silica	0.1
Neph. Cyanide	0.22
Sandstone	1.28

Figure 2. Drilling machine while drilling the rock samples

4. Regression analysis

According the data presented in Table 2 and Table 3, regression analysis was done and some mathematical relationships were achieved. For regression analyses, some famous types of mathematical equations were tested and the best equation with highest R^2 was selected as a regression equation between drilling rate and rock properties. Standard error bars were shown on data points. The plots of drilling rate versus the rock material properties are shown in Figure 3 to Figure 10. As shown in these figures, the drilling rate decreased logarithmically with an increase in the rock strength which is monitored by uniaxial compressive strength, tensile strength (Brazilian test) and Schmidt hammer rebound. As shown in the plots, among the above mentioned parameters, Brazilian tensile strength has the strongest relation between drilling rate (R^2=0.82).

Increasing the mean hardness of rocks drilling rate decreases exponentially and increasing Schimazek's F- abrasivity, penetration rate of drilling decreases by power equation However, the results reveal that the data show relatively good trends between drilling rate and dry density, Yuong's Modules and Equivalent Quartz Content, nevertheless, the achieved equations are not applicable for the prediction of penetration rate of pneumatic top hammer drills because of low R^2 values.

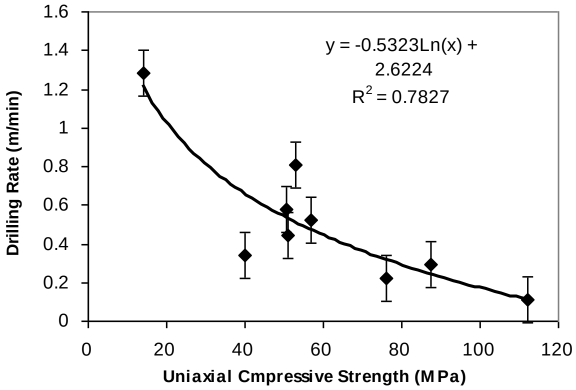

Figure 3. Drilling rate versus uniaxial compressive strength

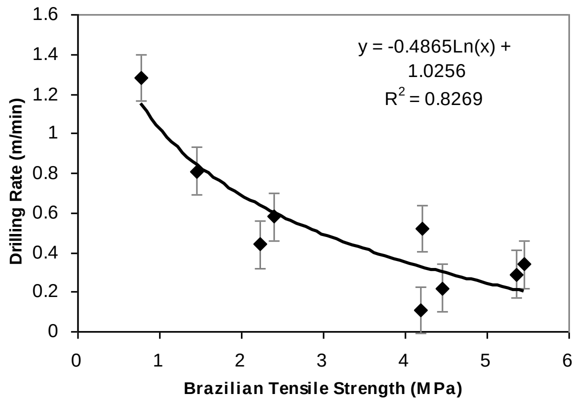

Figure 4. Drilling rate versus Brazilian tensile strength

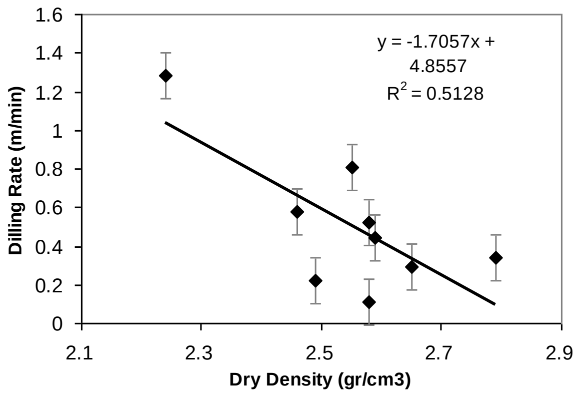

Figure 5. Drilling rate versus dry density

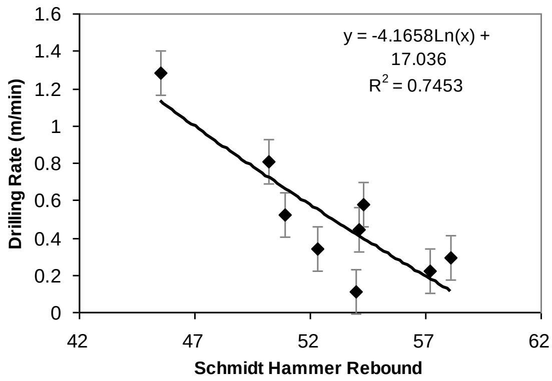

Figure 6. Drilling rate versus Schmidt hammer reboun

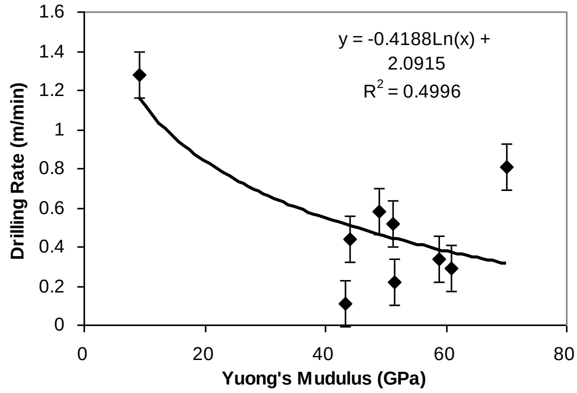

Figure 7. Drilling rate versus Young's modulus

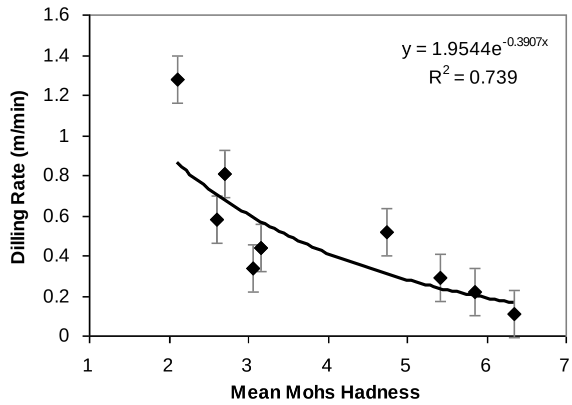

Figure 8. Drilling rate versus mean Mohs hardness

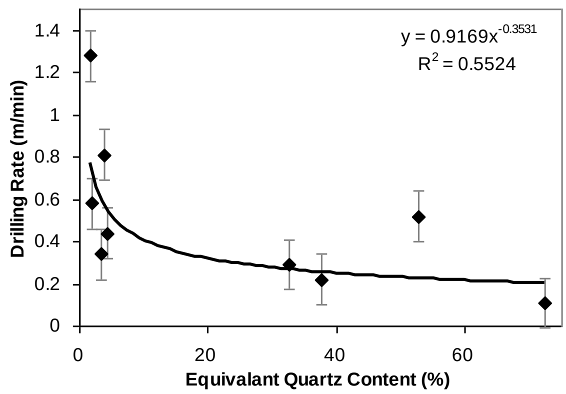

Figure 9. Drilling rate versus Equivalent Quartz Content

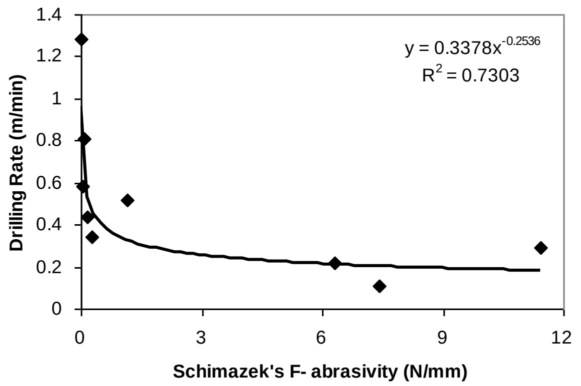

Figure 10. Drilling rate versus Schimazek's F-abrasivity

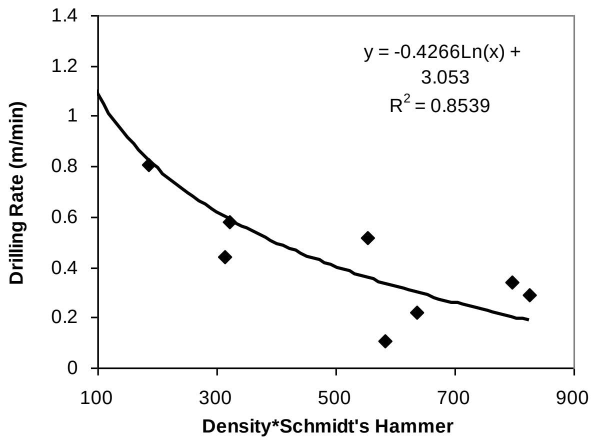

Figure 11. Drilling rate versus Density×Schmidt Hammer

Mean Mohs hardness and Schimazek's F-abrasivity show relatively acceptable correlation with drilling rate. The most attractive result in these case is that in low abrasive rocks (Equivalant Quartz Content < %15) the drilling rate is more sensitive to rock abrasiveness (Equivalant Quartz Content) and in medium and abrasive rocks (Equivalant Quartz Content > %15) this sensitivity is so low.

It is obvious that any individual parameter can not be used properly for the prediction of drilling rate because drilling is a very complicated process and many rock properties affect it simultaneously. Therefore, the application of a combination of parameters can be more effective. For example, as shown in Figure 11, with simple combination (multiplication) of density and Schmidt hammer values, the correlation improves. By adding the Brazilian tensile strength to this combination, the correlation becomes better than previous (Figure 12). Using these brief indexes, one can predict the drilling rate and estimate the rock drillability in a cheap, easier and fast way.

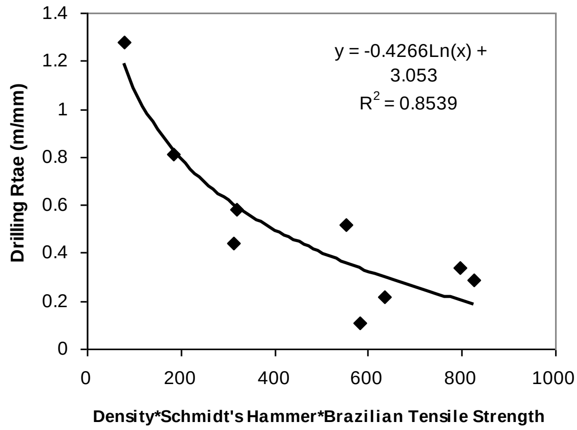

Figure 12. Drilling rate versus Density×Schmidt Hammer×Brazilian Tensile Strength

5. Conclusions

The results of previous studies show that numerous parameters such as the origin of rocks formation, Mohs hardness, texture of rock (shape and size of rock grains), porosity, density, abrasiveness, rigidity, P-wave velocity, elasticity and plasticity, UCS, tensile strength, affect the drilling rate and drillability of rocks.

In this paper the drilling rate of pneumatic top hammer drills was correlated with dry density, uniaxial compressive strength, Tensile strength (Brazilian test), Schmidt hammer rebound number, Young's modulus, mean hardness, mean grain size, equivalent quarts content and Schimazek's F- abrasivity of nine rocks.

The regression analyses showed that tensile strength (Brazilian test), uniaxial compressive strength and Schmidt hammer rebound are two important parameters affecting the drilling rate and have relatively an appropriate correlation with the drilling rate.

Considering the presented results, it is obvious that the correlations have been suggested according to uncontrollable factors governed by rock material physical and mechanical conditions. It is suggested that in future studies the parameters of drilling equipment and effects of bit diameter be incorporated.

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